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Second-Round Wage-Price Effects of Raw Material Costs: An Empirical Analysis Using a DSGE Model

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Second-Round Wage-Price Effects of Raw Material Costs: An Empirical Analysis Using a DSGE Model*

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Abstract

This paper empirically examines the second-round effect of raw material price increases using a DSGE model. Specifically, it explores how price increases driven by rising raw material costs spill over into wages, which then feed back into prices. The analysis focuses on Japan and Europe, which share similar structures in terms of raw material inputs. The results show that the first-round effect, which captures the pass-through of rising raw material costs to prices, is slower in Japan than in Europe. On the other hand, the second-round effect through wages is gradual but persistent in both Japan and Europe. Furthermore, during the period of high inflation since 2020, the first-round effect of higher raw material costs was the main driver of inflation in both Japan and Europe, while the second-round effect contributed to the persistence of inflation. The paper also suggests that the recent changes in wage rigidity in Japan may have strengthened the second-round effect.

JEL code: E17, E31, J30

Keywords: Wages, Prices, Second-Round Effects, DSGE Model

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1 Introduction

"We can't allow a wage–price spiral to happen. And we can't allow inflation expectations to become unanchored."

—— *Jerome Powell, FOMC Press Conference, May 4, 2022.*

"Our restrictive monetary policy stance, the ensuing strong decline in headline inflation and firmly anchored longer-term inflation expectations act as a safeguard against a sustained wage-price spiral."

—— *Christine Lagarde, speech at European Parliament, February 26, 2024.*

Understanding the second-round effect from wages to prices, where a price increase triggers wage growth that in turn fuels further price hikes, is essential for central banks to achieve stable economic and price conditions. The price surges observed in major countries in the 1970s are an example where the second-round effect turned out to be more pronounced than central banks had anticipated. Looking back, not only did the rise in raw material prices drive wage increases, but these wage hikes also triggered further price increases, creating a spiral where both wages and prices rose in tandem, destabilizing economies in many countries.

In recent years, factors such as supply chain disruptions and rising geopolitical tensions have caused raw material prices for energy, food, and other commodities to soar globally. In this context, both the U.S. and Europe have once again turned their attention to the risk of wages and prices spiraling upward, which could lead to price instability, similar to that of the 1970s. On the other hand, in Japan, where inflation has remained low for decades, the interaction between wages and prices has gained attention from a different perspective. Specifically, there is concern about whether a second-round effect from wages to prices will emerge, and whether price increases will align with the "price stability target" under these circumstances.

This paper empirically examines this familiar yet freshly pertinent issue of the second-round effect from wages to prices, using a Dynamic Stochastic General Equilibrium (DSGE) model and data from Japan and Europe. The reason for focusing on Japan and Europe is that both have similar input-output structures, heavily relying on imported raw materials, which allows for the application of the same model for analysis and comparison.

The contributions of this paper are as follows: The first contribution is the development of a structural model to analyze the transmission of raw material price changes to wages and prices. This study modifies and extends the Lorenzoni and Werning [2023a] (hereinafter, LW) model, which incorporates a non-substitutable production factor (raw materials), and nominal rigidities in both wages and prices, in several respects. In particular, a unique feature of this paper is the consideration of the channel through which a decline in real wages, caused by raw material price hikes, depresses consumption, which then spills over into wages and prices. This is analyzed using a TANK (Two-Agent New Keynesian) model that incorporates non-Ricardian households, which spend all their labor income each period.

The second contribution is the theoretical presentation of a method to decompose price increases resulting from raw material price hikes into a first-round effect (capturing the direct impact of raw material price hikes) and a second-round effect (through nominal wage increases). To the best of our knowledge, no existing research offers a theoretical method to capture these effects in a DSGE model.

The third contribution is the estimation of the model using data from Japan and Europe, along with an empirical analysis of the first- and second-round effects of raw material price hikes. The estimation results show that the first-round effect of price pass-through from raw material cost increases is slower in Japan than in Europe, while the second-round effect through wages is gradual but persistent in both regions. In the price increase phase after the COVID-19 pandemic since 2020, the first-round effect of raw material price hikes was the main driver of price increases in both Japan and Europe. Meanwhile, the second-round effect contributed to the persistence of price increases but did not accelerate them. This suggests that the spiraling increase in wages and prices was unlikely to have led to rampant inflation in recent phases of price increases.

The final contribution is the exploration of whether the characteristics of the second-round effect in Japan have changed in recent years. As monetary easing was gradually adjusted in response to inflation resulting from raw material price hikes, the second-round effect became more likely to manifest in recent years in Japan. Furthermore, by estimating a model that incorporates downward nominal wage rigidity, it is suggested that the recent decline in wage rigidity may be strengthening the second-round effect in Japan.

Literature Review

A large body of existing research analyzes the impact of exogenous price increases, such as crude oil prices, on the real economy and prices. This section does not comprehensively survey all such studies, but instead summarizes empirical research that explicitly examines the second-round effect of raw material prices on wages and prices, similar to that of this study.

Research on Europe

Several studies have analyzed the second-round effect of crude oil price fluctuations in Europe. Battistini et al. [2022], an analysis by ECB economists, defined the impact of crude oil prices on the GDP deflator through per capita employee compensation as the second-round effect. They estimated a Bayesian VAR model using aggregate data from the eurozone and found that a clear second-round effect was observed in the 1970s-80s, but since 1999, this effect has become very limited.

In contrast, Baba and Lee [2022] and Enders and Enders [2017] defined the effect of crude oil prices on nominal wages through consumer prices as the second-round effect. Baba and Lee [2022] confirmed that an increase in crude oil prices significantly raises nominal wages through consumer prices by applying the local projections method to country-specific panel data. They also pointed out that this effect is state-dependent: it is stronger when inflation is high, labor union density is high, and confidence in monetary policy is low. On the other hand, Enders and Enders [2017] applied a structural VAR model to aggregate eurozone data and concluded that there was no significant evidence to suggest that crude oil price shocks affect nominal wages through consumer prices.

Research on Japan

To the best of our knowledge, research analyzing the second-round effect in Japan is limited to Fukunaga et al. [2023]. They defined the effect of price-specific shocks feeding back into prices through wages as the second-round effect in a two-variable VAR model, which includes inflation rate and wage growth rate. Estimation results using Japan-US data showed that the second-round effect in Japan was larger than the U.S. in the 1970s-80s, but that effect has become very limited since the 1990s.

Research on Other Countries

Studies analyzing the second-round effect for countries and regions outside of Japan and Europe include Alp et al. [2023] and Ruch and du Plessis [2015].[1] Alp et al. [2023] defined the impact of crude oil prices on core CPI as the second-round effect and estimated this effect using panel data from 27 advanced countries (eurozone, UK, Canada). They concluded that the second-round effect of crude oil price hikes is gradual but persistent.

[1] Additionally, IMF [2022] surveys previous research on the wage-price spiral and examines wage and price trends in advanced economies since around 2020, concluding that the risk of a sustained spiral occurring in the current situation is limited.

Ruch and du Plessis [2015] defined the impact of food and energy price shocks on unit labor costs (ULC) and core CPI as the second-round effect and analyzed this effect by estimating a structural VAR model with South African data. The estimation results showed that a one percent increase in food and energy prices raised ULC and core CPI by about 0.3 percent one year later.

Feature of this paper

Empirical results regarding the second-round effect of crude oil price hikes on wages and prices vary depending on the target country, time period, and analysis method, as described above, suggesting the need for more multi-faceted analyses. This study defines the component of price increases associated with raw material price hikes that occurs through nominal wage increases as the second-round effect, which is aligned with the definition of Battistini et al. [2022]. However, a key feature of this research is that it estimates the second-round effect using a DSGE model, which has not been employed in the previous studies above. Our approach enables us to examine the raw material price transmission mechanism in accordance with the model's structure, including monetary policy. Furthermore, this research provides an analysis of Japan, where existing research is currently limited, including the possibility of changes in the characteristics of the second-round effect in recent years.

Structure of this paper

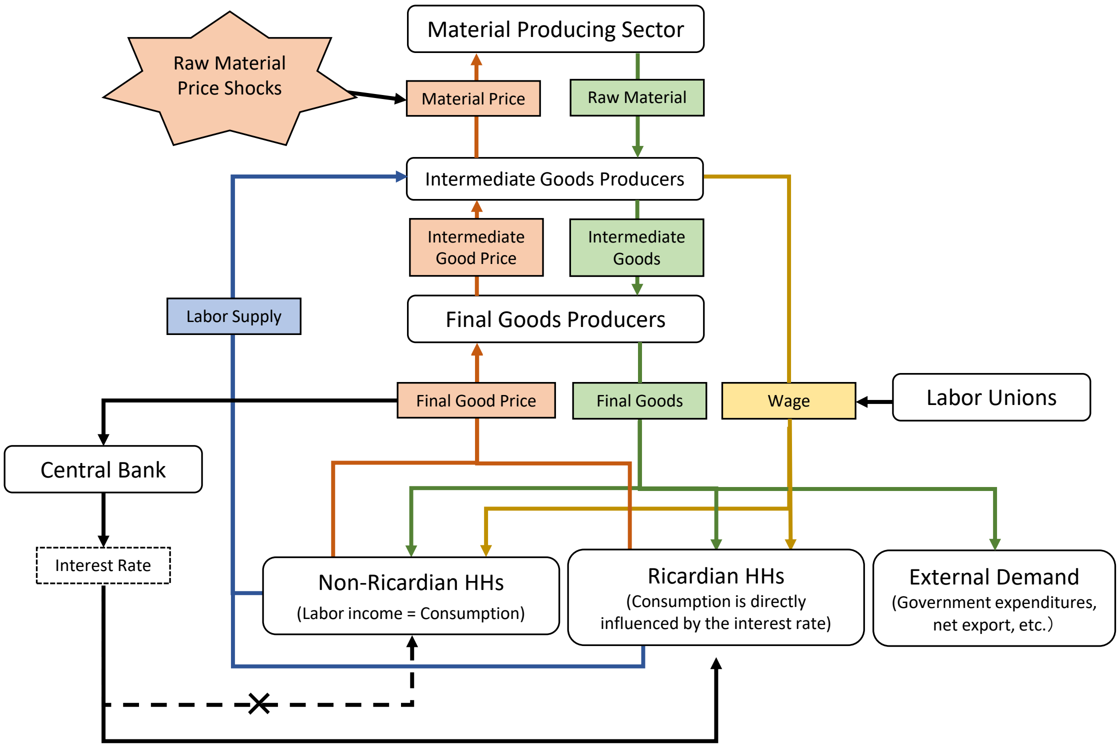
The structure of this paper is as follows: Section 2 presents the model used in this study. Section 3 provides a qualitative explanation of the raw material price transmission mechanism to prices within the model, followed by a method for quantifying the first-round effect of raw material price hikes and the second-round effect through wages. Section 4 outlines the framework for empirical analysis. Section 5 reports the estimation results and discusses the nature of the first- and second-round effects in Japan and Europe. Section 6 offers additional analysis focusing on Japan in recent years. Section 7 concludes.

2 Model

The overall structure of the model is summarized in Figure 1. The household sector consists of two types of households: Ricardian and non-Ricardian, reflecting household heterogeneity. The former smooths consumption given the interest rate determined by the central bank's monetary policy rule, while the latter's consumption is determined by labor income each period. The household sector supplies labor to intermediate goods producers and earns wages as compensation. Wages are determined by labor unions under Calvo [1983]-type (hereinafter, Calvo-type) wage rigidity and monopolistic competition.

Intermediate goods producers produce intermediate goods using labor and raw materials. Raw materials are supplied elastically under exogenously determined prices. The prices of intermediate goods are set by intermediate goods producers under Calvo-type price rigidity and monopolistic competition. Finally, final goods producers produce final goods using intermediate goods under perfect competition. Final goods are consumed by households or by exogenous demand factors (external demand).

Figure 1: Overview of the Model



This model modifies and extends the LW model, which incorporates Calvo-type wage and price rigidities and materials as a complementary production factor to labor, in the following ways:

First, while the LW model treats material supply as exogenous and its price as endogenous, with the U.S. in mind, which has high energy self-sufficiency, this paper assumes that supply is determined endogenously based on demand at a given price, considering the energy input structure in Japan and Europe. Although, in reality, Japan and Europe depend heavily on imported raw materials, this study simplifies the model by assuming that the price of elastically supplied raw materials fluctuates exogenously in a closed economy, without modeling exchange rates or the foreign sector, and analyzes the model's behavior in this scenario. While this formulation abstracts from the mechanism that raw material price hikes depress the real economy by deteriorating the terms of trade, it has the advantage of being unaffected by errors in the formulation of exchange rates or the foreign sector.[2]

Second, regarding wage setting, while LW adopts the formulation proposed by Erceg et al. [2000], this paper follows Colciago [2011], who incorporated Calvo-type wage rigidity into a TANK model, and adopts the formulation proposed by Schmitt-Grohe and Uribe [2005]. This modification affects the expression of the wage Phillips curve's slope but does not significantly alter the model's behavior.

Furthermore, to improve data fit, stochastic trends and habit formation in consumption are introduced, following Hirose and Kurozumi [2012]. The specific details of the model are explained below.

2-1 Household Sector

Utility Function

There is a continuum of households ($i \in [0,1]$) in the economy. Household i derives utility from real consumption C_t^i, while incurring disutility from labor supply l_t^i. The lifetime utility of the household, from the current period ($t = 0$) to infinity ($t = \infty$), is given by the following:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left\{ e^{z_t^b} \frac{\left(C_t^i - \theta^i C_{t-1}^i\right)^{1-\sigma}}{1-\sigma} - \Phi Z_t^{1-\sigma} e^{z_t^l} \frac{\left(l_t^i\right)^{1+\eta}}{1+\eta} \right\}$$

where $\beta \in (0,1)$ is the subjective discount factor, $\sigma > 0$ is the inverse of the intertemporal elasticity of substitution for consumption, $\theta^i \in [0,1)$ is the degree of habit formation in consumption, $\eta > 0$ is the inverse of the labor supply elasticity, and Φ is a parameter representing the disutility of labor. Also, $e^{z_t^b}$ and $e^{z_t^l}$ are preference shocks and labor supply shocks, respectively. Z_t represents the technology level, as described later. To ensure that the model satisfies the balanced growth constraint, the labor disutility is multiplied by $Z_t^{1-\sigma}$, as in Erceg et al. [2006].

