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Discussion Paper No. 2023-E-1

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IMES Discussion Paper Series 2023-E-1
January 2023

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Abstract

This study examines how automation can have an impact on the effectiveness of monetary policy and inflation dynamics. We incorporate a task-based production technology into a standard New Keynesian model with two kinds of nominal rigidities (price/wage rigidity). When monetary easing raises wages, automation opportunities allow firms to substitute costly human labor with cheaper machines. This yields the automation effect of monetary policy, which increases labor productivity and magnifies the rise in real output. In turn, automation lowers real marginal costs for firms, thereby restraining the rise of inflation and flattening the Phillips curve. When prices are rigid and wages are flexible, the automation effect of monetary policy is particularly large, and the flattening of the Phillips curve is most pronounced. The automation effect also depends on the automation frontier, i.e., the remaining opportunities for automation, and a kinked Phillips curve emerges when firms face technological constraints on automation.

Keywords: Automation; Monetary policy; Nominal rigidities; Phillips curve
JEL classification: E22, E31

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The authors are grateful to Kosuke Aoki, Luca Fornaro, Ippei Fujiwara, Masao Fukui, Hibiki Ichiue, Taisuke Nakata, Toshitaka Sekine, Mototsugu Shintani, Toyoichiro Shirota, Takayuki Tsuruga, Kenichi Ueda, Carl E. Walsh, Jiro Yoshida, and the seminar and conference participants at the Bank of Japan and the 24th TCER Macroeconomics Conference for their helpful comments. The views expressed in this paper are those of the authors and do not necessarily reflect the official views of the Bank of Japan.

1 Introduction

The rapid development of automation is perhaps the most remarkable structural change observed in modern times. The widespread movement to replace human labor with machines will reshape the economy on a broad scale. There is already a vast literature on how automation will affect employment and economy-wide productivity. The most influential study among them is the task-based production framework of Acemoglu and Restrepo (2018, AR henceforth). In their framework, automation is modeled as a process in which human labor is replaced by machines and the scope of machine-based tasks is expanded.[1] This framework integrates and organizes the multiple impacts of automation and has been widely applied in recent years to theoretical and empirical analyses.[2]

Previous studies which incorporate task-based production technology have concentrated on the impact of automation on the real side of the economy, discarding nominal frictions. Therefore, most existing studies based on this framework do not have implications for inflation dynamics or monetary policy effects. Recently, however, Fornaro and Wolf (2021, FW henceforth) have provided an analysis of the potential for monetary policy to promote automation. Their model incorporates task-based production technology into a New Keynesian model with fixed nominal wages. In their model, monetary easing promotes automation, thereby increasing real output and labor productivity. This new effect is referred to as the "automation effect of monetary policy."

Motivated by the work of FW, this study analyzes the impact of automation on the effectiveness of monetary policy.[3] To examine its quantitative importance, we incorporate two kinds of nominal rigidities, namely, price rigidity and nominal wage rigidity. As has been shown in the literature of New Keynesian economics, nominal rigidities are necessary ingredients to produce the real effects of monetary policy. Monetary easing raises wages by tightening the labor market, but opportunities for automation allow firms to substi-

[1] In contrast to previous studies which formalize automation as traditional "factor-augmenting technological change", the task-based approach can replicate the empirically plausible mechanism in which automation reduces labor demand, and thereby reduces labor share and the equilibrium wage unless the productivity gains from automation are sufficiently large.

[2] A task-based production framework is built on some earlier studies, such as Zeira (1998), Acemoglu and Zilibotti (2001), and Acemoglu and Autor (2011). See Acemoglu and Restrepo (2019) for an outline of a task-based production framework.

[3] Automation considered in this study covers the replacement of labor by machines in a wide range of industries, including the traditionally labor-intensive service sector, and is not limited to robotization in the sense of the introduction of robots on production lines in the manufacturing sector.

tute costly human labor with cheaper machines. This will increase labor productivity and magnify the rise in real output. The scope of this study is how the automation effect of monetary policy depends quantitatively on the combination of the two kinds of nominal rigidities.

This study also examines the implications of automation for the shape of the Phillips curve. When monetary policy eases, the automation effect magnifies the increase in real output through higher labor productivity. On the other hand, automation allows firms to restrain the increase in real marginal cost because, as more tasks are produced with cheaper capital, the weight of capital cost becomes larger in real marginal cost. As a result, any rise in the inflation rate is also mitigated, so that automation can contribute to a flattening of the Phillips curve. This *weight effect* is caused by the introduction of a task-based framework in which the weight placed on the rental cost of capital and wages in the real marginal cost function can change endogenously in response to automation. To the best of our knowledge, there are no studies that point to such a mechanism.[4] The present study also examines how the magnitude of the flattening of the Phillips curve due to automation depends on two kinds of nominal rigidities.

Our model is similar to FW in that it introduces AR's task-based production technology into a New Keynesian model. However, there are some differences from FW. First, we allow for a range of degrees of price and wage rigidity, while FW deals only with the limiting case in which prices are perfectly flexible and wages are fully rigid. We analyze how the automation effects depend on the degree of price and wage rigidities. Second, FW analyze the long-term effects of monetary policy by assuming that agents' utility depends on their asset holdings. While this is an interesting setting, whether monetary policy has a long-run real impact is a controversial issue. We use a more standard New Keynesian framework in which monetary policy has a short- or medium-term impact on labor productivity. In other words, monetary policy has no long-run impact on trend productivity growth, but it accelerates or decelerates the pace of underlying automation. Third, in addition to the automation effect of monetary policy, we focus on the implications of automation for the flattening of the Phillips curve.

[4]To determine the mechanism by which monetary policy endogenously gives rise to automation, this study focuses on the displacement effect, in which labor is replaced by capital in tasks for production. AR also analyze another aspect of automation, the reinstatement effect, in which new labor-intensive tasks are created. The implications of the reinstatement effect in the presence of nominal rigidities is a topic for future research.

Our analysis shows that when prices are rigid and wages are flexible, the automation effect of monetary policy is particularly large and the flattening of the Phillips curve due to automation is most pronounced. This tells us that the combination of price rigidity and wage rigidity is a key determinant of the size of the automation effect of monetary policy and its impact on the Phillips curve. Flattening occurs in the Phillips curve for prices and not in the Phillips curve for wages.

We also consider the possibility that firms may not be able to take full advantage of automation opportunities due to some technological constraint on automation, as suggested by AR. In the presence of automation constraints, the automation effect will depend on the automation frontier, i.e., the remaining opportunities for automation. In particular, we find that when firms face technological constraints on automation, the Phillips curve becomes kinked. That is, the slope of the Phillips curve is relatively flat when there is still plenty of room for automation, but steepens when firms have exhausted their automation opportunities.

Existing empirical studies using cross-country data such as Fujiwara and Zhu (2020), do not provide clear evidence that automation has had a systematic impact on inflation dynamics. Nevertheless, it is often pointed out that automation is one possible cause for the recent decline in the response of inflation to increased output. For instance, in its official outlook report, the Bank of Japan (2018) cited automation as one of the reasons why inflation in Japan has been slow to rise despite massive monetary easing.[5] The report also noted that in Japan, there was significant room for improvement in labor productivity through automation, which had led to the widespread behavior in which firms absorbed cost increases in order to avoid raising prices.[6] These observations are consistent with our mechanism showing that the slope of the Phillips curve is state-dependent.

The remainder of this study is organized as follows. In Section 2, we present the model used in our analysis. Specifically, we incorporate a task-based production technology into a

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[5]The report states that "firms have been making efforts to absorb upward pressure of costs on prices by raising productivity through labor-saving and efficiency-improving investment, making use of the progress in digital technology in recent years and streamlining existing business processes."

[6]The Bank of Japan (2018) considers the issue:"(w)hy do firms prioritize raising productivity rather than prices? One reason is that the productivity of Japanese firms is relatively low and there is large room to raise productivity, mainly in the nonmanufacturing sector. In fact, Japan's labor productivity remains at only 60 to 70 percent of the U.S. level. Partly because firms accelerated their efforts to raise productivity in response to acute labor shortage - in a situation where room for productivity improvements remained large - productivity growth in Japan in the 2010s was the highest among the G7 economies."

standard New Keynesian model with two kinds of nominal rigidities (price/wage rigidity). Also, we explain the mechanism by which firms' automation is determined as an arbitrage of production costs. In Section 3, we present model dynamics which clarify how the impact of the automation effect depends on the combination of price and wage rigidity. We then examine how advances in automation influence the shape of the Phillips curve under alternative settings for nominal rigidities. In Section 4, we examine situations in which firms are unable to take full advantage of automation opportunities due to some technological constraint. We show that in the presence of automation constraints, the automation effect will depend on the automation frontier, and that the Phillips curve becomes kinked when firms face technological constraints on automation. In Section 5, we examine the extent to which automation can reduce nominal adjustment costs under different scenarios of price and wage rigidities. In Section 6, we conclude our analysis.