Ricardian and Non-Ricardian Households

There are two types of households in the household sector. Households in $[0, \lambda]$ are non-Ricardian households. Non-Ricardian households cannot access financial markets and

[2] Van Nguyen [2020] compares the forecasting accuracy of closed-economy and small open-economy models using Australian data, reporting that the latter results in lower forecasting accuracy due to errors in the specification of the external sector and an increase in the number of parameters to be estimated.

consume all their labor income in each period. On the other hand, the remaining households in $(\lambda, 1]$ are Ricardian households, who have access to financial markets and determine their optimal consumption in each period to maximize lifetime utility, given the interest rate.

Each household is assumed to elastically supply the amount of labor demanded by firms under the wage determined by labor unions. Also, as described later, since the labor supply of all households is identical, let I_t be the real labor income of each household in period t. Under this assumption, the real consumption C_t^H of non-Ricardian households is given by the following:

$$C_t^H = I_t$$

Furthermore, assuming that the degree of habit formation in consumption for non-Ricardian households is zero, the marginal utility Λ_t^H of non-Ricardian household' consumption C_t^H in period t becomes as follows:

$$\Lambda_t^H = e^{z_t^b}(C_t^H)^{-\sigma}$$

Meanwhile, Ricardian households determine their real consumption C_t^U to maximize lifetime utility, subject to the following budget constraint:

$$C_t^U + \frac{B_t}{P_t} = I_t + R_{t-1}^n \frac{B_{t-1}}{P_t} + D_t$$

where B_t and D_t represent nominal bond holdings and real dividend income, respectively, with the latter being equal to firm profits. P_t and R_t^n represent the price level and the gross nominal interest rate, respectively. From this, the following conditions are derived:

$$\Lambda_t^U = e^{z_t^b}(C_t^U - \theta C_{t-1}^U)^{-\sigma} - \beta\theta E_t e^{z_{t+1}^b}(C_{t+1}^U - \theta C_t^U)^{-\sigma}$$

$$\Lambda_t^U = \beta E_t \Lambda_{t+1}^U \frac{R_t^n}{\pi_{t+1}}$$

Λ_t^U represents the marginal utility of Ricardian households' consumption C_t^U in period t. $\pi_t(\equiv P_t/P_{t-1})$ is the gross inflation rate. It is assumed that the degree of habit formation in consumption for Ricardian households is common and denoted by θ.

Labor Supply

Households elastically supply differentiated labor ($j \in [0,1]$) to intermediate goods producers. As mentioned earlier, it is assumed that households' labor supply is identical across all households. That is, each household supplies all types of labor j, and the quantity of each type of labor supplied is assumed to be identical across all households.

Intermediate goods producers $f \in [0,1]$ combine differentiated labor $l_t^{j,f}$ as follows to obtain effective labor l_t^f:

$$l_t^f = \left\{ \int_0^1 \left(l_t^{j,f}\right)^{\frac{1}{1+\lambda_t^w}} dj \right\}^{1+\lambda_t^w}$$

where $\lambda_t^w = 1/(\epsilon_t^w - 1) > 0$ is a variable defined with $\epsilon_t^w > 1$ as the elasticity of substitution for each type of labor, representing the wage markup rate. The demand function for each type of labor becomes as follows ($l_t^j \equiv \int_0^1 l_t^{j,f} df$):

$$l_t^j = \left(\frac{W_t^j}{W_t}\right)^{-\frac{1+\lambda_t^w}{\lambda_t^w}} l_t^d$$

where W_t^j is the real wage for each type of labor. W_t and l_t^d represent the aggregate real wage and effective labor, respectively, given by $W_t = \left\{ \int_0^1 \left(W_t^j\right)^{-\frac{1}{\lambda_t^w}} dj \right\}^{-\lambda_t^w}$ and $l_t^d = \int_0^1 l_t^f df$. From these, the total labor supply $l_t \equiv \int_0^1 l_t^j \, dj$ and real labor income I_t of households can be written as follows:

$$l_t = l_t^d \int_0^1 \left(\frac{W_t^j}{W_t}\right)^{-\frac{1+\lambda_t^w}{\lambda_t^w}} dj$$

$$I_t = \int_0^1 W_t^j l_t^j \, dj = l_t^d \int_0^1 W_t^j \left(\frac{W_t^j}{W_t}\right)^{-\frac{1+\lambda_t^w}{\lambda_t^w}} dj$$

2-2 Labor Union

For each type of labor j, there exists a labor union j representing workers. Labor unions determine nominal wages under monopolistic competition to maximize the utility of households belonging to the union. Unions are assumed to face Calvo-type wage rigidity. Specifically, in each period, only a proportion $1-\xi_w$ of labor unions can optimize wages, while for the remaining proportion ξ_w of labor unions, wages are assumed to be determined in line with the steady-state (gross) technology growth rate z and inflation rate π.

A labor union that obtains the opportunity to optimize wages in period t solves the following optimization problem:

$$\max_{W_t^j} E_t \sum_{s=0}^{\infty} (\beta\xi_w)^s (\bar{\Lambda}_{t+s} W_{t|t+s}^j - V_{t+s}^L) l_{t+s}^d \left(\frac{W_{t|t+s}^j}{W_{t+s}}\right)^{-\frac{1+\lambda_{t+s}^w}{\lambda_{t+s}^w}}$$

where $W_{t|t+s}^j$ represents the real wage if labor union j optimizes wages in period t and cannot optimize until period $t+s$, given by $W_{t|t+s}^j = W_t^j z^s \prod_{k=1}^{s} \pi/\pi_{t+k}$. V_{t+s}^L is the marginal disutility of labor, defined by $V_{t+s}^L \equiv \Phi Z_{t+s}^{1-\sigma} e^{z_{t+s}^l} l_{t+s}^{\eta}$. $\bar{\Lambda}_{t+s}$ is the average marginal utility of consumption, defined by $\bar{\Lambda}_{t+s} \equiv (1-\lambda)\Lambda_{t+s}^U + \lambda\Lambda_{t+s}^H$.

The solution to this problem, W_t^o, satisfies the following condition:

$$E_t \sum_{s=0}^{\infty} (\beta\xi_w)^s \Phi_{t,t+s}^w \left[W_{t|t+s}^o - (1+\lambda_{t+s}^w) MRS_{t+s}\right] = 0 \qquad (1)$$

where $\Phi_{t,t+s}^w = \frac{1}{\lambda_{t+s}^w} l_{t+s}^d \left(\frac{W_{t|t+s}^o}{W_{t+s}}\right)^{-\frac{1+\lambda_{t+s}^w}{\lambda_{t+s}^w}} \bar{\Lambda}_{t+s}$. MRS_{t+s} is the average marginal rate of substitution between consumption and labor, defined by $MRS_{t+s} \equiv V_{t+s}^L/\bar{\Lambda}_{t+s}$. From this, the optimal real wage when wages are perfectly flexible is the average marginal rate of substitution between consumption and labor, MRS_{t+s}, multiplied by the markup $1+\lambda_{t+s}^w$. On the other hand, when wages are sticky, labor unions demand wages such that the deviation between real wages and the optimal level under flexible wages is minimized over time. These demands come about because labor unions are conscious that they may not be able to optimize nominal wages in the future. This means that the marginal rate of substitution between consumption and labor, MRS_{t+s}, can be viewed as a factor that determines the wage level demanded by labor unions.

Using W_t^o, the aggregate real wage W_t can be expressed as follows:

$$W_t = (1-\xi_w)\left((W_t^o)^{-\frac{1}{\lambda_t^w}} + \sum_{s=1}^{\infty}\xi_w^s\left[z^s W_{t-s}^o \prod_{k=1}^{s}\frac{\pi}{\pi_{t-k+1}}\right]^{-\frac{1}{\lambda_t^w}}\right)^{-\lambda_t^w}$$

2-3 Firm Sectors

Final Goods Producers

Final goods producers produce final goods Y_t from differentiated intermediate goods Y_t^f ($f \in [0,1]$) using the following production technology:

$$Y_t = \left(\int_0^1 (Y_t^f)^{\frac{1}{1+\lambda_t^p}} df\right)^{1+\lambda_t^p}$$

where $\lambda_t^p = 1/(\epsilon_t^p - 1) > 0$ is a variable defined with $\epsilon_t^p > 1$ as the elasticity of substitution for each intermediate goods, representing the price markup rate for intermediate goods. Final goods producers determine the input quantity of intermediate goods Y_t^f to maximize profit $P_t Y_t - \int_0^1 P_t^f Y_t^f \, df$, given the final goods price P_t and intermediate goods price P_t^f. From this, the following demand function for intermediate goods is derived:

$$Y_t^f = \left(\frac{P_t^f}{P_t}\right)^{-\frac{1+\lambda_t^p}{\lambda_t^p}} Y_t \qquad (2)$$

where $P_t = \left\{\int_0^1 (P_t^f)^{-\frac{1}{\lambda_t^p}} df\right\}^{-\lambda_t^p}$.

Intermediate goods producers

Intermediate goods producers $f \in [0,1]$ use raw materials X_t^f and labor l_t^f in production. These production factors are assumed to be non-substitutable, i.e., the production function is Leontief-type.[3]

$$Y_t^f = \min\left\{\frac{Z_t l_t^f}{1-a_X}, \frac{X_t^f}{a_X}\right\}$$

a_X represents the input weight of raw materials. The technology level Z_t for intermediate goods production is assumed to follow a random walk with drift, as follows:

$$\log Z_t = \log z + \log Z_{t-1} + z_t^z$$

That is, the technology level Z_t grows at a constant rate z even in its steady state. In addition, due to the presence of technology shock z_t^z, the technology growth rate fluctuates stochastically.

To increase production by one unit, an intermediate goods producer f additionally requires $(1-a_X)/Z_t$ units of l_t^f and a_X units of X_t^f. Therefore, when p_t^X is the real raw material price, the real marginal cost mc_t of intermediate goods producers is given by the following:

$$mc_t = (1-a_X)\frac{W_t}{Z_t} + a_X p_t^X$$

Here, the subscript f is omitted, as the marginal cost of all intermediate goods producers is identical.

The real raw material price $p_t^X (\equiv P_t^X/P_t)$ follows an AR(1) process and is determined exogenously:

$$\log p_t^X = (1-\rho_x)\log p^X + \rho_x \log p_{t-1}^X + \epsilon_t^x$$

$\rho_x \in [0,1)$ is a parameter representing the persistence of raw material prices, and ϵ_t^x is a raw material price shock. Raw materials are assumed to be supplied elastically at this price.[4]

Intermediate goods producers determine nominal prices under Calvo-type price rigidity

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[3] As will be discussed later, because data on the input quantities of production factors (labor input, raw material input) are not used for estimation, estimating a more general CES production function would be difficult because of the difficulties in identifying the elasticity of substitution between production factors.

[4] The profits obtained in the raw materials sector are assumed to be distributed to Ricardian households.

and monopolistic competition. In each period, a proportion $1-\xi_p$ of firms optimize their prices. The prices of the remaining proportion ξ_p of firms are determined in line with the steady-state inflation rate π. Under this setting, a firm that optimizes the price in period t determines its real intermediate good price $p_t^f (\equiv P_t^f / P_t)$ to maximize the following objective function, given the demand function for intermediate goods (Equation (2)):

$$\max_{p_t^f} E_t \sum_{s=0}^{\infty} (\beta \xi_p)^s \frac{\Lambda_{t+s}^U}{\Lambda_t^U} \left(p_{t|t+s}^f - mc_{t+s}\right) Y_{t+s}^f$$

where $p_{t|t+s}^f$ represents the real intermediate good price if firm f optimizes price in period t and cannot optimize until period $t+s$, given by $p_{t|t+s}^f = p_t^f \prod_{k=1}^{s} \pi / \pi_{t+k}$. The solution to this problem, p_t^o, yields the following condition:

$$E_t \sum_{s=0}^{\infty} (\beta \xi_p)^s \Phi_{\mathrm{t,t+s}}^p \{p_{t|t+s}^o - (1+\lambda_{t+s}^p) mc_{t+s}\} = 0$$

where $p_{t|t+s}^o = p_t^o \prod_{k=1}^{s} \pi / \pi_{t+k}$ and $\Phi_{\mathrm{t,t+s}}^p = \frac{\Lambda_{t+s}^U}{\Lambda_t^U} \frac{1}{\lambda_{t+s}^p} \left(p_{t|t+s}^o\right)^{-\frac{1+\lambda_t^p}{\lambda_t^p}} Y_{t+s}$. This implies that λ_{t+s}^p represents the price markup rate when prices are perfectly flexible. Furthermore, from the definition of the aggregate price level P_t, the following condition holds:

$$1 = (1-\xi_p) \left((p_t^o)^{-\frac{1}{\lambda_t^p}} + \sum_{s=1}^{\infty} \xi_p^s \left(p_{t-s|t}^o\right)^{-\frac{1}{\lambda_t^p}} \right)$$

2-4 Central Bank

The central bank determines the nominal interest rate R_t^n according to the following monetary policy rule, in response to the inflation rate and real gross domestic product.

$$\log R_t^n = \phi_r \log R_{t-1}^n + (1-\phi_r) \left\{ \log R^n + \phi_\pi \left(\frac{1}{4} \sum_{s=0}^{3} \log \frac{\pi_{t-s}}{\pi} \right) + \phi_y \log \frac{Y_t / Z_t}{y} \right\} + z_t^r$$

where y and R^n represent the steady-state values of output Y_t / Z_t (detrended) and the nominal interest rate R_t^n, respectively. $\phi_r \in [0,1)$ is a parameter representing the degree of interest rate smoothing, ϕ_π is a parameter representing the sensitivity of the nominal interest rate to the inflation rate, ϕ_y is a parameter representing the sensitivity to real gross domestic products, and z_t^r is a monetary policy shock.

2-5 Equilibrium

Final goods are consumed by households or used for other purposes (external demand). Therefore, the market clearing condition for final goods is as follows:

$$Y_t = C_t + gZ_t e^{z_t^g}$$

where C_t is the total consumption of the household sector, represented by $C_t = (1-\lambda)C_t^U + \lambda C_t^H$, and $gZ_t e^{z_t^g}$ is external demand other than consumption, such as government spending and net exports. z_t^g represents an external demand shock.

2-6 Linearized Model

In this model, since the technology level Z_t has a stochastic trend, many real variables have non-stationary stochastic trends. Therefore, variables with trends are divided by Z_t (Λ_t^U, Λ_t^H are multiplied by Z_t^σ) to convert them into stationary variables, and then a log-linearized model around the steady state is used for analysis. Detrended variables are denoted by lowercase letters, and the deviation rate of variable a_t from the steady state is denoted by $\tilde{a}_t$. A list of the linearized equilibrium conditions is provided in the Appendix. All exogenous variables in the model are assumed to follow an AR(1) process.

3 Mechanism of Raw Material Price Transmission

This section qualitatively explains the mechanism of raw material price transmission to prices in this model, along with the factors that influence it. Furthermore, it presents a method for decomposing the impact of raw material price hikes on prices into a first-round effect and a second-round effect through wages.

3-1 Qualitative Overview of Raw Material Price Transmission Mechanism

Consider a situation where a positive raw material price shock ($\epsilon_t^X > 0$) occurs in period t (with other shocks being zero). In this case, with the increase in raw material price $\tilde{p}_t^X$, the marginal cost $\widetilde{mc}_t$ increases according to the following equation:[5]

[5] This discussion is about "deviation rates from the steady state," but the phrase "deviation rates from the steady state" is omitted, to avoid complicating the explanation.

$$\widetilde{mc}_t = a_X \tilde{p}_t^X + (1 - a_X)\widetilde{w}_t \tag{3}$$

Then, the inflation rate $\tilde{\pi}_t$ increases from the New Keynesian Phillips Curve (NKPC):

$$\tilde{\pi}_t = \Lambda^p \widetilde{mc}_t + \beta z^{1-\sigma} E_t \tilde{\pi}_{t+1} \tag{4}$$

Here, $\Lambda^p = \left(1 - \xi_p\right)\left(1 - \beta z^{1-\sigma}\xi_p\right)/\xi_p$ represents the slope of the NKPC, which determines the first-round effect of raw material price hikes to consumer prices. The first-round effect manifests more rapidly as the proportion of firms that can freely change prices $1 - \xi_p$ increases, i.e., as price rigidity decreases.

Next, consider the response of wages when the inflation rate $\tilde{\pi}_t$ rises. First, the real wage $\widetilde{w}_t$ falls in response to the increase in the inflation rate. However, as shown in the New Keynesian Wage Phillips Curve (NKWPC) below, the decline in the real wage $\widetilde{w}_t$ leads to an increase in the nominal wage growth rate $\tilde{\pi}_t^w$.

$$\tilde{\pi}_t^w = \Lambda^w(\widetilde{mrs}_t - \widetilde{w}_t) + \beta z^{1-\sigma} E_t \tilde{\pi}_{t+1}^w \tag{5}$$

Here, $\Lambda^w = (1 - \xi_w)(1 - \beta z^{1-\sigma}\xi_w)/\xi_w$ represents the slope of the NKWPC, which influences the wage catch-up to price increases. The larger the proportion of labor unions $(1 - \xi_w)$ that can achieve their wage demands, i.e., the lower the wage rigidity, the stronger the ability of wages to catch up with prices.

Furthermore, another factor that influences wage catch-up is the marginal rate of substitution between consumption and labor, $\widetilde{mrs}_t$, represented by the following equation:

$$\widetilde{mrs}_t = \eta \tilde{l}_t - \left\{(1 - \lambda)\tilde{\lambda}_t^U + \lambda \tilde{\lambda}_t^H\right\}$$

where $\tilde{l}_t$ represents labor demand, and $\tilde{\lambda}_t^U$ and $\tilde{\lambda}_t^H$ represent the marginal utility of consumption for Ricardian and non-Ricardian households, respectively.

In this model, when raw material prices rise, (1) consumption of non-Ricardian households decreases significantly due to a decline in purchasing power, and (2) consumption of Ricardian households also decreases somewhat due to interest rate hikes by the central bank. In response to this decline in domestic demand, firms' labor demand decreases. As a result, $\widetilde{mrs}_t$ falls due to raw material price hikes. This works to suppress wage catch-up, as indicated by Equation (5). This implies a mechanism where households' willingness to supply labor increases, leads to suppressed wages, in response to reduced working hours and lower consumption levels. In other words, the suppression of wage increases due to the decline in $\widetilde{mrs}_t$ reflects the impact of a loosening of the labor supply and demand balance caused by raw material price hikes.

These movements towards wage catch-up occurring on the NKWPC, in turn, increase the marginal cost $\widetilde{mc}_t$ on the firm side from Equation (3), leading to a further increase in the inflation rate $\tilde{\pi}_t$ from the NKPC. This is the second-round effect from wages to prices, triggered by raw material price hikes. Such feedback occurs not only in the present but also in future periods, with expectations playing a role. Specifically, expectations regarding the inflation rate and wage growth rate ($E_t\tilde{\pi}_{t+1}$ and $E_t\tilde{\pi}_{t+1}^{w}$) rise, pushing up the current inflation rate $\tilde{\pi}_t$.

To summarize, the price rigidity parameter (Calvo parameter) ξ_p is considered important as a factor determining the first-round effect of raw material price hikes. Furthermore, three factors are considered important as factors influencing the second-round effect through wages: the Calvo parameters for prices and wages (ξ_p and ξ_w), and the marginal rate of substitution between consumption and labor, $\widetilde{mrs}_t$.

Incidentally, when raw material prices rise, monetary policy is thought to primarily control prices by influencing the second-round effect. For example, if the central bank aggressively tries to suppress inflation through large interest rate hikes, the decline in $\widetilde{mrs}_t$ will be more pronounced due to the decrease in consumption by Ricardian households. As a result, the second-round effect will be dampened. Conversely, if the central bank raises interest rates cautiously, its ability to suppress wage catch-up weakens, making the second-round effect more likely to materialize.

3-2 Quantification Method for the First- and Second-Round Effects

Here, a method is presented to quantitatively assess the first- and second-round effects of raw material price hikes, which were discussed qualitatively in Section 3-1. The second-round effect, which is the main focus of this paper, refers to the force by which the increases in nominal wages drive up prices in response to raw material price hikes. This paper decomposes the price increase resulting from raw material price hikes into two components: one expressed by nominal raw material prices ($\tilde{\pi}_t^{1st}$) and the other expressed by nominal wages ($\tilde{\pi}_t^{2nd}$). The former is defined as the first-round effect of raw material price hikes, while the latter represents the second-round effect (see the Appendix for the proof of the proposition).

> ***Proposition****: Assume that all exogenous variables other than the raw material price shock are zero. In this case, the inflation rate* $\tilde{\pi}_t$ *can be decomposed*

into two components: one expressed by the sequence of nominal raw material price growth rates $\{E_t \tilde{\pi}^X_{t+k}\}^{\infty}_{k=0}$ *(*$\equiv \tilde{\pi}^{1st}_t$*) and the other expressed by the sequence of nominal wage growth rates* $\{E_t \tilde{\pi}^w_{t+k}\}^{\infty}_{k=0}$ *(*$\equiv \tilde{\pi}^{2nd}_t$*). That is,* $\tilde{\pi}_t = \tilde{\pi}^{1st}_t + \tilde{\pi}^{2nd}_t \; \forall t$ *holds.*

$$\tilde{\pi}^{1st}_t = \frac{\lambda_1 \Lambda_p}{1-\lambda_2^{-1}} \left\{ \widetilde{mc}^{1st}_{t-1} + a_X E_t \sum_{k=0}^{\infty} \lambda_2^{-k} \tilde{\pi}^X_{t+k} \right\} \tag{6}$$

$$\tilde{\pi}^{2nd}_t = \frac{\lambda_1 \Lambda_p}{1-\lambda_2^{-1}} \left\{ \widetilde{mc}^{2nd}_{t-1} + (1-a_X) E_t \sum_{k=0}^{\infty} \lambda_2^{-k} \tilde{\pi}^w_{t+k} \right\} \tag{7}$$

where $\widetilde{mc}^{1st}_t$, $\widetilde{mc}^{2nd}_t$ *represent the components of real marginal cost expressed by nominal raw material price growth rate and nominal wage growth rate, respectively, and satisfy* $\widetilde{mc}^{1st}_t = a_X \tilde{\pi}^X_t + \widetilde{mc}^{1st}_{t-1} - \tilde{\pi}^{1st}_t$, $\widetilde{mc}^{2nd}_t = (1-a_X)\tilde{\pi}^w_t + \widetilde{mc}^{2nd}_{t-1} - \tilde{\pi}^{2nd}_t$, $\widetilde{mc}_t = \widetilde{mc}^{1st}_t + \widetilde{mc}^{2nd}_t \; \forall t$. *Also,* $\lambda_1 + \lambda_2 = (\beta z^{1-\sigma})^{-1}(1 + \Lambda_p + \beta z^{1-\sigma})$, $\lambda_1 \lambda_2 = (\beta z^{1-\sigma})^{-1}$ *and* $0 < \lambda_1 < 1 < \lambda_2$.

The first- and second-round effects, as defined, are consistent with the qualitative discussion presented in Section 3-1.[6] Namely, as is clear from Equation (6), the first-round effect of raw material price hikes depends on the slope of the NKPC, Λ_p. Also, the second-round effect of raw material price hikes depends on the three factors: Λ_p, Λ_w, and $\widetilde{mrs}_t$. This can be verified by transforming a portion of the second term on the right-hand side of Equation (7) using the NKWPC, as shown below:

$$\Lambda_p E_t \sum_{k=0}^{\infty} \lambda_2^{-k} \tilde{\pi}^w_{t+k} = E_t \sum_{k=0}^{\infty} \lambda_2^{-k} \{ \Lambda_p \Lambda_w (\widetilde{mrs}_{t+k} - \tilde{w}_{t+k}) + \beta z^{1-\sigma} \Lambda_p E_t \tilde{\pi}^w_{t+k+1} \} \tag{8}$$

Finally, a note on the difference from existing literature. As mentioned earlier, to the best of our knowledge, no research has performed such a decomposition using a DSGE model. However, for measuring second-round effects using VAR models, there is a method proposed by Bachmann and Sims [2012],[7] which has been adopted by Enders and Enders [2017] and Fukunaga et al. [2023]. Their method defines the ripple effect of an exogenous shock on variable B through variable A as the difference between the "hypothetical impulse response of variable B when variable A is held constant" and the "actual impulse response." When calculating this "hypothetical impulse response," the method involves applying a

[6] The discussion in this section is also related to LW's analysis based on the concept of "spiral inflation." For further details, see the Appendix.
[7] Bachmann and Sims [2012] analyze the second-round effects of government spending shocks on the real economy through household and firm sentiment, using a VAR model.

sequence of specific shocks to variable A to keep it constant and recalculating the equilibrium. Therefore, the second-round effect by Bachmann and Sims [2012]'s method inevitably includes the influence of changes in other variables caused by equilibrium recalculation. In contrast, the method proposed in this paper analytically decomposes the inflation rate into two components: one expressed by nominal raw material prices and the other by nominal wages, ensuring that the influence of equilibrium recalculation is excluded from the second-round effect.

4 Empirical Analysis Framework

This section outlines the framework for empirical analysis, including the data used for estimation and the estimation method.

4-1 Data Used for Estimation and Observation Equations

The estimation uses quarterly data from Q1 2002 to Q4 2024. The sample period is based on the availability of data for raw material prices in Europe, as described later in this paper.

The series used for estimation consist of six variables for both Japan and Europe: per capita real gross domestic product (Y_t^{obs}), per capita real consumption (C_t^{obs}), consumer prices (P_t^{obs}), nominal wages ($W_t^{n,obs}$), real raw material prices ($p_t^{X,obs}$), and nominal short-term interest rates ($R_{\mathrm{t}}^{n,obs}$).[8]

Details of the data are shown in Figure 2, and the time series of the data are shown in Figure 3. Real gross domestic product and real consumption are converted into real values by dividing the nominal values by consumer prices. For consumer prices, the overall CPI (HICP) is used. For Japan's CPI, data adjusted for the impact of consumption tax increases are used. For nominal interest rates, shadow rates from Krippner [2013] are used for both Japan and Europe, as they contain periods of considerable length during which policy rates were at or below zero.[9]

For nominal wage data, for Europe, the Labor Cost Index's Wages and Salaries, an hourly wage indicator, is used. For Japan, the scheduled cash earnings for full-time employees

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[8] The number of observed variables (6) is one short of the number of structural shocks (7) in the model. Using labor hour data as an additional observed variable could be considered. However, it was not used for estimation, considering that the results could vary significantly depending on how its secular downward trend and composition effects (increase in non-regular employment ratio) are handled.

[9] The method of using shadow rates as observational data is one of the methods used when estimating DSGE models with data that includes many periods of zero or negative interest rates (Comin et al. [2023], Abe et al. [2019], etc.). As Abe et al. [2019] mention, this method has the advantage of capturing the effects of unconventional monetary policies such as forward guidance and quantitative easing, and also has a smaller computational burden, compared to methods that estimate nonlinear models considering the effective lower bound of nominal interest rates.

from the Monthly Labour Survey, which is frequently used as a representative wage indicator, is used, although it is not necessarily an hourly wage indicator.[10]

For the raw material price data, for Japan, the raw material price from the Corporate Goods Price Index were used for the period prior to 2014, and from 2015 onward, the Stage 1 intermediate goods demand price from the FD-ID index has been used.[11] For Europe, the import price index for raw materials is used.

The observation equations are as follows:

$$100\Delta \log Y_t^{obs} = z^* + z_t^z + \tilde{y}_t - \tilde{y}_{t-1}$$

$$100\Delta \log C_t^{obs} = z^* + z_t^z + \tilde{c}_t - \tilde{c}_{t-1}$$

$$100\Delta \log P_t^{obs} = \pi^* + \tilde{\pi}_t$$

$$100\Delta \log W_t^{n,obs} = z^* + \pi^* + \tilde{\pi}_t^w$$

$$100(\log p_t^{X,obs} - \overline{\log p^{X,obs}}) = \tilde{p}_t^X$$

$$R_t^{n,obs} = r^* + \pi^* + \tilde{R}_t^n$$

where $\Delta \log a_t^{obs}$ represents the log-period-on-period difference of the observed variable a_t^{obs}, and $\overline{a^{obs}}$ represents the sample mean. $z^* = 100(z-1)$, $\pi^* = 100(\pi - 1)$, and $r^* = 100(z^\sigma/\beta - 1)$, representing the steady-state technology growth rate, inflation rate, and real interest rate, respectively.