2 Model

We introduce AR's task-based production technology into a standard New Keynesian framework, such as those of Christiano, Eichenbaum, and Evans (2005), and Smets and Wouters (2007), which incorporate two kinds of nominal rigidities, namely, price and wage rigidities. In order to obtain realistic model dynamics, the model also introduces real rigidities, such as consumption habit formation, investment adjustment cost, and capital utilization adjustment cost.

Figure 1 shows the overall picture of our model. The model consists of six types of agents: a final-good producer, intermediate goods producers, task aggregators, task producers, households, and a monetary authority. In the task-based framework (the area circled in red in Figure 1), tasks are competitively produced by task producers. These tasks are aggregated by task aggregators and sold to intermediate goods producers. Intermediate goods producers facing price rigidity sell intermediate goods to a final-good producer who competitively produces and sells a final good to households. Each household supplies capital and labor service, and faces wage rigidity.

2.1 Final-Good Producer

A perfectly competitive final-good producer purchases differentiated intermediate goods $Y_t(f)$, $f \in [0,1]$ to produce a unique final good Y_t with the following production function

$$Y_t = \left(\int_0^1 Y_t(f)^{\frac{\epsilon_p - 1}{\epsilon_p}} df \right)^{\frac{\epsilon_p}{\epsilon_p - 1}}, \tag{1}$$

where ϵ_p is the elasticity of substitution between intermediate goods. The profit maximization problem of the final-good producer is given by

$$\max_{Y_t(f)} \quad P_t Y_t - \int_0^1 P_t(f) Y_t(f) df,$$

subject to the equation (1). P_t is the price of the final good, and $P_t(f)$ is the price of the intermediate good f. Under perfect competition, the profit maximization yields the demand function for intermediate good f:

$$Y_t(f) = \left(\frac{P_t(f)}{P_t} \right)^{-\epsilon_p} Y_t. \tag{2}$$

2.2 Intermediate Goods Producers

An intermediate good producer f produces a unique intermediate good $Y_t(f)$ in a monopolistically competitive manner, using an aggregated task $y_t(f)$ at price $p_t(f)$. The production function of the intermediate good producer f is

$$Y_t(f) = y_t(f). \tag{3}$$

As in Rotemberg (1982), we assume that intermediate goods firms face the Rotemberg-type price adjustment cost Φ_p:

$$\Phi_p(\pi_t(f)) = \frac{\phi_p}{2} \left(\pi_t(f) - 1 \right)^2, \tag{4}$$

where $\pi_t(f)$ is the price inflation rate, which we define as $\pi_t(f) = P_t(f)/P_{t-1}(f)$, and ϕ_p is the price rigidity parameter that governs the size of the price adjustment cost.

Subject to the equations (2), (3), and (4), the profit maximization problem of the intermediate good firm f is given by

$$\max_{P_t(f)} E_t \sum_{k=0}^{\infty} \Omega_{t,t+k} \Big[P_{t+k}(f) Y_{t+k}(f) - p_{t+k}(f) y_{t+k}(f) - \Phi_p(\pi_{t+k}(f)) P_{t+k} Y_{t+k} \Big],$$

where $\Omega_{t,t+k}$ is the stochastic discount factor that is defined in Section 2.6.

In Rotemberg-type price setting, all of the intermediate goods firms face the same problem, and thus will choose the same price and the same quantity. As a result, the first order condition of the profit maximization problem gives the Rotemberg-type nonlinear price Phillips curve:

$$(1-\epsilon_p)+\epsilon_p RMC_t - \phi_p (\pi_t - 1) \pi_t + \phi_p E_t \left[\Omega_{t,t+1} (\pi_{t+1} - 1) \pi_{t+1}^2 \frac{Y_{t+1}}{Y_t} \right] = 0, \tag{5}$$

where RMC_t is the real marginal cost, defined as

$$RMC_t = \frac{p_t}{P_t}. \tag{6}$$

2.3 Task Aggregators

A perfectly competitive task aggregator f produces a unique aggregated task $y_t(f)$ by combining a unit measure of tasks $y_{f,t}(i), i \in [N-1, N]$, with the following production function:

$$y_t(f) = B \left(\int_{N-1}^{N} y_{f,t}(i)^{\frac{\sigma-1}{\sigma}} di \right)^{\frac{\sigma}{\sigma-1}}, \tag{7}$$

where $B > 0$ is the scale parameter, and $\sigma > 0$ is the elasticity of substitution between tasks. The profit maximization problem of the task aggregator f is

$$\max_{y_{f,t}(i)} \quad p_t(f) y_t(f) - \int_{N-1}^{N} p_{f,t}(i) y_{f,t}(i) di,$$

subject to the equation (7). Under perfect competition, the demand function for task i is

$$y_{f,t}(i) = B^{\sigma-1} \left(\frac{p_{f,t}(i)}{p_t(f)} \right)^{-\sigma} y_t(f). \tag{8}$$

The price of aggregated task $p_t(f)$ is given by

$$p_t(f) = \frac{1}{B}\left(\int_{N-1}^{N} p_{f,t}(i)^{1-\sigma} di\right)^{\frac{1}{1-\sigma}}. \tag{9}$$

2.4 Task Producers

A perfectly competitive task producer i produces a unique task $y_{f,t}(i)$ using capital service $k_{f,t}(i)$ and human labor $l_{f,t}(i)$. In exactly the same manner as in AR, we assume that there exists a "technological constraint" on automation, $I \in [N-1, N]$, such that tasks $i \leq I$ are technologically automated, that is, can be produced with capital, and conversely, tasks $i > I$ are *not* technologically automated, so that they must be produced with labor. In this sense, the production function of the task producer i takes the following form:

$$y_{f,t}(i) = \begin{cases} k_{f,t}(i) + \gamma(i) l_{f,t}(i) & (i \leq I) \\ \gamma(i) l_{f,t}(i) & (i > I) \end{cases}, \tag{10}$$

where $\gamma(i)$ is the productivity of labor in task i. As in AR, we assume that $\gamma(i)$ is strictly increasing for i so that the human labor has a strict comparative advantage in tasks with a higher index.

For task producers $i \leq I$, the profit maximization problem is given by

$$\max_{\{k_{f,t}(i), l_{f,t}(i)\}} \quad p_{f,t}(i) y_{f,t}(i) - \left(R_t^k k_{f,t}(i) + W_t l_{f,t}(i)\right),$$

subject to

$$y_{f,t}(i) = k_{f,t}(i) + \gamma(i) l_{f,t}(i),$$

where R_t^k denotes the nominal rental cost of capital, and W_t denotes the nominal wage.

Also, for task producers $i > I$, the profit maximization problem is given by

$$\max_{l_{f,t}(i)} \quad p_{f,t}(i) y_{f,t}(i) - W_t l_{f,t}(i),$$

subject to

$$y_{f,t}(i) = \gamma(i) l_{f,t}(i).$$

Since all the tasks are produced in a perfectly competitive manner, their prices are equal to the minimum unit cost of production:

$$p_{f,t}(i) = \begin{cases} \min\left\{R_t^k, \frac{W_t}{\gamma(i)}\right\} & (i \leq I) \\ \frac{W_t}{\gamma(i)} & (i > I) \end{cases}. \tag{11}$$

Following AR, the functional form of the productivity of labor in task i is

$$\gamma(i) = e^{\mu i}, \tag{12}$$

where $\mu > 0$.

As $\gamma(i)$ is strictly increasing for i, there exists a unique threshold task $\tilde{I}_t$:

$$r_t^k = \frac{w_t}{e^{\mu \tilde{I}_t}}, \tag{13}$$

where r_t^k is real rental cost, and w_t is real wage, in terms of the final-good price P_t.

The equation (13) implies that it is indifferent as to the use of either capital or human labor to produce the task $\tilde{I}_t$.[7] Notice that the threshold $\tilde{I}_t$ is an endogenous variable which is determined by the arbitrage between real rental cost r_t^k and real wage w_t. We will discuss this determination mechanism in more detail in Section 2.8.

Finally, there exists a unique equilibrium threshold task I_t^*:

$$I_t^* = \min\{I, \tilde{I}_t\}. \tag{14}$$

The equation (14) implies that all of the tasks $i \leq I_t^*$ will be produced with capital, and all of the tasks $i > I_t^*$ will be produced with labor.

Importantly, I_t^* can be interpreted as a variable representing the degree of automation progress. The rise in I_t^* represents the advance of automation because the proportion of

[7] As in AR, we assume that firms use capital service when it is indifferent as to the use of either capital or human labor.

tasks produced with capital increases. In this sense, we call I_t^* the *automation rate*. On the other hand, if $I_t^* = I$ holds, the rise in I_t^* does not occur because any more tasks are not technologically automated. We refer to this situation as "the technological constraint binds".

2.5 Aggregation

As explained in Section 2.2, all intermediate goods firms take the same decisions in our economy, so we can ignore the f subscript.

In this symmetric equilibrium setting, combining the equations (3), (8),(10), and (11), we get the task-level capital demand equation

$$k_t(i) = \begin{cases} B^{\sigma-1} Y_t R_t^{k-\sigma} p_t^{\sigma} & (i \leq I_t^*) \\ 0 & (i > I_t^*) \end{cases},$$

and the task-level labor demand equation

$$l_t(i) = \begin{cases} 0 & (i \leq I_t^*) \\ B^{\sigma-1} Y_t \frac{1}{\gamma(i)} \left(\frac{W_t}{\gamma(i)}\right)^{-\sigma} p_t^{\sigma} & (i > I_t^*) \end{cases}.$$

Combining these equations with the equations (6) and (12), and aggregating across tasks, the capital and labor market clearing conditions are given by

$$r_t^k = RMC_t \left[B^{\frac{\sigma-1}{\sigma}} (I_t^* - N + 1)^{\frac{1}{\sigma}} \left(\frac{Y_t}{K_t}\right)^{\frac{1}{\sigma}} \right], \tag{15}$$

$$w_t = RMC_t \left[B^{\frac{\sigma-1}{\sigma}} \left\{ \frac{e^{(\sigma-1)\mu N} - e^{(\sigma-1)\mu I_t^*}}{(\sigma-1)\mu} \right\}^{\frac{1}{\sigma}} \left(\frac{Y_t}{L_t}\right)^{\frac{1}{\sigma}} \right]. \tag{16}$$

Combining the equations (6), (9), (11), and (12), the real marginal cost is expressed as

$$RMC_t = \frac{1}{B} \left[(I_t^* - N + 1) r_t^{k\,1-\sigma} + \left\{ \frac{e^{(\sigma-1)\mu N} - e^{(\sigma-1)\mu I_t^*}}{(\sigma-1)\mu} \right\} w_t^{1-\sigma} \right]^{\frac{1}{1-\sigma}}. \tag{17}$$

Finally, combining the equations (15), (16), and (17), the aggregate production function is derived as

$$Y_t = B\left[(I_t^* - N + 1)^{\frac{1}{\sigma}} K_t^{\frac{\sigma-1}{\sigma}} + \left\{\frac{e^{(\sigma-1)\mu N} - e^{(\sigma-1)\mu I_t^*}}{(\sigma-1)\mu}\right\}^{\frac{1}{\sigma}} L_t^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}. \quad (18)$$

2.6 Household

We assume that there is a continuum of households in our economy. The preference of the household $j \in [0, 1]$ is given by

$$E_t \sum_{k=0}^{\infty} \beta^k b_{t+k} \left[\frac{(C_{t+k}(j) - hC_{t+k-1}(j))^{1-\sigma_c}}{1-\sigma_c} - \frac{L_{t+k}(j)^{1+\eta}}{1+\eta}\right], \quad (19)$$

where $C_t(j)$ is consumption, and $L_t(j)$ is labor supply. Also, β denotes the discount rate, σ_c denotes the risk aversion parameter, and h is the consumption-habit parameter.

Lastly, b_t is the preference shock which follows $AR(1)$ process in log as

$$\log(b_t) = \rho_b \log(b_{t-1}) + \zeta_t^b, \quad (20)$$

where ζ_t^b is an iid normal random variable with mean zero and variance σ_b^2.

The household j faces the following budget constraint:

$$\begin{aligned} &C_t(j) + \frac{B_t(j)}{P_t} + S_t(j) + \Psi(u_t(j))\bar{K}_t(j) \\ &= \frac{W_t(j)}{P_t} L_t(j)\left(1 - \Phi_w(\pi_t^w(j))\right) + \frac{R_t^k}{P_t} u_t(j)\bar{K}_t(j) + \frac{R_{t-1}^b}{\pi_t}\frac{B_{t-1}(j)}{P_{t-1}} + \frac{\Gamma_t}{P_t}, \end{aligned} \quad (21)$$

where $B_t(j)$ is nominal government bond, $S_t(j)$ is investment, $u_t(j)$ is capital utilization rate, $\bar{K}_t(j)$ is capital stock holding. Also, $\pi_t^w(j)$ is the nominal wage inflation rate which we define as $\pi_t^w(j) = W_t(j)/W_{t-1}(j)$, R_t^b is the risk-free nominal interest rate, and Γ_t is the dividend from firms. We will discuss the capital utilization cost function $\Psi(\cdot)$ and the wage adjustment cost function $\Phi_w(\cdot)$ in detail later.

The household j also faces the following capital stock accumulation equation:

$$\bar{K}_{t+1}(j) = (1-\delta)\bar{K}_t(j) + \left\{1 - \frac{\tau}{2}\left(\frac{S_t(j)}{S_{t-1}(j)} - 1\right)^2\right\} S_t(j), \quad (22)$$

where δ is the capital depreciation rate, and τ governs the size of the investment adjustment cost.

The household j rents the capital service $K_t(j)$ to firms by R_t^k. Also, the household can adjust the amount of the capital service by changing the utilization rate $u_t(j)$. In this sense, we define the capital service $K_t(j)$ as

$$K_t(j) = u_t(j)\bar{K}_t(j). \tag{23}$$

Following Christiano, Trabandt, and Walentin (2010), we assume the capital utilization cost function $\Psi(\cdot)$ to be

$$\Psi(u_t(j)) = 0.5\sigma_a\sigma_b u_t(j)^2 + \sigma_b(1-\sigma_a)u_t(j) + \sigma_b\left(\frac{\sigma_a}{2} - 1\right), \tag{24}$$

where σ_b is chosen to satisfy that $\Psi(u_{ss}) = \Psi'(u_{ss}) = 0$ in steady state, and u_{ss} is the steady state level of the utilization rate.

Next, we assume that the household j supplies differentiated labor service $L_t(j)$ with the demand equation:

$$L_t(j) = \left(\frac{W_t(j)}{W_t}\right)^{-\epsilon_w} L_t, \tag{25}$$

where ϵ_w is the elasticity of substitution between differentiated labor services. We assume that the household j faces the Rotemberg-type nominal wage adjustment cost Φ_w which is defined as

$$\Phi_w(\pi_t^w(j)) = \frac{\phi_w}{2}\left(\pi_t^w(j) - 1\right)^2, \tag{26}$$

where ϕ_w is the wage rigidity parameter that governs the size of the wage adjustment cost.

Finally, the household j chooses $C_t(j)$, $B_t(j)$, $S_t(j)$, $u_t(j)$, $\bar{K}_t(j)$, and $W_t(j)$ in order to maximize the expected lifetime utility (19), subject to the equations (21), (22), (24), (25), and (26). Then, in our Rotemberg-type wage setting assumption, all households take the same decisions, so that we can ignore the j subscript.

The first order condition for consumption is

$$\lambda_t = b_t(C_t - hC_{t-1})^{-\sigma_c} - \beta h E_t\left[b_{t+1}(C_{t+1} - hC_t)^{-\sigma_c}\right], \tag{27}$$

where λ_t is the Lagrange multiplier imposed on the budget constraint (21).