[10] Even if the hourly regular wages (total employment types) from the Monthly Labour Survey were used as wage data, the main conclusions of this paper would not change.
[11] The correlation between both series during the period when both were available is 0.99, indicating a very strong correlation.

Figure 2: Data Used for Estimation

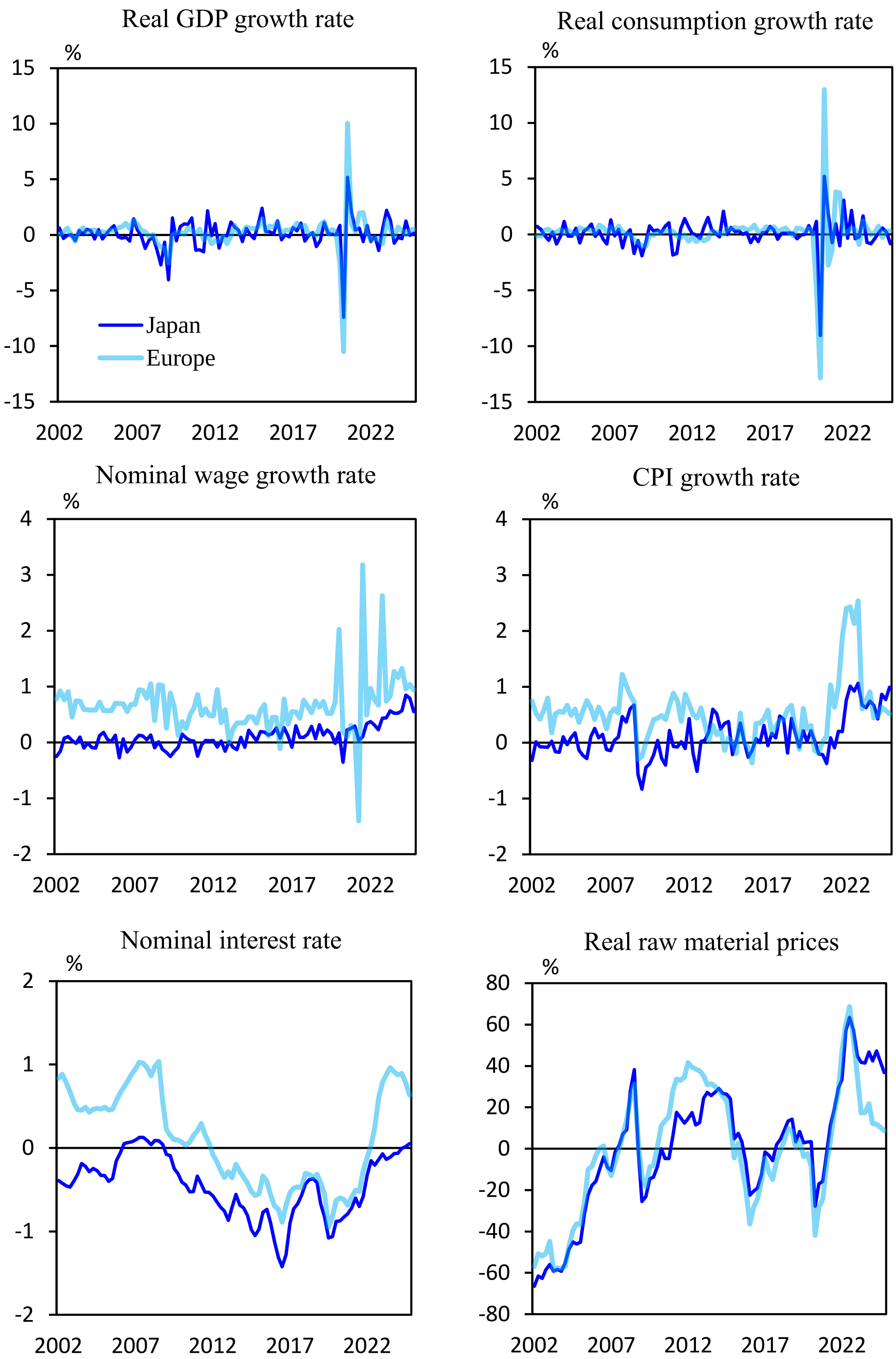
Japan

Observed Variables	Data Description	Sources
Per capita real GDP (Y_t^{obs})	Nominal GDP divided by population aged 15 and over, then by consumer prices (seasonally adjusted). Values for quarters with consumption tax increases are omitted.	Cabinet Office "National Accounts"; Ministry of Internal Affairs and Communications "Labor Force Survey"; Ministry of Internal Affairs and Communications "Consumer Price Index"
Per capita real consumption (C_t^{obs})	Nominal final consumption expenditure of households divided by population aged 15 and over, then by consumer prices (seasonally adjusted). Values for quarters with consumption tax increases are omitted.	
Consumer prices (P_t^{obs})	CPI (overall, seasonally adjusted). The impact of consumption tax increases in April 2014 and October 2019 is excluded by level shift.	Ministry of Internal Affairs and Communications "Consumer Price Index"
Nominal wages ($W_t^{n,obs}$)	Scheduled cash earnings for general workers (establishment size = 5 persons or more, seasonally adjusted). To exclude the effect of sample changes, for periods from Q1 2016 onwards where common establishment-based figures are available, values connected using year-on-year changes based on common establishments are used.	Ministry of Health, Labour and Welfare "Monthly Labour Survey"
Real raw material prices ($p_t^{X,obs}$)	Intermediate goods demand price index for Stage 1 converted to real terms by dividing by CPI (overall, seasonally adjusted). Before December 2014, prices of raw materials among domestic demand goods in the Corporate Goods Price Index.	Bank of Japan "Corporate Goods Price Index"; Bank of Japan "Final Demand and Intermediate Demand Price Index"
Nominal interest rates ($R_t^{n,obs}$)	Krippner [2013] shadow rate (%). Multiplied by 1/4 for quarterly conversion.	Haver Analytics

Europe

Observed Variables	Data Details	Sources
Per capita real GDP (Y_t^{obs})	GDP (nominal value) for Euro area (20 countries) divided by working-age population, then by consumer prices (seasonally adjusted).	Eurostat; World Bank
Per capita real consumption (C_t^{obs})	Final consumption expenditure of households (nominal value) for Euro area (20 countries) divided by working-age population, then by consumer prices (seasonally adjusted).	
Consumer prices (P_t^{obs})	HICP (all items, seasonally adjusted) for Euro Area (19 countries).	Eurostat; FRED
Nominal wages ($W_t^{n,obs}$)	Labor Cost Index, Wages and Salaries (Business economy, seasonally adjusted) for Euro area (20 countries).	Eurostat
Real raw material prices ($p_t^{X,obs}$)	Average of Import prices of Raw materials (SITC 2 + SITC 4) and Mineral fuels, lubricants and related materials (SITC 3) for Euro area (20 countries), weighted by by import value.	Eurostat; Haver Analytics
Nominal interest rates ($R_t^{n,obs}$)	Krippner [2013] shadow rate (%). Multiplied by 1/4 for quarterly conversion.	Haver Analytics

Figure 3: Time Series of Data



Note: Each series represents the time series of the left-hand side of the observation equations.

4-2 Estimation Method and Prior Distributions

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.[12]

The prior distributions for the parameters are set as shown in Figure 4, following Hirose and Kurozumi [2012], who estimated a DSGE model with Japanese data. However, the prior distributions for the Calvo parameters for wages and prices, ξ_w and ξ_p, which are closely related to the second-round effect of raw material prices, are set to a more neutral Beta distribution with a mean of 0.5 and a standard deviation of 0.2.[13] Also, to avoid any asymmetric effects on the estimation results for Japan and Europe due to differences in prior distributions, common prior distributions are used for both regions.[14]

For prior distributions of parameters not included in Hirose and Kurozumi [2012], they are set as follows: The prior distribution for the proportion of non-Ricardian households λ is a Beta distribution, with a prior mean of 0.15 (and a standard deviation of 0.05), based on the empirical analysis of this proportion using Japanese survey data by Hara et al. [2016]. The prior distribution for the raw material weight a_X in the production function is set to a Beta distribution with a mean of 0.15 and a standard deviation of 0.05, referencing An and Kang [2011], who estimated a DSGE model including crude oil production inputs. The prior distributions for the persistence and standard deviation of raw material price shocks are set to be identical to those of other exogenous shocks. Note that the steady-state consumption-to-GDP ratio c/y is calibrated at the sample average (0.542 for Japan, 0.532 for Europe), and the subjective discount factor β is fixed at 0.9985, and not estimated.

[12] Dynare (Adjemian et al. [2024]) was used for model estimation.
[13] Hirose and Kurozumi [2012] use a Beta distribution with a mean of 0.375 and a standard deviation of 0.1.
[14] The prior means for the steady-state technology growth rate and inflation rate are set to the sample means of the per capita real GDP growth rate and the CPI change rate, respectively.

Figure 4: Prior and Posterior Distributions of Parameters

		Prior Distributions			Posterior Distributions			
					Japan		Europe	
		Distribution	Mean	S.D.	Mean	90% CI	Mean	90% CI
σ	Inverse of intertemporal elasticity of substitution for consumption	Gamma	1	0.375	0.71	[0.25, 1.13]	0.88	[0.40, 1.37]
η	Inverse of labor supply elasticity	Gamma	2	0.75	2.34	[1.54, 3.04]	2.91	[1.74, 4.09]
θ	Degree of habit formation in consumption	Beta	0.5	0.2	0.92	[0.88, 0.97]	0.94	[0.91, 0.98]
λ	Proportion of non-Ricardian households	Beta	0.15	0.05	0.21	[0.11, 0.31]	0.25	[0.13, 0.37]
a_X	Raw material weight	Beta	0.15	0.05	0.10	[0.06, 0.15]	0.10	[0.07, 0.13]
ξ_p	Price Calvo parameter	Beta	0.5	0.2	0.84	[0.77, 0.90]	0.74	[0.67, 0.81]
ξ_w	Wage Calvo parameter	Beta	0.5	0.2	0.95	[0.93, 0.96]	0.95	[0.93, 0.97]
ϕ_r	Interest rate inertia	Beta	0.8	0.1	0.81	[0.75, 0.87]	0.86	[0.81, 0.91]
ϕ_π	Interest rate sensitivity to inflation	Gamma	1.7	0.1	1.66	[1.51, 1.81]	1.68	[1.52, 1.84]
ϕ_y	Interest rate sensitivity to GDP	Gamma	0.125	0.05	0.09	[0.04, 0.14]	0.08	[0.04, 0.12]
ρ_x	Raw material price shock persistence	Beta	0.5	0.2	0.94	[0.90, 0.97]	0.93	[0.89, 0.97]
ρ_w	Wage shock persistence	Beta	0.5	0.2	0.23	[0.09, 0.35]	0.08	[0.01, 0.15]
ρ_r	Monetary policy shock persistence	Beta	0.5	0.2	0.75	[0.65, 0.87]	0.55	[0.34, 0.76]
ρ_p	Price shock persistence	Beta	0.5	0.2	0.31	[0.09, 0.52]	0.33	[0.06, 0.62]
ρ_b	Preference shock persistence	Beta	0.5	0.2	0.10	[0.02, 0.19]	0.09	[0.01, 0.17]
ρ_g	External demand shock persistence	Beta	0.5	0.2	0.92	[0.88, 0.97]	0.95	[0.92, 0.98]
ρ_z	Technology shock persistence	Beta	0.5	0.2	0.39	[0.15, 0.66]	0.50	[0.20, 0.80]
z^*	Steady-state technology growth rate	Normal	0.050/ 0.240	0.05	0.02	[-0.03, 0.08]	0.19	[0.13, 0.25]
π^*	Steady-state inflation rate	Normal	0.125/ 0.528	0.05	0.10	[0.03, 0.17]	0.54	[0.47, 0.61]
σ_x	S.D. of raw material price shock	Inverse Gamma	0.5	Inf	9.19	[8.11, 10.3]	9.54	[8.34, 10.7]
σ_w	S.D. of wage shock	Inverse Gamma	0.5	Inf	0.11	[0.09, 0.14]	0.46	[0.39, 0.51]
σ_r	S.D. of monetary policy shock	Inverse Gamma	0.5	Inf	0.11	[0.09, 0.12]	0.12	[0.10, 0.13]
σ_p	S.D. of price shock	Inverse Gamma	0.5	Inf	0.18	[0.14, 0.22]	0.22	[0.16, 0.28]
σ_b	S.D. of preference shock	Inverse Gamma	0.5	Inf	15.2	[7.65, 22.2]	40.85	[16.8, 67.2]
σ_g	S.D. of external demand shock	Inverse Gamma	0.5	Inf	1.99	[1.74, 2.24]	1.53	[1.32, 1.72]
σ_z	S.D. of technology shock	Inverse Gamma	0.5	Inf	0.29	[0.14, 0.43]	0.34	[0.16, 0.52]

5 Estimation Results

5-1 Posterior Distributions of Model Parameters

The estimated posterior distributions of the parameters are shown in Figure 4. Here, we discuss the estimated values of parameters that affect the first- and second-round effects mentioned in Section 3, along with parameters specific to this paper's model.

First, the estimated values of the price Calvo parameter ξ_p differ slightly between Japan and Europe. The posterior mean for Japan is 0.84, whereas for Europe, it is 0.74, indicating higher price rigidity in Japan. Compared to previous literature, the result for Japan is relatively close to the posterior mean of 0.88 reported by Sugo and Ueda [2008]. The estimated value for Europe (0.74) is also generally consistent with the estimated values of the three types of DSGE models reported by McAdam and Warne [2019] (0.75; 0.76; 0.83).