The first order condition for the risk free bond is

$$\lambda_t = \beta E_t \left[\lambda_{t+1} \frac{R_t^b}{\pi_{t+1}} \right]. \tag{28}$$

Then, we define the stochastic discount factor $\Omega_{t,t+1}$ as

$$\Omega_{t,t+1} = \beta \frac{\lambda_{t+1}}{\lambda_t}. \tag{29}$$

The first order condition for investment is

$$\begin{aligned} q_t \left\{ 1 - \tau \left(\frac{S_t}{S_{t-1}} - 1 \right) \frac{S_t}{S_{t-1}} - \frac{\tau}{2} \left(\frac{S_t}{S_{t-1}} - 1 \right)^2 \right\} \\ = 1 - E_t \left[\Omega_{t,t+1} q_{t+1} \tau \left(\frac{S_{t+1}}{S_t} - 1 \right) \left(\frac{S_{t+1}}{S_t} \right)^2 \right], \end{aligned} \tag{30}$$

where we define *Tobin's q* as $q_t \equiv \psi_t / \lambda_t$, and ψ_t is the Lagrange multiplier imposed on the capital stock accumulation equation (22)

The first order condition for capital stock is

$$q_t = E_t \left[\Omega_{t,t+1} \left\{ u_{t+1} r_{t+1}^k - \Psi(u_{t+1}) + (1 - \delta) q_{t+1} \right\} \right]. \tag{31}$$

The first order condition for the capital utilization rate is

$$r_t^k = \sigma_a \sigma_b (u_t - 1) + \sigma_b. \tag{32}$$

Lastly, the first order condition for nominal wage is

$$\begin{aligned} \epsilon_w b_t \frac{1}{w_t} \frac{L_t^\eta}{\lambda_t} - \left(\frac{\phi_w}{2} \left\{ (3 - \epsilon_w)(\pi_t^w)^2 - 2(2 - \epsilon_w)\pi_t^w + (1 - \epsilon_w) \right\} - (1 - \epsilon_w) \right) \\ + E_t \left[\Omega_{t,t+1} \phi_w \left\{ (\pi_{t+1}^w)^2 - \pi_{t+1}^w \right\} \pi_{t+1}^w \left(\frac{L_{t+1}}{L_t} \right) \right] = 0. \end{aligned} \tag{33}$$

The equation (33) is the Rotemberg-type nonlinear wage Phillips curve.

2.7 Monetary Authority and Market Clearing

The monetary authority sets the nominal interest rate following the rule of the form:

$$\frac{R_t^b}{R_{ss}^b} = \left(\frac{R_{t-1}^b}{R_{ss}^b}\right)^{\rho_r} \left[(\pi_t)^{\zeta_\pi} \left(\frac{Y_t}{Y_t^n}\right)^{\zeta_Y}\right]^{1-\rho_r} m_t, \tag{34}$$

where R_{ss}^b is the steady state level of the nominal interest rate, and Y_t^n is the natural output which is the level of output under flexible price and flexible wage. Therefore, Y_t/Y_t^n denotes the output gap.

Transition of monetary policy shock m_t follows $AR(1)$ process in log as

$$\log(m_t) = \rho_m \log(m_{t-1}) + \zeta_t^m, \tag{35}$$

where ζ_t^m is an iid normal random variable with mean zero and variance σ_m^2.

Finally, the market clearing condition is given by

$$C_t + S_t + \Psi(u_t)\bar{K}_t = \left\{1 - \frac{\phi_p}{2}(\pi_t - 1)^2\right\} Y_t - \frac{\phi_w}{2}(\pi_t^w - 1)^2 w_t L_t. \tag{36}$$

2.8 Mechanism: Automation as Arbitrage of Production Costs

In this section, we explain that automation occurs as arbitrage of production costs. When the technological constraint on automation does not bind (that is, $I_t^* = \tilde{I}_t < I$ holds), the equation (13) can be written as

$$r_t^k = \frac{W_t/P_t}{e^{\mu I_t^*}}. \tag{37}$$

The equation (37) indicates that the automation rate I_t^* is determined as a result of the arbitrage between real rental cost r_t^k and real wage W_t/P_t. Suppose that an exogenous shock raises real wages more than real rental costs. In this case, since it is more efficient to produce tasks with cheaper capital than with expensive labor, automation rate I_t^* increases so that the equation (37) holds.[8,9]

[8]In accordance with the AR, this study assumes that firms do not incur any costs when they change their automation rate I_t^*. However, in our model, firms will at least have to bear some adjustment cost of investment with respect to the change in investment associated with automation as in the equation (22).

[9]What is needed for monetary easing to promote automation is that it will cause real wages to rise only relative to real rental costs. In other words, it is not necessary for monetary easing to result in an unrealistically

The combination of price and wage rigidity matters in determining the automation rate. Assume an expansionary monetary policy shock occurs. When price is sticky and nominal wage is flexible, real wage rises significantly. In this case, if real rental cost r_t^k is lower than real wage w_t, it is more efficient to produce tasks with cheaper capital, so that automation is more advanced. On the contrary, when price is flexible and nominal wage is sticky, real wage does not increase much in response to expansionary monetary policy shocks. In this case, automation is not very advanced.

As we will see later, advances in automation change the dynamics of macroeconomics dramatically. To get an intuition of this finding, we approximate the real marginal cost equation (17) as follows

$$RMC_t \simeq \frac{1}{B}\left[\alpha(I_t^*){r_t^k}^{1-\sigma} + (1-\alpha(I_t^*))w_t^{1-\sigma}\right]^{\frac{1}{1-\sigma}}.$$

As this equation shows, real marginal cost RMC_t can be expressed as a weighted average of real rental cost r_t^k and real wage w_t with the weight variable $\alpha(I_t^*)$. We can interpret $\alpha(I_t^*)$ as the share of capital cost and $1-\alpha(I_t^*)$ as the share of labor cost in real marginal cost. In a standard New Keynesian model with constant elasticity of substitution (CES) production technology, this weight is constant ($\alpha(I_t^*) = \alpha$). In our model, on the other hand, $\alpha(I_t^*)$ is endogenous, and an increasing function of I_t^*. Therefore, real marginal cost is affected by advances in automation I_t^* through variation of the weight variable $\alpha(I_t^*)$.

Assume monetary policy expands and the demand for capital and labor input increases. If real rental cost r_t^k is lower than real wage w_t, it is more efficient to produce tasks with cheaper capital than expensive labor. Then advances in automation increase the weight of cheaper capital $\alpha(I_t^*)$ and decrease that of expensive labor cost $1-\alpha(I_t^*)$. This *weight effect* mitigates the rise in real marginal cost, and thus the rise in the inflation rate. In standard New Keynesian models, the weight is constant and real marginal cost increases sharply in response to expansionary monetary shocks.

The *weight effect* in our model is caused by the introduction of a task-based framework in which the weight variable $\alpha(I_t^*)$ changes endogenously in response to the automation progress. To the best of our knowledge, there are no studies that point to such a mechanism.

large increase in real wages.

Notice that this automation effect mainly affects the price Phillips curve, but not the wage Phillips curve, because the change of automation rate influences the real marginal cost term in the New Keynesian price Phillips curve equation (5), but does not affect any variable in the New Keynesian wage Phillips curve equation (33). As will be shown later, the slope of the price Phillips curve can be significantly affected by advances in automation, but not the slope of the wage Phillips curve.

3 Model Dynamics with Automation Effect

3.1 Parameters

The parameters of our model are summarized in Table 1. The first four parameters are specific to the task-based framework. The scale parameter B is set so that the steady state equilibrium exists. The elasticity of substitution between tasks σ is, in our setting, equal to the elasticity of substitution between capital and labor as shown in the aggregate production function equation (18). Therefore, we set $\sigma = 0.4$, following Chirinko and Mallick (2017), who estimate the parameter using U.S. industry data.[10] Lastly, we set the curve parameter in the labor productivity function as $\mu = 1$, and the parameter of range of tasks as $N = 1$ for simplicity.

Most of the remaining parameters follow the results of Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007). We set the relative risk aversion parameter $\sigma_c = 1.38$, which is higher than 1.26 in Moura (2018), but smaller than 1.39 and 1.41 in Harding, Lindé, and Trabandt (2022). The consumption habit parameter $h = 0.71$ and the inverse of the Frisch elasticity of labor supply $\eta = 1.83$ are in line with the results of Ikeda (2015) and Harding, Lindé, and Trabandt (2022). The investment adjustment cost parameter $\tau = 5.74$ and the capital utilization cost parameter $\sigma_a = 0.01$ are close to the estimated values of the Calvo-type sticky wage model in Christiano, Eichenbaum, and Trabandt (2016) (5.03 and 0.03, respectively).[11] For markup-related parameters (ϵ_p and ϵ_w), we follow the results of Iwasaki, Muto, and Shintani (2021).

[10] Humlum (2021) estimates this parameter with Danish data, and finds that the value of this parameter is 0.49. This is close to our calibrated value above.

[11] The parameter σ_a plays an important role in determining the automation rate because it governs the magnitude of variation in real rental costs. Except for large values of σ_a, the automation rate rises in response to an easing monetary shock because real wages rise more than the increase in real rental costs.

3.2 Impulse Responses under Alternative Settings for Nominal Rigidities

We derive impulse response functions by using a 1% expansionary monetary policy shock. To see clearly how advances in automation can change macroeconomic dynamics, we assume that the shocks occur to the economy for 12 consecutive periods.[12] In this section, we show that advances in automation affect the dynamics of an economy, and in particular, they change the relationship between the price inflation rate and the output gap. To clarify this point, we assume two scenarios for advances in automation. The first scenario is that the technological constraint always binds, and so there are no advances at all in automation. We call this case "Without Automation Effect". The second scenario is that the technological constraint never binds, and so advances in automation can occur without any restrictions. We call this case "With Automation Effect".

We will also show that the degree of nominal price/wage rigidity is the key element in determining the impact of the automation effect on macroeconomic dynamics. To clarify this point, we set up an ad-hoc combination set of nominal price/wage rigidity parameters (ϕ_p and ϕ_w): when $\phi_p = 10$ or $\phi_w = 10$, we call these cases "Flexible Price" and "Flexible Wage" respectively. On the other hand, when $\phi_p = 100$ or $\phi_w = 100$, we call these cases "Sticky Price" and "Sticky Wage" respectively.

3.2.1 Flexible Price and Flexible Wage

Figure 2 shows impulse responses in the case of Flexible Price and Flexible Wage.[13] In the Without Automation Effect scenario, the output gap and price inflation rate increase in response to the expansionary monetary policy shock. Reflecting the increase in aggregate demand, both capital service and labor increase, so that both real rental costs and real wages increase. These results are consistent with those of standard New Keynesian models. It is worth of noticing that wages are rising more than rental costs, which implies that there is an incentive to substitute expensive labor with cheaper capital, and so an incentive to advance automation.

In the case of With Automation Effect, the automation rate I_t^* increases in response to an expansionary monetary policy shock. Since there are no restrictions on automation,

[12] Since our model is based on a quarterly basis, we are considering a three-year continuous monetary policy shock. This setting is consistent with the fact that many central banks, especially in advanced economies, have maintained monetary easing policies over a long period of time.

[13] The graph scales in Figures 2, 3, 4 and 5 are aligned for easy comparison.

firms have an incentive to reduce real marginal costs by using cheaper capital rather than costly human labor. Reflecting this substitution effect, the increase in rental costs is greater and the increase in real wages is smaller. Since the use of capital input increases, labor productivity, which we define as Y_t/L_t, increases significantly, and the rise in the output gap is magnified by the automation effect. Also, advances in automation mitigate the rise of real marginal costs through the weight effect, but not to a large extent. As a result, the rise in the price inflation rate is dampened through the New Keynesian Phillips curve, although not to a significant degree in this case.

3.2.2 Flexible Price and Sticky Wage

Figure 3 shows impulse responses in the case of Flexible Price and Sticky Wage. In this case, the automation effect is smaller, than in the previous case. The increase in the automation rate is small because, as already explained, when wages are sticky, the increase in real wages relative to the increase in real rental costs is limited, and this makes automation less likely to occur. Consequently, the increase in inflation is contained and the increase in the output gap is amplified compared with the Without Automation Effect, but to a lesser extent than in the case of Flexible Price and Flexible Wage.

3.2.3 Sticky Price and Flexible Wage

Figure 4 shows impulse responses in the case of Sticky Price and Flexible Wage. The figure indicates that the automation effect is quite large in this case. Compared to the previous two cases, the automation rate increases more significantly. As a result, the rise in price inflation is more restrained and the increase in the output gap is amplified. As already explained, this is because when prices are sticky and wages are flexible, the increase in real wages relative to the increase in real rental costs is magnified, and this makes automation more likely to occur.

3.2.4 Sticky Price and Sticky Wage

Finally, Figure 5 shows impulse responses in the case of Sticky Price and Sticky Wage. The automation effect is smaller than in the case of Sticky Price and Flexible Wage, since the rise in real wages is smaller than in the previous case due to the stickiness of the nominal wage.

These impulse responses indicate that the size of the automation effect depends positively on (i) the degree of price rigidity and (ii) the degree of wage flexibility. As for the former, when firms need to pay large costs for adjusting their prices, they have considerable incentive to avoid large price adjustments by making use of automation opportunities, thereby mitigating variations in production costs. As for the latter, when the nominal wage is flexible (and price is sticky to some degree), the rise in real wages becomes substantial in response to an expansionary monetary policy shock. Then firms need to restrain the rise in real marginal costs by shifting their production inputs from costly human labor to cheaper capital.

3.3 The Flattening of Phillips Curve

In this section, we examine how advances in automation influence inflation dynamics. Specifically, we examine the impact of the automation effect on the shape of the price/wage Phillips curve under alternative settings with respect to price/wage rigidities. For this purpose, we carry out a stochastic simulation by adding randomly generated monetary policy shocks to the model.[14] Figure 6 shows the price Phillips curves that illustrate the relationship between the price inflation rate and the output gap. The upper left scatter plot of Figure 6 shows the price Philips curve in the case of Flexible Price and Flexible Wage. This shows that automation flattens the price Phillips curve: the slope of the price Phillips curve in the case of With Automation Effect is smaller than that in the case of Without Automation Effect. This result is consistent with the finding in Section 3.2, that is, the automation effect magnifies the increase in output and suppresses the increase in the price inflation rate in response to an easing monetary shock.[15]

The upper right scatter plot of Figure 6 shows the price Philips curve in the case of Flexible Price and Sticky Wage, which also shows that the slope of the price Phillips curve in the case of With Automation Effect is smaller than that in the case of Without Automation Effect. The magnitude of flattening, however, is smaller than in the case of Flexible Price

[14]To validate the results in this section, we also derive the price/wage Phillips curve using randomly generated preference shocks. It turns out that the qualitative results remain the same as those under monetary policy shocks. See Figures 8 and 9.

[15]Introducing variable capital utilization rates may also play a similar role to automation in that it would result in a flattening of the Phillips curve. For example, Christiano, Eichenbaum, and Evans (2005) report that if the adjustment cost parameter for capital utilization were made extremely large so that capital utilization remained unchanged, the increase in output in response to an expansionary monetary policy shock would be suppressed, while inflation would rise more.

and Flexible Wage. This is because, as we have already shown in our analysis of the impulse response, the automation effect is smaller when wages are sticky. The lower left scatter plot of Figure 6 shows the price Philips curve in the case of Sticky Price and Flexible Wage, and the lower right one is in the case of Sticky Price and Sticky Wage. The flattening of the Phillips curve occurs in both cases, but the magnitude of flattening is greatest among all four cases in the case of Sticky Price and Flexible Wage.

Figure 7 shows the wage Phillips curve representing the relationship between the nominal wage inflation rate and the labor gap, which we define as L_t/L_t^n in exactly the same manner as the output gap, that is, the ratio of the actual labor service L_t to the natural level of labor service L_t^n. Regardless of the degree of nominal price/wage rigidity, the flattening of the wage Phillips curve does not occur. This is because, as already indicated, the automation effect arises mainly through variation in real marginal costs, which affects the Phillips curve for prices but not for wages.

3.4 Applying Nominal Rigidities in the U.S. and Japan

The analysis has so far analyzed the size of the automation effect and its impact on the Phillips curve by applying ad-hoc parameter sets regarding price/wage rigidity. Here we use the values of the nominal price/wage rigidity parameters estimated in Iwasaki, Muto, and Shintani (2021).

Figures 10 and 11 show impulse responses against a 1 % expansionary monetary policy shock for 12 consecutive terms, in the case of the U.S. and Japan respectively.[16,17] These results suggest that the automation effect can have a non-negligible impact on economic dynamics in both countries.

Figure 12 shows the price Phillips curve derived by stochastic simulation in the same setting as in Section 3.3. The figure shows that, under the estimated parameters of price/wage rigidities in both countries, the flattening of the price Phillips curve can occur. In addition, the two charts also suggest that the flattening of the price Phillips curve is more pronounced in Japan than in the U.S. This is because wages are relatively more

[16] As discussed in footnote 11, whether automation increases or decreases in response to an expansionary monetary policy shock depends on the value of σ_a, which controls the cost of capital utilization. For example, automation increases in response to a monetary easing shock when σ_a is less than 0.32 in the case of the U.S., and 0.99 in the case of Japan.