Next, the posterior mean of the wage Calvo parameter ξ_w is 0.95 for both Japan and Europe, indicating high nominal wage rigidity in both regions. Direct comparison of ξ_w with previous literature is difficult, as the expression for the NKWPC slope involving ξ_w differs.[15] However, when looking at the estimated values of ξ_w in previous literature, Sugo and Ueda [2008] report an estimate of 0.52 for Japan, while McAdam and Warne [2019] report values of 0.50, 0.55, and 0.61 for Europe. The fact that there is no large difference in the wage Calvo parameters between Japan and Europe is broadly consistent with these previous studies.[16]

Regarding the estimation results for parameters unique to this paper, the posterior mean of the raw material weight a_X in production factors is approximately 0.10 for both Japan and Europe, indicating roughly similar levels. The persistence ρ_x and standard deviation σ_x of raw material price shocks also show little difference, suggesting similar characteristics of these shocks in Japan and Europe. Furthermore, no clear difference is observed in the estimated results for the proportion of non-Ricardian households λ between Japan and Europe.[17]

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[15] Specifically, in previous literature, the wage setting often adopts the formulation by Erceg et al. [2000], where the slope of the NKWPC is expressed as $\Lambda_w = \frac{(1-\xi_w)(1-\beta z^{1-\sigma}\xi_w)}{\xi_w(1+\epsilon_w\eta)}$. That is, in the Erceg et al. [2000] type model, a term related to real rigidity ($\epsilon_w\eta$), which does not appear in the Schmitt-Grohe and Uribe [2005] formulation relied upon in this paper, is included in Λ_w. Therefore, if the estimated value of Λ_w is held constant, this paper's estimated value of ξ_w is considered to be larger than in many previous studies due to the absence of real rigidity.

[16] As Taylor [1989] once pointed out, wage rigidity in Japan may be lower than in the U.S. and Europe due to the existence of *Shunto*, where companies revise wages simultaneously once a year. Thus, there is no established conclusion regarding the level of wage rigidity between Japan and Europe.

[17] The introduction of non-Ricardian households improved the model's fit to some extent. Specifically, the

Other parameters, excluding estimated values for some shocks (wage shock, preference shock), also show limited differences between Japan and Europe. For the wage shock, persistence ρ_w is larger for Japan, but standard deviation σ_w is larger for Europe. For the preference shock, standard deviation σ_b is larger for Europe.[18]

5-2 Impulse Response

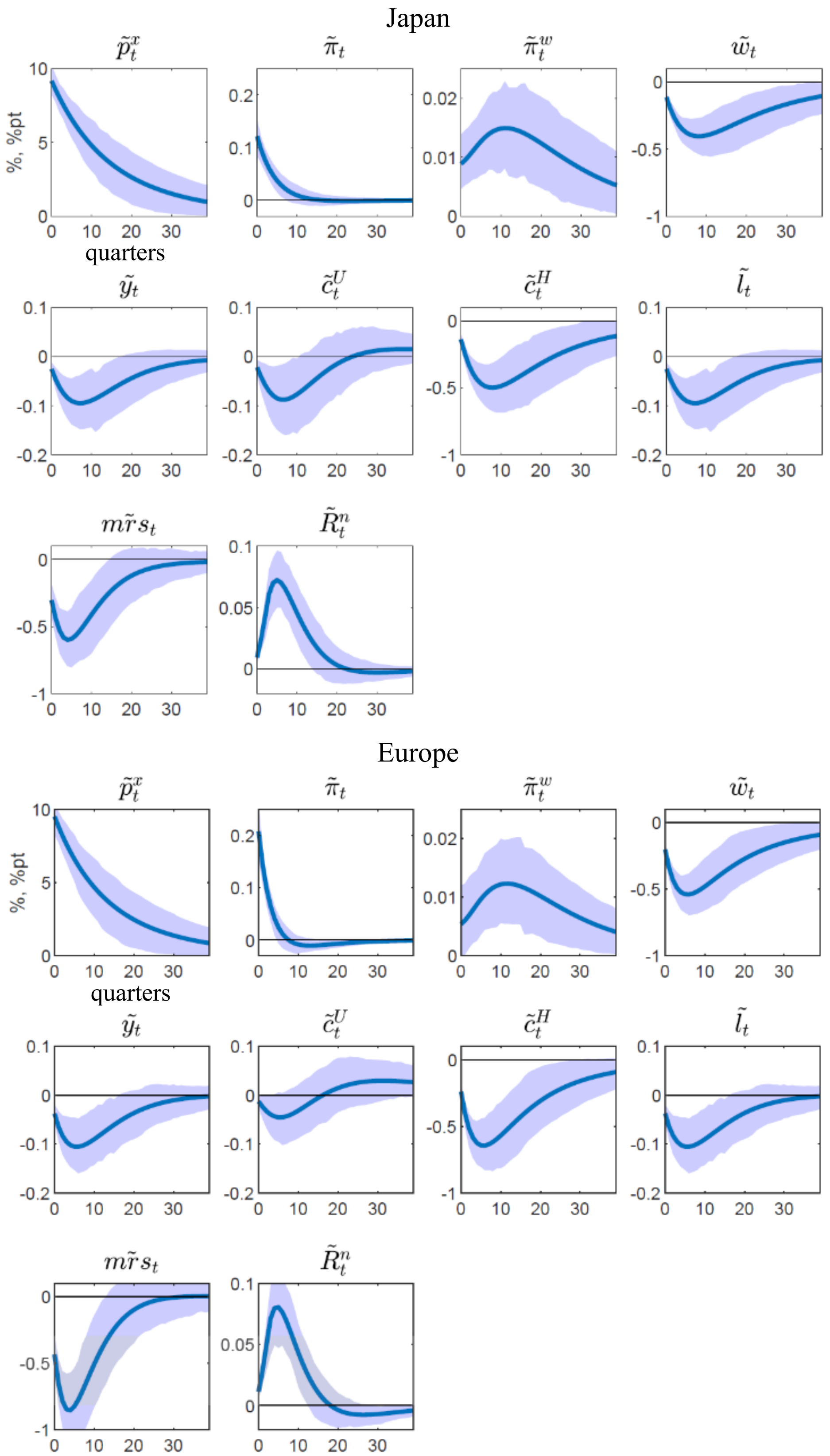
Figure 5 shows the impulse responses of various variables to a one-standard-deviation raw material price shock. First, as suggested by the parameter estimates, the magnitude and persistence of raw material shocks are very similar in Japan and Europe. The initial response of the inflation rate $\tilde{\pi}_t$ to such equivalent shocks is weaker in Japan. This is likely attributable to differences in price rigidity.

On the other hand, the catch-up of nominal wages ($\tilde{\pi}_t^w$) is very gradual in both Japan and Europe, which is considered to reflect, in part, the high wage rigidity. Furthermore, the loosening of labor supply and demand due to raw material price hikes is also thought to be suppressing wage increases. Specifically, in response to a decline in real wages, consumption of non-Ricardian households $\tilde{c}_t^H$ decreases significantly. Also, as the central bank raises interest rates in response to price increases, consumption of Ricardian households $\tilde{c}_t^U$ also decreases somewhat. In response to this decline in domestic demand, firms' labor demand $\tilde{l}_t$ also decreases. As a result, the marginal rate of substitution between consumption and labor $\widetilde{mrs}_t$ decreases, suppressing wage increases.

posterior likelihood for Japan (Europe) improved from -499.30 (-678.42) when only Ricardian households were assumed, to -493.98 (-671.61).

18 The very large estimated value for the standard deviation of the preference shock is likely to explain the large fluctuations in consumption during the 2020 pandemic. The model was also estimated with data prior to 2019, but the main estimation results of this paper remained unchanged, except for the estimation results of the preference shock.

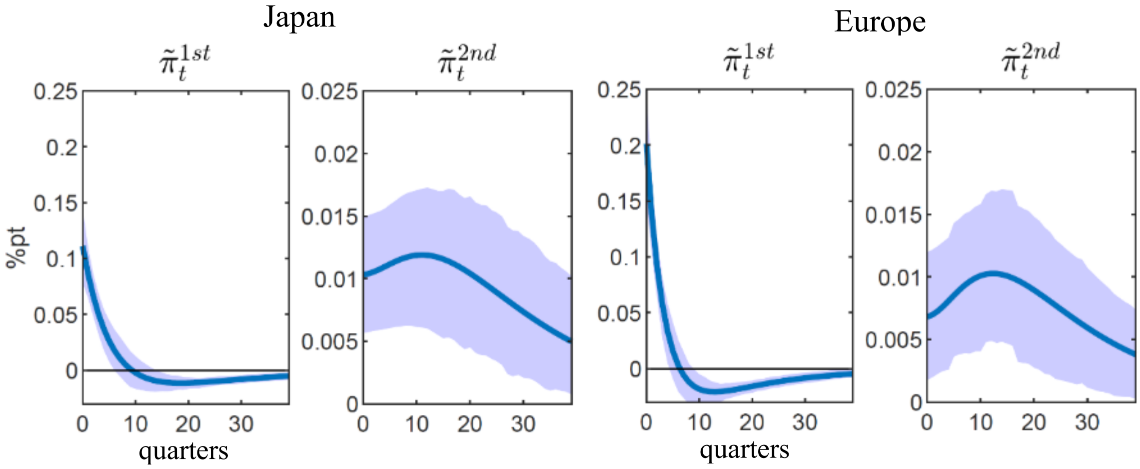
Figure 5: Impulse Response to Raw Material Price Shock



Note: Bayesian impulse response to a one-standard-deviation raw material price shock. The bold line represents the mean, and the shaded area represents the 90 percent credible interval.

Next, Figure 6 decomposes the impulse response of the inflation rate to a raw material price shock into first- and second-round effects using the method presented in Section 3.

Figure 6: First- and Second-Round Effects of Raw Material Price Hikes



Note: Bayesian impulse response to a one-standard-deviation raw material price shock. The bold line represents the mean, and the shaded area represents the 90 percent credible interval.

First, comparing the shapes of the first- and second-round effects, both Japan and Europe show that the first-round effect manifests more rapidly and decays more quickly,[19] whereas the second-round effect pushes prices up more gradually and persistently.

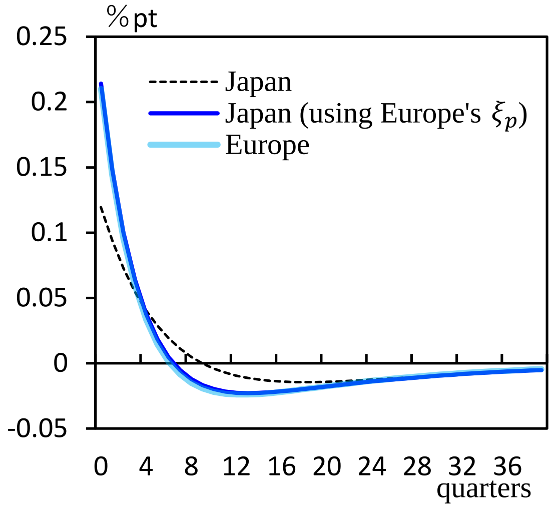
Next, comparing the first- and second-round effects between Japan and Europe, the impulse response of the first-round effect is more gradual in Japan. This is attributable to the difference in the price Calvo parameter ξ_p. Indeed, when Japan's ξ_p is replaced with Europe's estimated value, the first-round effect generally matches between Japan and Europe (Figure 7). In contrast, for the second-round effect, no significant difference is observed between Japan and Europe, either in magnitude or persistence.

This very gradual second-round effect in both Japan and Europe is likely due to two factors: (1) high wage rigidity and (2) the loosening of labor supply and demand resulting from raw material price hikes. The impact of point (1) will be discussed in the next section using Japan as an example; here, we will focus on point (2). As suggested by Equation (8), the second-round effect can ultimately be decomposed into two factors: real wages $\tilde{w}_t$ and the marginal rate of substitution $\widetilde{mrs}_t$. The contribution of the former represents the pure catch-up of nominal wages due to the decline in real wages, while the contribution of the latter can be interpreted as representing the extent to which the loosening of labor supply and demand due to raw material price hikes suppresses the catch-up of nominal wages. As shown in Figure 8, the decline in the marginal rate of substitution $\widetilde{mrs}_t$, which represents

[19] The first-round effect turns negative because the nominal raw material price begins to decline.

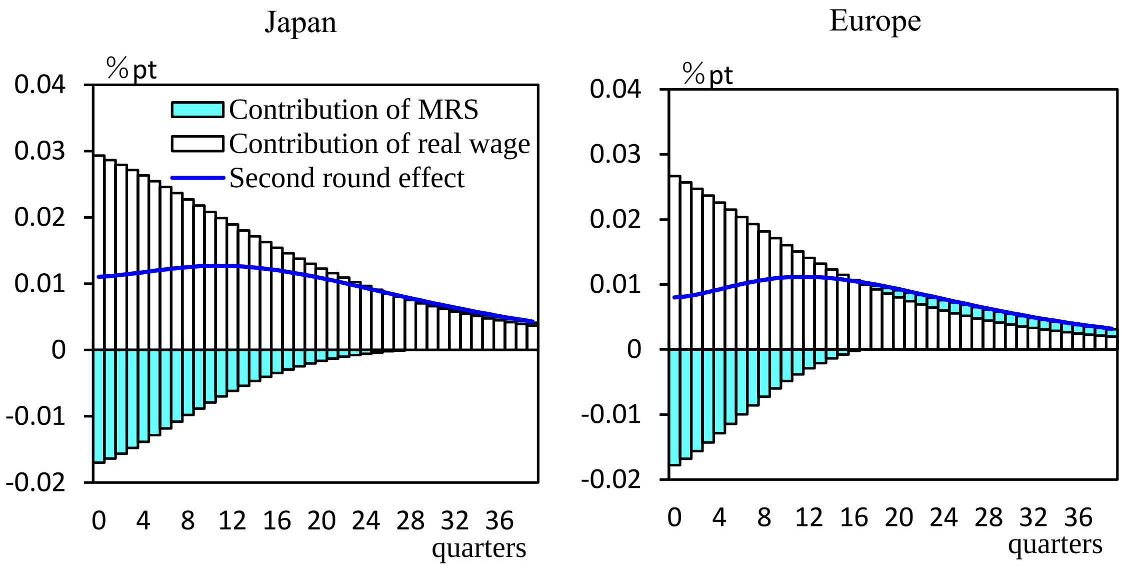
the impact of the loosening of labor supply and demand resulting from raw material price hikes, suppresses the initial second-round effect, causing it to materialize more gradually.

Figure 7: Impact of Price Rigidity on First-Round Effect



Note: Impulse response of $\tilde{\pi}_t^{1st}$ to a one-standard-deviation raw material price shock. Posterior means are used for parameters. "Japan (using Europe's ξ_p)" refers to the impulse response when Europe's posterior mean is used for ξ_p, and Japan's posterior means are used for other parameters.