[17] The graph scales in Figures 10 and 11 are aligned for easy comparison.

flexible than prices in Japan, while the opposite is true in the U.S.

Finally, Figure 13 shows the wage Phillips curve. The results indicate that, for both countries, the wage Phillips curve does not flatten due to automation.

4 Constrained Automation: Kinked Phillips Curve

In Section 3, we showed that automation leads to a flattening of the price Phillips curve. However, the impact of automation on inflation dynamics might not be as systematic. So far, we have considered the situation in which firms can make full use of automation opportunities, or none at all. In reality, however, firms are likely to face some degree of technological constraint on automation. The automation effect then depends on the automation frontier, that is, the remaining opportunity for automation. This means that the automation effect is state-dependent, as it depends on the extent to which room for automation remains. In fact, the Bank of Japan (2018), which cited automation as a reason for the flattening of Japan's price Phillips curve, noted that in Japan, there was significant room for improvement in labor productivity through automation, which had led to the widespread behavior in which firms absorbed cost increases in order to avoid raising prices.

To examine this point, we additionally consider the impact of "Constrained Automation" in which firms are not free to adjust the automation rate due to some technological constraints. In this case, the automation effect depends on how much room there is for automation. In line with AR, we assume that the technological constraint is the upper limit of automation (defined in equation (14)). That is, tasks that are above the technological constraint must be produced solely with human labor and cannot be produced with capital. In this setting, firms are not able to increase the automation rate beyond a certain upper bound. We analyze how such a technological constraint affects macroeconomic dynamics, in particular the shape of the Phillips curve. We introduce the technological constraint as an occasionally binding constraint and employ the OccBin algorithm developed by Guerrieri and Iacoviello (2015) to solve the model.

Figure 14 shows impulse responses to an expansionary monetary policy shock in the case of Japan. In this impulse response analysis, two scenarios of Constrained Automation are assumed. The first scenario is when automation is allowed to proceed up to the

10% ceiling relative to the steady-state automation rate. The second scenario is when automation can increase to the 5% ceiling. In the first scenario, firms have relatively much room for automation, while in the second scenario, they have little room for automation. We refer to these cases as Constrained Automation (+10%) and Constrained Automation (+5%), respectively. In the case of Constrained Automation (+10%), the impulse response is closer to that of the With Automation Effect case. Conversely, in the case of Constrained Automation (+5%), the impulse response is closer to that of the Without Automation Effect case. These results show that the automation effect of monetary policy on macroeconomic dynamics is state-dependent. Specifically, the automation effect is bigger (smaller) when there is more (less) room for automation. For example, with more room for automation, the rise in the inflation rate is suppressed, while the increase in the output gap is amplified.

Figure 15 shows the price Phillips curve for Constrained Automation (+10%) under the rigidity parameters in the case of Japan. In this case, the automation rate cannot increase beyond the upper limit of 10%. Then the Phillips curve is kinked; if the output gap is negative or a small positive value, the slope is relatively flat, but if the output gap is a large positive value, the slope becomes much steeper.

To clarify the impact of technological constraints on the shape of the Phillips curve, we decompose this kinked Phillips curve into two parts. The yellow squares are the set of price inflation rates and the output gaps when the automation rate does not reach the 10% ceiling, i.e., when no technological constraints are applied. We call this region of the price Phillips curve "Constrained Automation (+10%, Nonbind)". The slope of this Phillips curve is then 0.247. This is close to the slope of the Phillips curve in the case of With Automation Effect (Figure 12). This is because the technological constraints are not binding in either case. As already discussed in respect of Figure 14, increased automation moderates the increase in inflation and amplifies the rise in the output gap. Thus, automation flattens the Phillips curve.

The red triangles, on the other hand, are the sets when the automation rate reaches the upper limit of 10%. We call these sets the Phillips curve for the "Constrained Automation (+10%, Bind)" case. The slope of this Phillips curve is then 0.597, which is close to the slope of the Without Automation Effect case (Figure 12). In either case, firms would like to increase the automation rate in response to an expansionary monetary policy shock, but they cannot do so because the technological constraint binds. As shown in Figure 14, if the increase in the automation rate is limited, the increase in the inflation rate will be larger and the increase in the output gap will be smaller. As a result, the slope of the Phillips curve is steeper.

Figure 16 shows the price Phillips curve for the Constrained Automation (+5%) case, which is decomposed into two parts, as in Figure 15. In this case, the automation rate cannot increase beyond the upper limit of 5%, and thus faces a more severe technological constraint than in the Constrained Automation (+10%) case. In both Figures 15 and 16, the Phillips curve is kinked. The results show that the level of the output gap at the kink point is smaller for Constrained Automation (+5%) than for Constrained Automation (+10%). This is because, in the Constrained Automation (+5%) case, firms are more severely technologically constrained, so that the automation rate reaches the upper limit even with smaller monetary expansion.

These results suggest that the impact of automation on the slope of the price Phillips curve also depends on the room for automation. As discussed in Section 1, this mechanism offers a possible reason why the flattening of the Phillips curve due to the automation effect of monetary policy is observed only in countries like Japan, where there is greater room for labor productivity improvement.

5 Nominal Adjustment Cost Reduction through Automation

The previous analysis shows that firms can save nominal adjustment costs by taking advantage of automation opportunities. In this section, we examine the extent to which automation can reduce nominal adjustment costs under different scenarios of price and wage rigidities.

Figure 17 shows the difference of nominal adjustment costs (sum of the level of price adjustment cost (4) and the level of wage adjustment cost (26)) between With Automation Effect and Without Automation Effect, in response to a 1% expansionary monetary policy shock for 12 consecutive periods. When the bars in the graph are below zero, the nominal adjustment costs are smaller in the case of With Automation Effect than Without Automation Effect. We can interpret this situation as being one in which automation can mitigate the rise in nominal adjustment costs in response to monetary policy shocks.

For any combination of nominal rigidities, automation reduces price and wage adjustment costs. This provides a good incentive for firms to save on nominal adjustment costs by shifting production inputs from costly workers to cheaper machines. However, the benefits of automation are quantitatively different under alternative scenarios of price and wage rigidity. When prices are sticky and wages are flexible, nominal adjustment costs are reduced most significantly by automation. In this case, price adjustment costs are particularly reduced by taking advantage of automation opportunities. This indicates that automation is a particularly effective tool for firms to reduce price adjustment costs.

6 Conclusion

In this study we have examined how automation can have an impact on the effectiveness of monetary policy and inflation dynamics. To do so, we have incorporated a task-based production technology into a standard New Keynesian model with price/wage rigidity. When monetary easing raises wages, automation opportunities allow firms to substitute costly human labor with cheaper machines. This yields the automation effect of monetary policy, which increases labor productivity and magnifies the rise in real output. In turn, automation lowers real marginal costs for firms, thereby restraining the rise of inflation and flattening the Phillips curve. Our analysis shows that when prices are rigid and wages are flexible, the automation effect of monetary policy is particularly large and the flattening of the Phillips curve is most pronounced. Furthermore, we show that the automation effect also depends on the automation frontier, i.e., the remaining opportunities for automation, and a kinked Phillips curve emerges when firms face technological constraints on automation.

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Appendix

Details of Equilibrium Conditions

1. Optimality condition for risk free bonds:

$$\lambda_t = \beta E_t \left[\lambda_{t+1} \frac{R_t^b}{\pi_{t+1}} \right]$$

2. Optimality condition for consumption:

$$\lambda_t = b_t (C_t - hC_{t-1})^{-\sigma_c} - \beta h E_t \left[b_{t+1} (C_{t+1} - hC_t)^{-\sigma_c} \right]$$

3. Definition of stochastic discount factor:

$$\Omega_{t,t+1} = \beta \frac{\lambda_{t+1}}{\lambda_t}$$

4. Capital stock accumulation equation:

$$\bar{K}_{t+1} = (1-\delta)\bar{K}_t + \left\{ 1 - \frac{\tau}{2} \left(\frac{S_t}{S_{t-1}} - 1 \right)^2 \right\} S_t$$

5. Optimality condition for investment:

$$q_t \left\{ 1 - \tau \left(\frac{S_t}{S_{t-1}} - 1 \right) \frac{S_t}{S_{t-1}} - \frac{\tau}{2} \left(\frac{S_t}{S_{t-1}} - 1 \right)^2 \right\} = 1 - E_t \left[\Omega_{t,t+1} q_{t+1} \tau \left(\frac{S_{t+1}}{S_t} - 1 \right) \left(\frac{S_{t+1}}{S_t} \right)^2 \right]$$

6. Optimality condition for capital stock:

$$q_t = E_t \left[\Omega_{t,t+1} \left\{ u_{t+1} r_{t+1}^k - \Psi(u_{t+1}) + (1-\delta) q_{t+1} \right\} \right]$$

7. Definition of capital service:

$$K_t = u_t \bar{K}_t$$

8. Definition of utilization cost function:

$$\Psi(u_t) = 0.5\sigma_a\sigma_b u_t^2 + \sigma_b(1-\sigma_a)u_t + \sigma_b\left(\frac{\sigma_a}{2} - 1\right)$$

9. Optimality condition for utilization rate:

$$r_t^k = \sigma_a\sigma_b(u_t - 1) + \sigma_b$$

10. Definition of nominal wage inflation rate:

$$\pi_t^w = \frac{w_t}{w_{t-1}}\pi_t$$

11. Wage Phillips curve:

$$\epsilon_w b_t \frac{1}{w_t}\frac{L_t^\eta}{\lambda_t} - \left(\frac{\phi_w}{2}\left\{(3-\epsilon_w)(\pi_t^w)^2 - 2(2-\epsilon_w)\pi_t^w + (1-\epsilon_w)\right\} - (1-\epsilon_w)\right) + E_t\left[\Omega_{t,t+1}\phi_w\left\{(\pi_{t+1}^w)^2 - \pi_{t+1}^w\right\}\pi_{t+1}^w\left(\frac{L_{t+1}}{L_t}\right)\right] = 0$$

12. Production function:

$$Y_t = B\left[(I_t^* - N + 1)^{\frac{1}{\sigma}} K_t^{\frac{\sigma-1}{\sigma}} + \left\{\frac{e^{(\sigma-1)\mu N} - e^{(\sigma-1)\mu I_t^*}}{(\sigma-1)\mu}\right\}^{\frac{1}{\sigma}} L_t^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$$

13. Marginal product of capital:

$$r_t^k = RMC_t\left[B^{\frac{\sigma-1}{\sigma}}(I_t^* - N + 1)^{\frac{1}{\sigma}}\left(\frac{Y_t}{K_t}\right)^{\frac{1}{\sigma}}\right]$$

14. Marginal product of labor:

$$w_t = RMC_t\left[B^{\frac{\sigma-1}{\sigma}}\left\{\frac{e^{(\sigma-1)\mu N} - e^{(\sigma-1)\mu I_t^*}}{(\sigma-1)\mu}\right\}^{\frac{1}{\sigma}}\left(\frac{Y_t}{L_t}\right)^{\frac{1}{\sigma}}\right]$$

15. Price Philips curve:

$$(1-\epsilon_p) + \epsilon_p RMC_t - \phi_p(\pi_t - 1)\pi_t + \phi_p E_t\left[\Omega_{t,t+1}(\pi_{t+1} - 1)\pi_{t+1}^2\frac{Y_{t+1}}{Y_t}\right] = 0$$

16. Definition of I_t^*:

$$I_t^* = \min\{I, \tilde{I}_t\}$$

17. Definition of $\tilde{I}_t$:

$$r_t^k = \frac{w_t}{e^{\mu \tilde{I}_t}}$$

18. Resource constraint:

$$C_t + S_t + \Psi(u_t)\bar{K}_t = \left\{1 - \frac{\phi_p}{2}(\pi_t - 1)^2\right\} Y_t - \frac{\phi_w}{2}(\pi_t^w - 1)^2 w_t L_t$$

19. Monetary policy rule:

$$\frac{R_t^b}{R_{ss}^b} = \left(\frac{R_{t-1}^b}{R_{ss}^b}\right)^{\rho_r} \left[(\pi_t)^{\zeta_\pi} \left(\frac{Y_t}{Y_t^n}\right)^{\zeta_Y}\right]^{1-\rho_r} m_t$$

20. Transition of monetary policy shocks:

$$\log(m_t) = \rho_m \log(m_{t-1}) + \zeta_t^m$$

21. Transition of preference shocks:

$$\log(b_t) = \rho_b \log(b_{t-1}) + \zeta_t^b$$

Table 1: List of Parameters

B	Scale Parameter	0.03	
σ	Elasticity of substitution between tasks	0.4	Chirinko and Mallick (2017)
μ	Curve of $\gamma(i)$	1	
N	Parameter of range of tasks	1	
β	Discount rate	0.99	
σ_c	Relative risk aversion	1.38	Smets and Wouters (2007)
h	Consumption habit	0.71	Smets and Wouters (2007)
δ	Capital depreciation rate	0.025	
τ	Investment adjustment cost	5.74	Smets and Wouters (2007)
σ_a	Capital utilization cost (curvature)	0.01	Christiano, Eichenbaum, and Evans (2005)
σ_b	Capital utilization cost	0.035	
η	Inverse of the Frisch elasticity of labor supply	1.83	Smets and Wouters (2007)
ϕ_p	Price adjustment cost (U.S.)	69.8	Iwasaki, Muto, and Shintani (2021)
	Price adjustment cost (Japan)	30.8	Iwasaki, Muto, and Shintani (2021)
ϕ_w	Nominal wage adjustment cost (U.S.)	97.9	Iwasaki, Muto, and Shintani (2021)
	Nominal wage adjustment cost (Japan)	20.3	Iwasaki, Muto, and Shintani (2021)
ϵ_p	Elasticity of substitution between intermediate goods	0.17^{-1}	Iwasaki, Muto, and Shintani (2021)
ϵ_w	Elasticity of substitution between labor services	0.31^{-1}	Iwasaki, Muto, and Shintani (2021)
ρ_r	Taylor rule, interest rate smoothing	0.81	Smets and Wouters (2007)
ζ_π	Taylor rule, inflation	2.04	Smets and Wouters (2007)
ζ_y	Taylor rule, output gap	0.08	Smets and Wouters (2007)
ρ_m	Persistence of monetary policy shock	0.15	Smets and Wouters (2007)
ρ_b	Persistence of preference shock	0.78	Ikeda (2015)
σ_m	Standard deviation of monetary policy shock	0.01	
σ_b	Standard deviation of preference shock	1.69×10^{-2}	Ikeda (2015)