Figure 8: Decomposition of Second-Round Effect

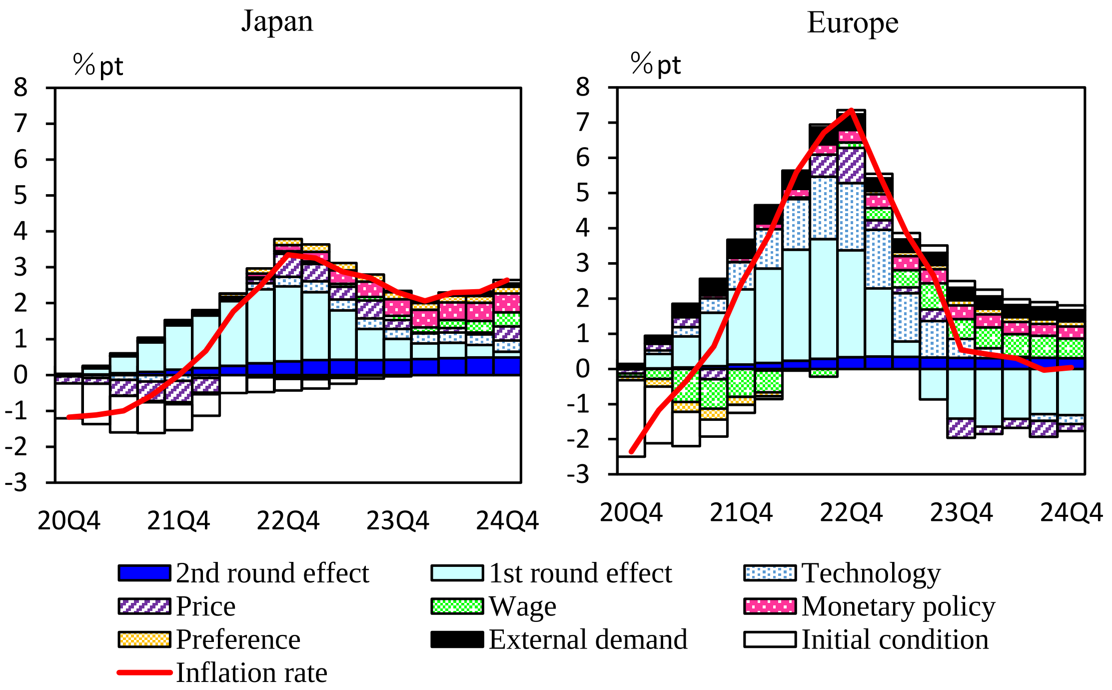


Note: Impulse response of $\tilde{\pi}_t^{2nd}$ to a one-standard-deviation raw material price shock. Posterior means are used for parameters.

5-3 Role of First- and Second-Round Effects in Recent Price Increases

Figure 9 shows the factor decomposition of the inflation rate during the price increase phase of the 2020s. The contribution of raw material price shocks, which is the main focus of this paper, is decomposed into first- and second-round effects. From this figure, the first-round effect, which captures the price pass-through of raw material price hikes, was the main cause of price increases in both Japan and Europe since the pandemic.

Figure 9: Factor Decomposition of Recent Inflation



Note: Inflation rate (year-on-year, deviation from steady state, percent point) decomposed into contributions of shocks occurring from Q4 2020 onwards. Initial conditions are contributions of shocks before Q3 2020. Posterior means are used for parameters and shocks.

Comparing the contribution of this first-round effect between Japan and Europe, during the high inflation phase up to 2022, its manifestation may have been faster in Europe. After inflation peaked, in Europe, with relatively rapid price pass-through, the first-round effect lowered the inflation rate, reflecting the decline in raw material prices. In contrast, in Japan, the first-round effect has continued to push up the inflation rate persistently, due to (1) the longer time required for price pass-through and (2) the sustained high raw material prices against the backdrop of the depreciating yen,[20] among other factors.

Regarding the second-round effect, in terms of the magnitude of its contribution, it was not the main driver of recent price increases in both Japan and Europe. That is, the possibility that a spiraling increase in wages and prices led to rampant inflation in the recent phase of price increases is considered low. However, the gradual but persistent second-round effect is suggested to have played a role in enhancing the persistence of price increases, even after the first-round effect had run its course.

[20] As can be seen from the Figure 3, the recent trends in raw material prices differ between Japan and Europe.

Since 2023, wage shocks have played a larger role in driving up prices than the second-round effect in Europe. This suggests that wage increases, which are not fully explained by the second-round effect as defined in this paper, may have contributed to the persistence of inflation in Europe. Furthermore, in Japan, the contribution of wage shocks has recently expanded somewhat. A possible explanation for this is that the characteristics of the second-round effect may have changed in recent years. The next section will discuss the relationship between the recent expansion of wage shocks and the second-round effect, using Japan as an example. Other major differences between Japan and Europe include the larger contributions of technology and price shocks in Europe. It should be noted that the identification of technology and price shocks may be unclear in this paper, as labor hours data were not used for estimation. However, this suggests that, at least in Europe, there were considerable price increases that could not be explained by wage or raw material price hikes.[21]

6 Further Investigation of Recent Second-Round Effects in Japan

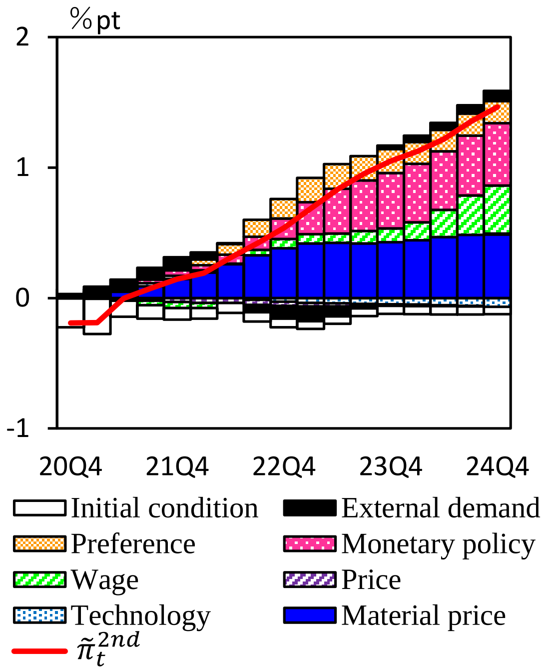
The previous section highlighted that the second-round effect of raw material price hikes through wages is likely to be very gradual, due to high wage rigidity and the loosening of labor supply and demand caused by the rise in raw material prices. This section explores the possibility that the characteristics of the second-round effect have changed in Japan in recent years.

To gain insight, we interpret $\tilde{\pi}_t^{2nd}$ defined in Section 3 as the "inflation rate driven by wage increases" and confirm its recent trend (Figure 10).[22] This figure suggests that the inflation rate driven by wage increases has steadily risen in recent years. Factors contributing to this include a persistent upward push from the second-round effect of raw material prices, as well as an increased contribution from (1) monetary policy shocks and (2) wage shocks. Below, we explore the possibility that these factors are related to the second-round effect.

[21] Such results may be consistent with the argument of so-called "Greedflation" in Europe, where companies raised prices by more than the increase in costs.

[22] The contribution of "Material price" in Figure 10 corresponds to "2nd round effect" in Figure 9.

Figure 10: Inflation Driven by Wage Increases in Japan



Note: $\tilde{\pi}_t^{2nd}$ (year-on-year, percent point) decomposed into contributions of shocks occurring from 2020/Q4 onwards. Initial conditions are contributions of shocks before 2020/Q3. Posterior means are used for parameters and shocks.

Monetary Policy and Second-Round Effects

First, the result that monetary policy shocks contribute to pushing up prices suggests that, against the backdrop of price increases primarily caused by raw material price hikes, interest rate hikes (as reflected in shadow rates) were conducted cautiously, maintaining accommodative financial conditions compared to what the monetary policy rule implies. Indeed, when estimating the relationship between the estimated raw material price shock $\hat{\epsilon}_t^x$ and the monetary policy shock $\hat{z}_t^r$ using the following equation, the estimated coefficient α was negative, -0.0058 (p-value: 0.087):[23,24]

$$\hat{z}_t^r = \hat{\rho}_r \hat{z}_{t-1}^r + \alpha \times \frac{1}{4} \sum_{k=1}^{4} \hat{\epsilon}_{t-k}^x + u_t^r \tag{9}$$

As qualitatively stated in Section 3, a gradual increase in interest rates in response to rising raw material prices is likely to make the second-round effect of raw material price hikes

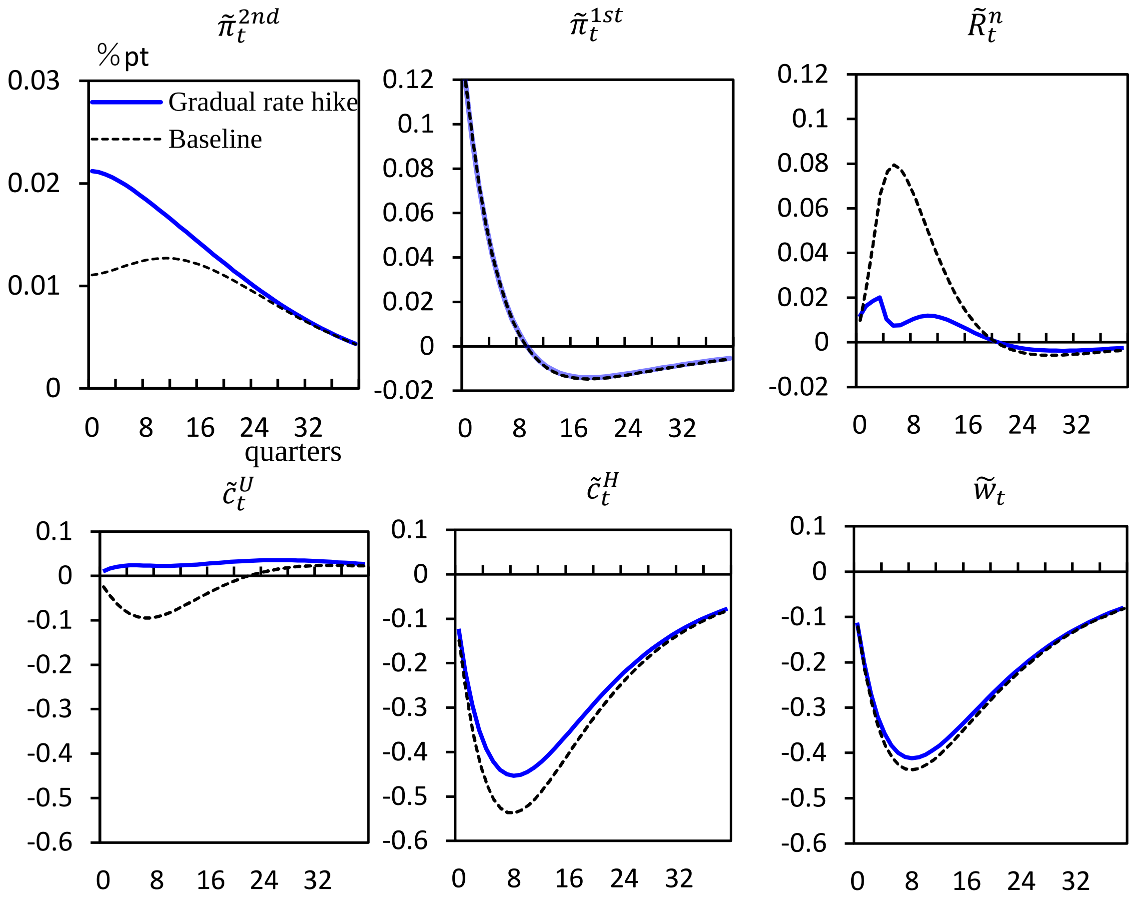
[23] The estimation period is from Q1 2020 to Q4 2024. For the monetary policy shock $\hat{z}_t^r$, raw material price shock $\hat{\epsilon}_t^x$, and persistence parameter $\hat{\rho}_r$, the posterior means estimated in the previous section are used.

[24] Even when the steady-state inflation rate was calibrated to 2%, the relationship between the estimated values of the monetary policy shock $\hat{z}_t^r$ and the raw material price shock $\hat{\epsilon}_t^x$ was broadly similar.

more pronounced. To verify this, we calculated the impulse responses of variables to a raw material price shock after replacing the stochastic process of the monetary policy shock with Equation (9) (Figure 11).

Looking at the result, when interest rates are raised gradually during a raw material price increase, the first-round effect $\tilde{\pi}_t^{1st}$ is not affected, but the second-round effect $\tilde{\pi}_t^{2nd}$ becomes larger. Behind this, with the limited increase in interest rates $\tilde{R}_t^n$, Ricardian households' consumption $\tilde{c}_t^U$ no longer decreases. Also, under these circumstances, the decline in labor demand and real wages $\tilde{w}_t$ is also mitigated, and the drop in non-Ricardian households' consumption $\tilde{c}_t^H$ becomes smaller.

Figure 11: Impact of Monetary Policy



Note: Impulse response to a one-standard-deviation raw material price shock. "Baseline" refers to the impulse response of the original model (posterior means used for parameters). "Gradual rate hike" refers to the impulse response when the stochastic process of the monetary policy shock is replaced with Equation (9).

Wage Rigidity and Second-Round Effects

The recent expansion of wage shocks may reflect a reduction in additional labor supply capacity in Japan,[25] but given the recent widespread wage increases, it is also possible that

[25] Ikeda et al. [2025] discuss the impact of demographic changes on labor market and wage trends.

wage rigidity has decreased compared to the past. Here, we examine part of this possibility by incorporating downward nominal wage rigidity into the model in a simplified manner.

To incorporate downward nominal wage rigidity, an additional assumption is made: if the optimal nominal wage $P_t W_t^o$[26] for the proportion $(1-\xi_w)$ of jobs optimizing wages in period t falls below the average nominal wage $\pi z P_{t-1} W_{t-1}$ of other jobs, the actual nominal wage $P_t V_t$ set by this proportion of jobs is determined as follows:

$$P_t V_t = (1-\delta) P_t W_t^o + \delta \pi z P_{t-1} W_{t-1}$$

where $\delta \in (0,1)$ is a parameter representing downward nominal wage rigidity. The closer δ is to 1, the greater the downward rigidity. In other words, as δ approaches 1, even if $P_t W_t^o$ fluctuates due to economic changes, the actual nominal wage $P_t V_t$ will remain relatively stable.

Under this assumption, the NKWPC switches depending on the relative magnitude between $P_t W_t^o$ and $\pi z P_{t-1} W_{t-1}$. Specifically, the NKWPC becomes as follows:

$$\tilde{\pi}_t^w = \frac{(1-\xi_w)(1-\beta z^{1-\sigma}\xi_w)(1-\delta)}{\xi_w + (1-\xi_w)\delta}(\widetilde{mrs}_t - \tilde{w}_t) + \frac{\beta z^{1-\sigma}\xi_w}{\xi_w + (1-\xi_w)\delta} E_t \tilde{\pi}_{t+1}^w + \frac{\xi_w(1-\delta)}{\xi_w + (1-\xi_w)\delta} z_t^w$$

$$\delta > 0 \quad if \quad \tilde{w}_t^o < \tilde{w}_{t-1} - \tilde{\pi}_t - z_t^z; \quad \delta = 0 \quad otherwise$$

where $\tilde{w}_t^o$ is determined by the following equation:

$$\tilde{w}_t^o = \beta z^{1-\sigma}\xi_w (E_t \tilde{w}_{t+1}^o + E_t \tilde{\pi}_{t+1} + E_t z_{t+1}^z) + (1-\beta z^{1-\sigma}\xi_w)\widetilde{mrs}_t + z_t^w$$

When the economy is subject to the downward nominal wage rigidity constraint (= Regime 1), the NKWPC becomes flatter due to the presence of δ. Conversely, when the economy exits the downward nominal wage rigidity constraint (= Regime 0), the NKWPC becomes steeper.

This model is a nonlinear model that includes so-called occasionally-binding constraints. Therefore, Dynare's Occbin toolbox[27] is used for estimation. Considering the high computational load, only three parameters $\{\delta, \xi_w, \rho_w\}$ are estimated, and other parameters are calibrated using the posterior means estimated in Section 5. Also, only the mode is estimated, not the entire posterior distribution. For the prior distribution of δ, a Beta

[26] W_t^o is determined according to Equation (1).

[27] For details on the Occbin toolbox, refer to Guerrieri and Iacoviello [2015] and Adjemian et al. [2024].

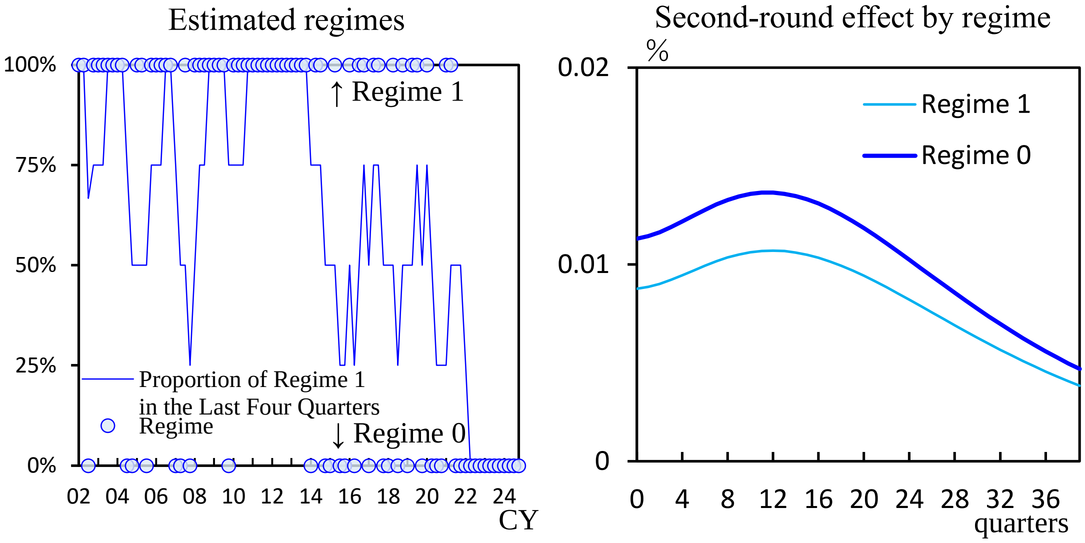
distribution with a mean of 0.5 and a standard deviation of 0.2 is used (prior distributions for ξ_w and ρ_w are the same as in Figure 4).

As a result of the estimation, the modes of the posterior distributions were $\delta = 0.239\ (0.008)$, $\xi_w = 0.941\ (0.004)$, $\rho_w = 0.327\ (0.011)$ (with standard deviations in parentheses). The mode of δ is significantly different from 0, suggesting that the slope of the NKWPC becomes smaller when the constraint is binding.

Next, for each period of the sample, we examine whether the downward nominal wage rigidity constraint is binding. It is estimated that a considerable period before 2013 was under Regime 1, i.e., the economy was subject to the constraint (Figure 12, left). After that, for the period from 2014 to 2019, Regime 1 and Regime 0 were roughly equally distributed, and for the past approximately three years, it is suggested that the economy has completely exited the downward nominal wage rigidity constraint.

Comparing the second-round effect of raw material price increases under these two different regimes, it is slightly stronger under Regime 0 (not subject to constraint) than under Regime 1 (subject to constraint) (Figure 12, right).[28] This suggests that in recent years in Japan, the second-round effect through wages may have become somewhat stronger compared to past phases of raw material price increases (e.g., before the global financial crisis).

Figure 12: Impact of Downward Nominal Wage Rigidity



Note: "Regime 1" refers to periods when the economy is constrained by downward nominal wage rigidity, while "Regime 0" refers to periods when this constraint is not present. The right figure shows the impulse response of $\tilde{\pi}_t^{2nd}$ to a one-standard-deviation raw material price shock. Posterior means are used for parameters. "Regime 1" ("Regime 0") second-round effect indicates the second-round effect when the economy is always subject to (not subject to) the constraint.

[28] This result also suggests the possibility that the existence of downward nominal wage rigidity causes the second-round effects on prices through wages to be asymmetric in deflationary and inflationary phases.

7 Conclusion

This paper empirically examined the second-round effect of raw material price increases using a DSGE model. More specifically, it explored how price increases driven by rising raw material costs spill over into wages, which then feedback into prices. The results showed that the first-round effect, which captures the pass-through of rising raw material costs to prices, is slower in Japan than in Europe. On the other hand, the second-round effect through wages is gradual but persistent in both Japan and Europe. Additionally, during the period of high inflation since 2020, the first-round effect of higher raw material costs was the main driver of inflation in both Japan and Europe, while the second-round effect contributed to the persistence of inflation. The paper also suggested that the recent changes in wage rigidity in Japan may have strengthened the second-round effect.

When interpreting the results of this paper, the following limitations should be noted:

First, the analysis assumes that people's long-term inflation expectations are stable. That is, the channel through which prices spiral upward due to unstable inflation expectations, as seen in the 1970s, is not captured by the second-round effect analyzed in this paper.

Second, the model's structural parameters are assumed to be constant throughout the estimation period. That is, this analysis does not consider the possibility that people's wage- and price-setting behaviors may structurally change when faced with large shocks, such as a surge in raw material prices.

Third, as the model assumes a closed economy, it abstracts away the mechanism that rising raw material prices depress the real economy by worsening the terms of trade.

Future research will aim to improve and extend the model by addressing these points.

References

Abe, N., T. Fueki, and S. Kaihatsu [2019], "Estimating a Markov Switching DSGE Model with Macroeconomic Policy Interaction," Bank of Japan Working Paper Series 19-E-3.

Adjemian, S., M. Juillard, F. Karamé, W. Mutschler, J. Pfeifer, M. Ratto, N. Rion, and S. Villemot [2024], "Dynare: Reference Manual, Version 6," Dynare Working Papers, 80, CEPREMAP.

Alp, H., M. Klepacz, and A. Saxena [2023], "Second-Round Effects of Oil Prices on Inflation in the Advanced Foreign Economies," FEDS Notes. Washington: Board of Governors of the Federal Reserve System, December 15, 2023.

An, S. and H. Kang [2011], "Oil Shocks in a DSGE Model for the Korean Economy," Commodity Prices and Markets, pp. 295-321, National Bureau of Economic Research.

Baba, C. and J. Lee [2022], " Second-Round Effects of Oil Price Shocks - Implications for Europe's Inflation Outlook," IMF Working Papers, 2022(173).

Bachmann, R. and E. R. Sims [2012], "Confidence and the Transmission of Government Spending Shocks," *Journal of Monetary Economics*, 59(3), pp. 235-249.

Battistini, N., H. Grapow, E. Hahn, and M. Soudan [2022], "Wage Share Dynamics and Second-Round Effects on Inflation after Energy Price Surges in the 1970s and Today," Economic Bulletin Boxes, 2022(5), European Central Bank.

Calvo, G. A. [1983], "Staggered Prices in a Utility-Maximizing Framework," *Journal of Monetary Economics*, 12(3), pp. 383-398.

Colciago, A. [2011], "Rule-of-Thumb Consumers Meet Sticky Wages," *Journal of Money, Credit and Banking*, 43(2-3), pp. 325-353.

Comin, D. A., R. C. Johnson, and C. J. Jones [2023], "Supply Chain Constraints and Inflation," NBER Working Papers, 31179.

Enders, A. and Z. Enders [2017], "Second-Round Effects after Oil-Price Shocks: Evidence for the Euro Area and Germany," *Economics Letters*, 159(C), pp. 208-213.

Erceg, C. J., L. Guerrieri, and C. Gust [2006], "SIGMA: A New Open Economy Model for Policy Analysis," *International Journal of Central Banking*, 2(1).

Erceg, C. J., D. W. Henderson, and A. T. Levin [2000], "Optimal Monetary Policy with Staggered Wage and Price Contracts," *Journal of Monetary Economics*, 46(2), pp. 281-

313.

Fukunaga, I., K. Furukawa, S. Haba, Y. Hogen, Y. Kido, T. Okubo, K. Suita, and K. Takatomi [2023], "Wage Developments in Japan: Four Key Issues for the Post-COVID-19 Wage Growth," Bank of Japan Working Paper Series 23-E-4.

Gali, J. [2015], "Monetary Policy, Inflation, and the Business Cycle: An Introduction to the New Keynesian Framework and Its Applications," Second edition, Princeton University Press.

Guerrieri, L. and M. Iacoviello [2015], "OccBin: A Toolkit for Solving Dynamic Models with Occasionally Binding Constraints Easily," *Journal of Monetary Economics*, 70(C), pp. 22-38.

Hara, R., T. Unayama, and J. Weidner [2016], "The Wealthy Hand to Mouth in Japan," *Economics Letters*, 141(C), pp. 52-54.

Hirose, Y. and T. Kurozumi [2012], "Do Investment-Specific Technological Changes Matter for Business Fluctuations? Evidence from Japan," Pacific Economic Review, 17(2), pp. 208-230.

Ikeda, S., U. Kawano, Y. Makabe, K. Takata, and T. Yagi [2025], "Effects of Demographic Change on Labor Market and Wage Developments," Bank of Japan Review Series 2025-E-2.

Internationl Monetary Fund (IMF) [2022], "Wage Dynamics Post-COVID-19 and Wage-Price Spiral Risks," World Economic Outlook, October, Chapter 2.

Krippner, L. [2013], "Measuring the Stance of Monetary Policy in Zero Lower Bound Environments," *Economics Letters*, 118(1), pp. 135-138.

Lorenzoni, G. and I. Werning [2023a], "Wage-Price Spirals," *Brookings Papers on Economic Activity*, 54(2), pp. 317-393.

_ and _ [2023b], "Inflation is Conflict," NBER Working Papers, 31099.

McAdam, P. and A. Warne [2019], "Euro Area Real-Time Density Forecasting with Financial or Labor Market Frictions," *International Journal of Forecasting*, 35(2), pp. 580-600.

Ruch, F. and S. du Plessis [2015], "Second-Round Effects from Food and Energy Prices: an SBVAR Approach," South African Reserve Bank Working Paper Series, 7008.

Schmitt-Grohe, S. and M. Uribe [2005], "Optimal Fiscal and Monetary Policy in a

Medium-Scale Macroeconomic Model," NBER Macroeconomics Annual, pp. 383-425.

Sugo, T. and K. Ueda [2008], "Estimating a Dynamic Stochastic General Equilibrium Model for Japan," *Journal of the Japanese and International Economies*, 22(4), pp. 476-502.

Taylor, J. B. [1989], "Differences in Economic Fluctuations in Japan and the United States: The Role of Nominal Rigidities," *Journal of the Japanese and International Economies*, 3(2), pp. 127-144.

Van Nguyen, P. [2020], "Evaluating the Forecasting Accuracy of the Closed- and Open Economy New Keynesian DSGE Models," Dynare Working Papers, 59, CEPREMAP.

Appendix

A1 Linearized Model

[Ricardian Household's Marginal Utility of Consumption]

$$\left(1-\frac{\theta}{z}\right)\left(1-\frac{\beta\theta}{z^{\sigma}}\right)\tilde{\lambda}_t^U = -\sigma\left\{\tilde{c}_t^U - \frac{\theta}{z}(\tilde{c}_{t-1}^U - z_t^z)\right\} + \left(1-\frac{\theta}{z}\right)z_t^b + \frac{\beta\theta}{z^{\sigma}}\left\{\sigma\left(E_t\tilde{c}_{t+1}^U + E_t z_{t+1}^z - \frac{\theta}{z}\tilde{c}_t^U\right) - \left(1-\frac{\theta}{z}\right)E_t z_{t+1}^b\right\} \quad \text{(A1)}$$

[Ricardian Household's Euler Equation]

$$\tilde{\lambda}_t^U = E_t\tilde{\lambda}_{t+1}^U - \sigma E_t z_{t+1}^z + \tilde{R}_t^n - E_t\tilde{\pi}_{t+1} \quad \text{(A2)}$$

[Non-Ricardian Household's Consumption]

$$\tilde{c}_t^H = \tilde{w}_t + \tilde{l}_t \quad \text{(A3)}$$

[Non-Ricardian Household's Marginal Utility of Consumption]

$$\tilde{\lambda}_t^H = z_t^b - \sigma\tilde{c}_t^H \quad \text{(A4)}$$

[Total Household Consumption]

$$\tilde{c}_t = \lambda\tilde{c}_t^H + (1-\lambda)\tilde{c}_t^U \quad \text{(A5)}$$

[Wage Phillips Curve (NKWPC)]

$$\tilde{\pi}_t^W = \frac{(1-\xi_w)(1-\beta z^{1-\sigma}\xi_w)}{\xi_w}(\widetilde{mrs}_t - \tilde{w}_t) + \beta z^{1-\sigma}E_t\tilde{\pi}_{t+1}^W + z_t^W \quad \text{(A6)}$$

[Average Marginal Rate of Substitution between Consumption and Labor]

$$\widetilde{mrs}_t = \eta\tilde{l}_t - \left\{(1-\lambda)\tilde{\lambda}_t^U + \lambda\tilde{\lambda}_t^H\right\} \quad \text{(A7)}$$

[Nominal Wage Growth Rate]

$$\tilde{\pi}_t^W = \tilde{w}_t - \tilde{w}_{t-1} + \tilde{\pi}_t + z_t^z \quad \text{(A8)}$$

[Real Marginal Cost]

$$\widetilde{mc}_t = a_X\tilde{p}_t^X + (1-a_X)\tilde{w}_t \quad \text{(A9)}$$

[Nominal Raw Material Price Growth Rate]

$$\tilde{\pi}_t^X = \tilde{p}_t^X - \tilde{p}_{t-1}^X + \tilde{\pi}_t \quad \text{(A10)}$$

[Optimal Input Ratio]

$$\tilde{l}_t = \tilde{x}_t \quad \text{(A11)}$$

[Production Function]

$$\tilde{y}_t = a_X\tilde{x}_t + (1-a_X)\tilde{l}_t \quad \text{(A12)}$$

[Phillips Curve (NKPC)]

$$\tilde{\pi}_t = \frac{(1-\xi_p)(1-\beta z^{1-\sigma}\xi_p)}{\xi_p}\widetilde{mc}_t + \beta z^{1-\sigma}E_t\tilde{\pi}_{t+1} + z_t^p \quad \text{(A13)}$$

[Monetary Policy Rule]

$$\tilde{R}_t^n = \phi_r \tilde{R}_{t-1}^n + (1-\phi_r)\left(\phi_\pi\left(\frac{1}{4}\sum_{s=0}^{3}\tilde{\pi}_{t-s}\right) + \phi_y \tilde{y}_t\right) + z_t^r \tag{A14}$$

[Market Clearing Condition]

$$\tilde{y}_t = \frac{c}{y}\tilde{c}_t + (1-\frac{c}{y})z_t^g \tag{A15}$$

[Real Raw Material Price]

$$\tilde{p}_t^X = \rho_x \tilde{p}_{t-1}^X + \epsilon_t^x \tag{A16}$$

[Technology Shock]

$$z_t^z = \rho_z z_{t-1}^z + \epsilon_t^z \tag{A17}$$

[Wage Shock]

$$z_t^w = \rho_w z_{t-1}^w + \epsilon_t^w \tag{A18}$$

[Price Shock]

$$z_t^p = \rho_p z_{t-1}^p + \epsilon_t^p \tag{A19}$$

[Monetary Policy Shock]

$$z_t^r = \rho_r z_{t-1}^r + \epsilon_t^r \tag{A20}$$

[Preference Shock]

$$z_t^b = \rho_b z_{t-1}^b + \epsilon_t^b \tag{A21}$$

[External Demand Shock]

$$z_t^g = \rho_g z_{t-1}^g + \epsilon_t^g \tag{A22}$$

where we define

$z_t^p = \frac{\tilde{\lambda}_t^p(1-\xi_p)(1-\beta z^{1-\sigma}\xi_p)}{\xi_p}$ $\left(\tilde{\lambda}_t^p = \log\left\{\frac{1+\lambda_t^p}{1+\lambda^p}\right\}\right)$, $z_t^w = (\tilde{\lambda}_t^w + z_t^l)(1-\xi_w)(1-\beta z^{1-\sigma}\xi_w)/$ ξ_w $(\tilde{\lambda}_t^w = \log\{\frac{1+\lambda_t^w}{1+\lambda^w}\})$.

A2 Proof of Proposition

Transforming Equation (A9):

$$\widetilde{mc}_t = (1 - a_X)\tilde{\pi}_t^W + a_X\tilde{\pi}_t^X + \widetilde{mc}_{t-1} - \tilde{\pi}_t. \tag{A23}$$

Let L be the lag operator and L^{-1} be the forward operator. That is, $y_{t-1} = Ly_t$ and $y_{t+1} = L^{-1}y_t$. Using this:

$$\widetilde{mc}_t = \frac{(1 - a_X)\tilde{\pi}_t^W + a_X\tilde{\pi}_t^X - \tilde{\pi}_t}{1 - L}. \tag{A24}$$

Substituting this into Equation (A13) and transforming:

$$\{(1 - L)(1 - \hat{\beta}L^{-1}) + \Lambda_p\}\tilde{\pi}_t = \Lambda_p\{(1 - a_X)\tilde{\pi}_t^W + a_X\tilde{\pi}_t^X\} - \hat{\beta}L^{-1}(1 - L)\xi_t. \tag{A25}$$

where ξ_t is the forecast error of $\tilde{\pi}_t$ in period t where $\xi_t = \tilde{\pi}_t - E_{t-1}\tilde{\pi}_t$. Also, $\hat{\beta} = \beta z^{1-\sigma}$. Define the coefficient of the left side as $B \equiv \{(1 - L)(1 - \hat{\beta}L^{-1}) + \Lambda_p\}$:

$$B = -\hat{\beta}L^{-1}\{1 - \hat{\beta}^{-1}(1 + \Lambda_p + \hat{\beta})L + \hat{\beta}^{-1}L^2\}. \tag{A26}$$

Hence B can be factored as follows:

$$B = -\hat{\beta}L^{-1}(1 - \lambda_1 L)(1 - \lambda_2 L). \tag{A27}$$

where $\lambda_1 + \lambda_2 = \hat{\beta}^{-1}(1 + \Lambda_p + \hat{\beta}), \lambda_1\lambda_2 = \hat{\beta}^{-1}$, and

$$\lambda_1 = \frac{2}{(1+\Lambda_p+\hat{\beta}) + \sqrt{(1+\Lambda_p+\hat{\beta})^2 - 4\hat{\beta}}}, \lambda_2 = \frac{2}{(1+\Lambda_p+\hat{\beta}) - \sqrt{(1+\Lambda_p+\hat{\beta})^2 - 4\hat{\beta}}}.$$

Also, note that λ_1 and λ_2 are the solutions to the following quadratic equation in λ.

$$f(\lambda) \equiv \lambda^2 - \hat{\beta}^{-1}(1 + \Lambda_p + \hat{\beta})\lambda + \hat{\beta}^{-1} = 0. \tag{A28}$$

Here, the function $f(\lambda)$ is a downward-convex quadratic function, and from $f(0) = \hat{\beta}^{-1} > 0, f(1) = -\Lambda_p/\hat{\beta} < 0$, it can be verified that $0 < \lambda_1 < 1 < \lambda_2$.

Substituting Equation (A27) into Equation (A25) yields:

$$\begin{aligned}(1 - \lambda_1 L)&(1 - \lambda_2^{-1}L^{-1})\tilde{\pi}_t \\ &= \beta^{-1}\lambda_2^{-1}\Lambda_p\{(1 - a_X)\tilde{\pi}_t^W + a_X\tilde{\pi}_t^X\} - \lambda_2^{-1}(L^{-1} - 1)\xi_t.\end{aligned} \tag{A29}$$

Since $|\lambda_2^{-1}| < 1$, divide both sides by $1 - \lambda_2^{-1}L^{-1}$ and take the expectation operator $\mathrm{E_t}$:

$$(1-\lambda_1 L)\tilde{\pi}_t = \beta^{-1}\lambda_2^{-1}\Lambda_p E_t[\frac{(1-a_X)\tilde{\pi}_t^W + a_X\tilde{\pi}_t^X}{1-\lambda_2^{-1}L^{-1}}] - \lambda_2^{-1}E_t[\frac{\xi_{t+1}-\xi_t}{1-\lambda_2^{-1}L^{-1}}]. \quad \text{(A30)}$$

Furthermore:

$$\tilde{\pi}_t = \lambda_1\tilde{\pi}_{t-1} + \lambda_2^{-1}E_t\sum_{k=0}^{\infty}\lambda_2^{-k}(\xi_{t+k} - \xi_{t+k+1}) + \lambda_1\Lambda_p E_t\sum_{k=0}^{\infty}\lambda_2^{-k}((1-a_X)\tilde{\pi}_{t+k}^W + a_X\tilde{\pi}_{t+k}^X). \quad \text{(A31)}$$

Here, $\lambda_1 = \hat{\beta}^{-1}\lambda_2^{-1}$. Note that $\mathrm{E_t}\xi_{t+k} = \mathrm{E_t}\tilde{\pi}_{t+k} - \mathrm{E_t}\mathrm{E}_{t+k-1}\tilde{\pi}_{t+k} = \mathrm{E_t}\tilde{\pi}_{t+k} - \mathrm{E_t}\tilde{\pi}_{t+k} = 0\ \forall k \geq 1$ (by the law of iterated expectation). Therefore:

$$\tilde{\pi}_t = \lambda_1\tilde{\pi}_{t-1} + \lambda_2^{-1}\xi_t + \lambda_1\Lambda_p E_t\sum_{k=0}^{\infty}\lambda_2^{-k}((1-a_X)\tilde{\pi}_{t+k}^W + a_X\tilde{\pi}_{t+k}^X). \quad \text{(A32)}$$

Using the definition of ξ_t and the NKPC, reorganize the above equation:

$$\tilde{\pi}_t = \frac{\lambda_1\Lambda_p}{1-\lambda_2^{-1}}\left\{\widetilde{mc}_{t-1} + E_t\sum_{k=0}^{\infty}\lambda_2^{-k}((1-a_X)\tilde{\pi}_{t+k}^W + a_X\tilde{\pi}_{t+k}^X)\right\}. \quad \text{(A33)}$$

Here, defining $\widetilde{mc}_t^{1st} = a_X\tilde{\pi}_t^X + \widetilde{mc}_{t-1}^{1st} - \tilde{\pi}_t^{1st}, \widetilde{mc}_t^{2nd} = (1-a_X)\tilde{\pi}_t^W + \widetilde{mc}_{t-1}^{2nd} - \tilde{\pi}_t^{2nd}$ and $\widetilde{mc}_t \equiv \widetilde{mc}_t^{1st} + \widetilde{mc}_t^{2nd}$, $\widetilde{mc}_t$ satisfies Equation (A9). That is, the real marginal cost $\widetilde{mc}_t$ can be decomposed into $\widetilde{mc}_t^{1st}$ and $\widetilde{mc}_t^{2nd}$.

Similarly, defining $\tilde{\pi}_t^{1st}, \tilde{\pi}_t^{2nd}$ as variables that satisfy Equation (6) and (7), and $\tilde{\pi}_t \equiv \tilde{\pi}_t^{1st} + \tilde{\pi}_t^{2nd}$, $\tilde{\pi}_t$ satisfies Equation (A33). That is, the inflation rate $\tilde{\pi}_t$ can be decomposed into $\tilde{\pi}_t^{1st}$ and $\tilde{\pi}_t^{2nd}$. ■

A3 Spiral Inflation and Conflict Inflation

Spiral inflation, as presented by LW, refers to the cumulative price increase over an infinite horizon caused by an exogenous shock, such as a raw material supply shock. That is, if a shock occurs in period t, the spiral inflation generated by that shock is defined as follows:

$$\Pi_{\mathrm{t}}^{\mathrm{spiral}} = \sum_{k=0}^{\infty} \tilde{\pi}_{t+k} = \sum_{k=0}^{\infty} \tilde{\pi}_{t+k}^{w} \tag{A34}$$

Here, the cumulative price increase equals the wage increase (the second equality holds) because real wages converge to their steady-state value in the long run. This implies that spiral inflation can be interpreted as capturing price increases associated with the interaction between wages and prices, in the sense that $\Pi_{\mathrm{t}}^{\mathrm{spiral}} = 0$ if nominal wages remain unchanged in response to a shock.

Furthermore, LW showed that for cases where the marginal rate of substitution between consumption and labor and the marginal productivity of labor decay exponentially, this spiral inflation matches the "*conflict inflation*" (Π_t^c) proposed in Lorenzoni and Werning [2023b].[29]

$$\Pi_t^c = \frac{\Lambda_p \Lambda_w}{\Lambda_p + \Lambda_w} E_t \sum_{\mathrm{k}=0}^{\infty} \beta^k (\widetilde{mrs}_{t+k} - \widetilde{mpl}_{t+k}) \tag{A35}$$

where mpl_t represents the marginal productivity of labor. The name "conflict inflation" derives from the fact that mrs_t represents the aspiration level for real wages on the household side, and mpl_t represents the aspiration level for real wages on the firm side, so Π_t^c represents price increases resulting from the conflict regarding real wage aspiration levels between households and firms.

From this expression, the following can be said about spiral inflation when a negative raw material supply shock occurs: First, as a decrease in raw material supply is a shock that lowers the marginal productivity of labor mpl_t, (if other conditions are held constant) a positive spiral inflation will occur as a result. The magnitude of this spiral inflation is

[29] Conflict inflation also relates to an inflation indicator that Gali [2015] calls "composite inflation." Composite inflation is a weighted average of the inflation rate $\tilde{\pi}_t$ and the nominal wage change rate $\tilde{\pi}_t^w$ by their respective rigidities, Λ_p^{-1} and Λ_w^{-1}. Furthermore, the composite inflation is an inflation component caused by the output gap viewed as a deviation from a flexible-price economy.

determined by the three factors discussed in Section 3 (Λ_w, Λ_p, and $\widetilde{mrs}_t$). Furthermore, Λ_p and Λ_w multiplicatively determine the magnitude of spiral inflation. That is, as can be seen from Equation (A35), there is a property that spiral inflation is maximized when $\Lambda_p = \Lambda_w$, given a constant sum of Λ_p and Λ_w.