Figure 1: Overall View of Our Model

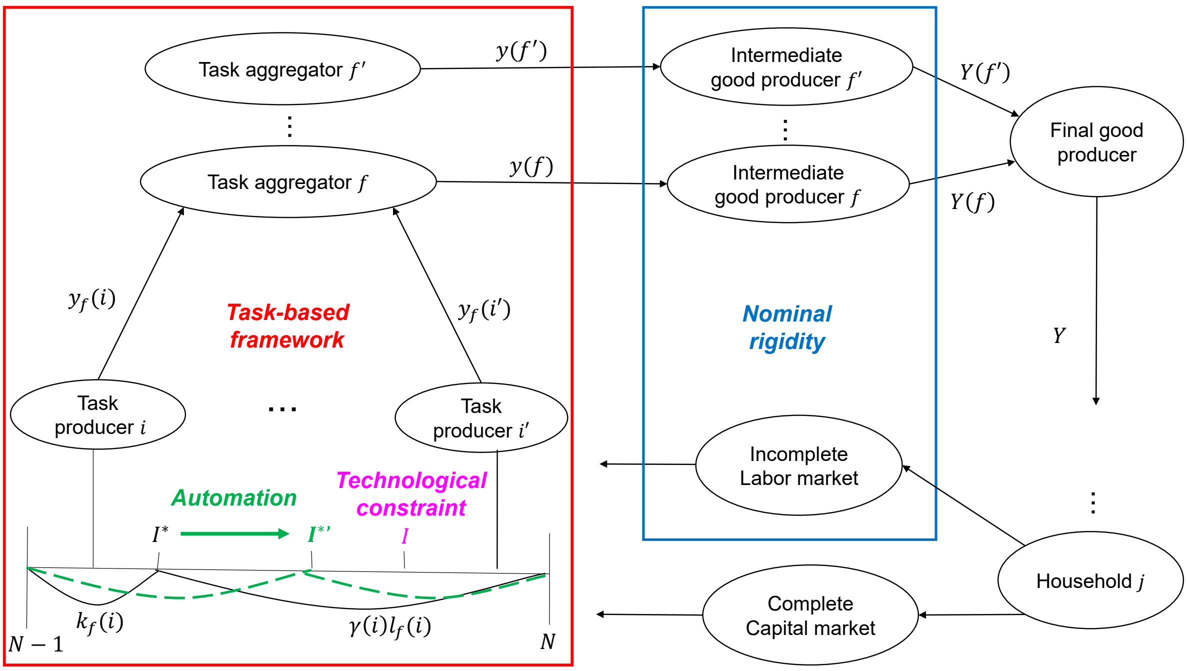
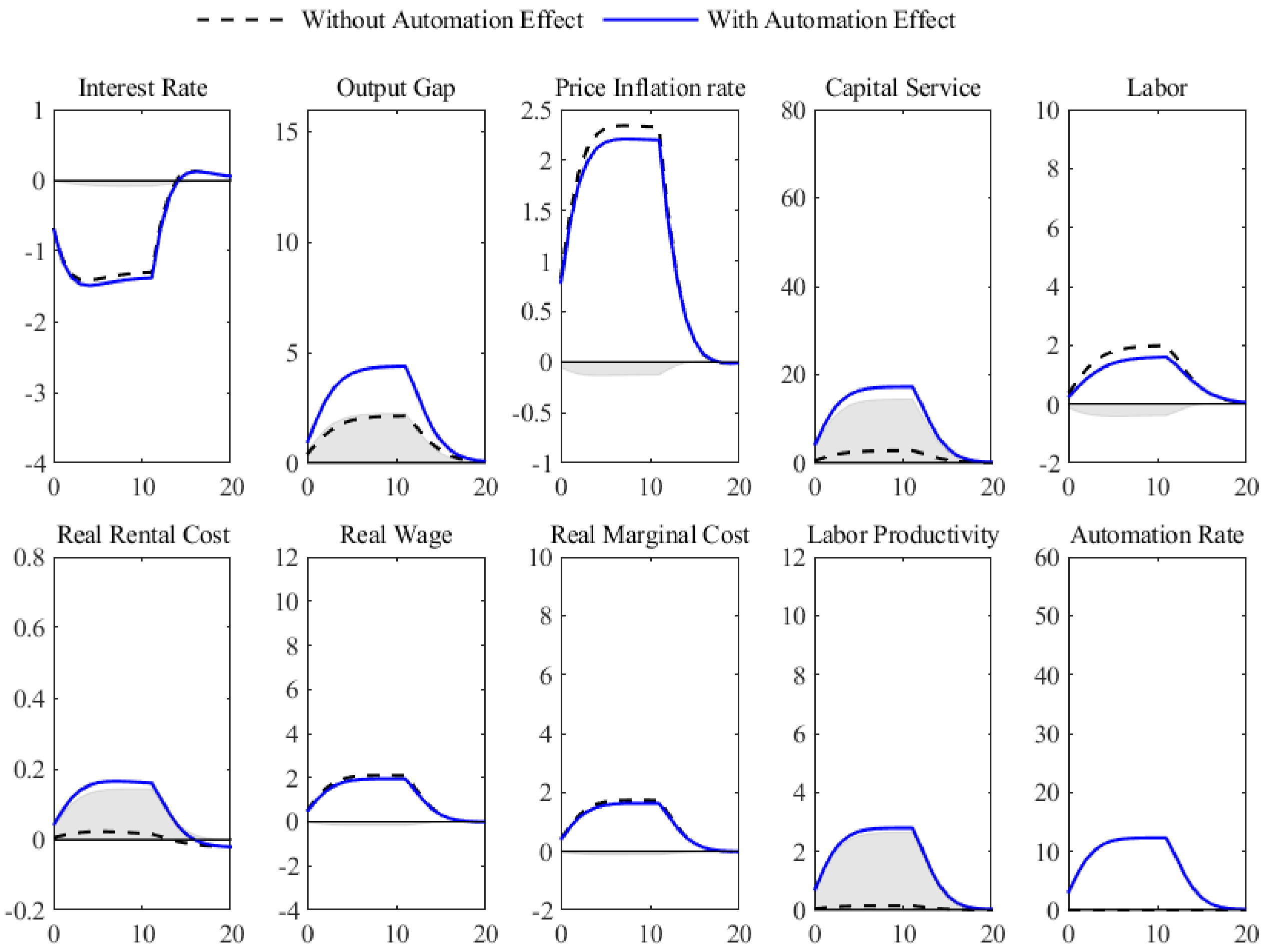
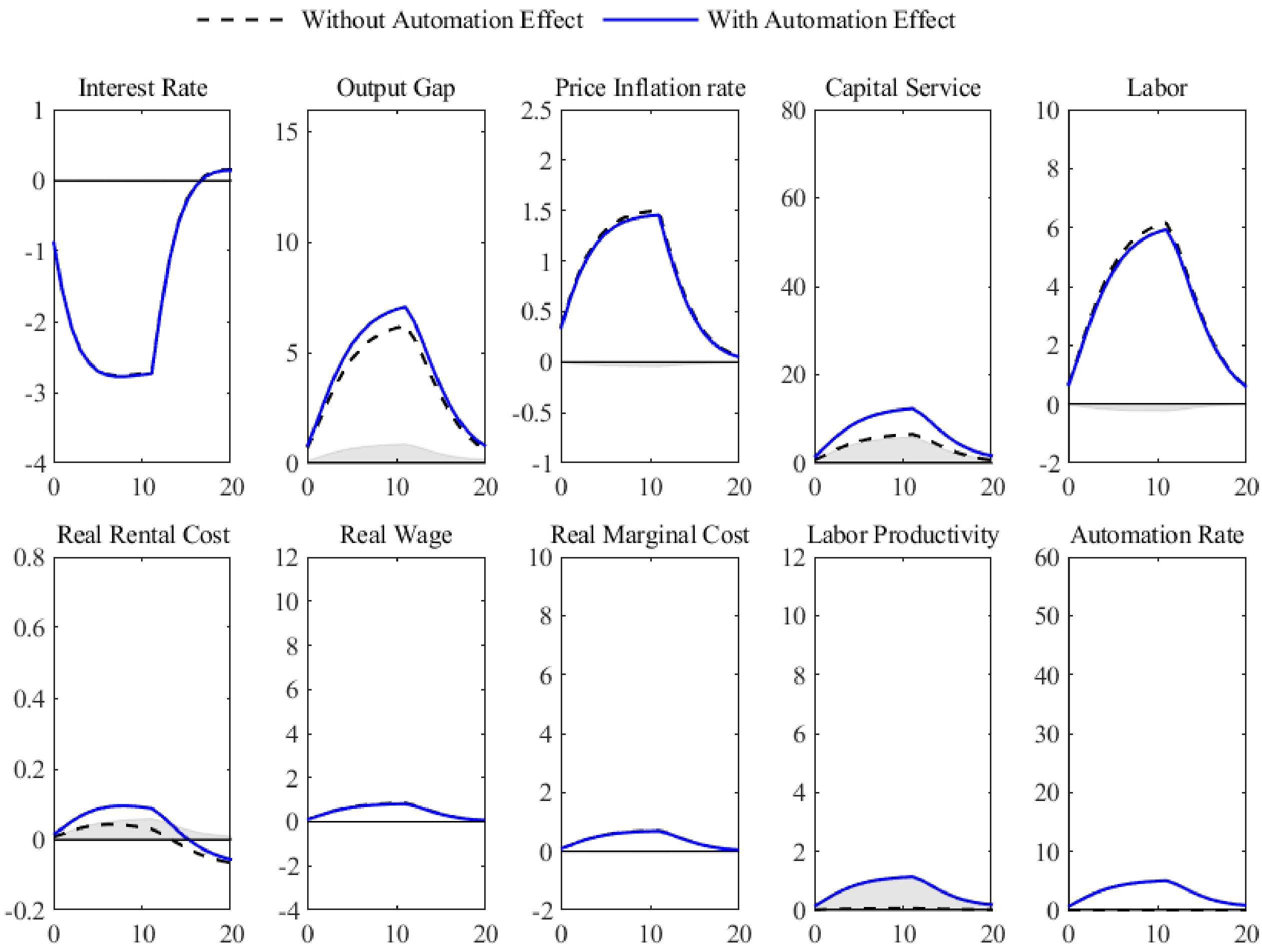


Figure 2: IRs: Flexible Price and Flexible Wage: Monetary Policy Shock



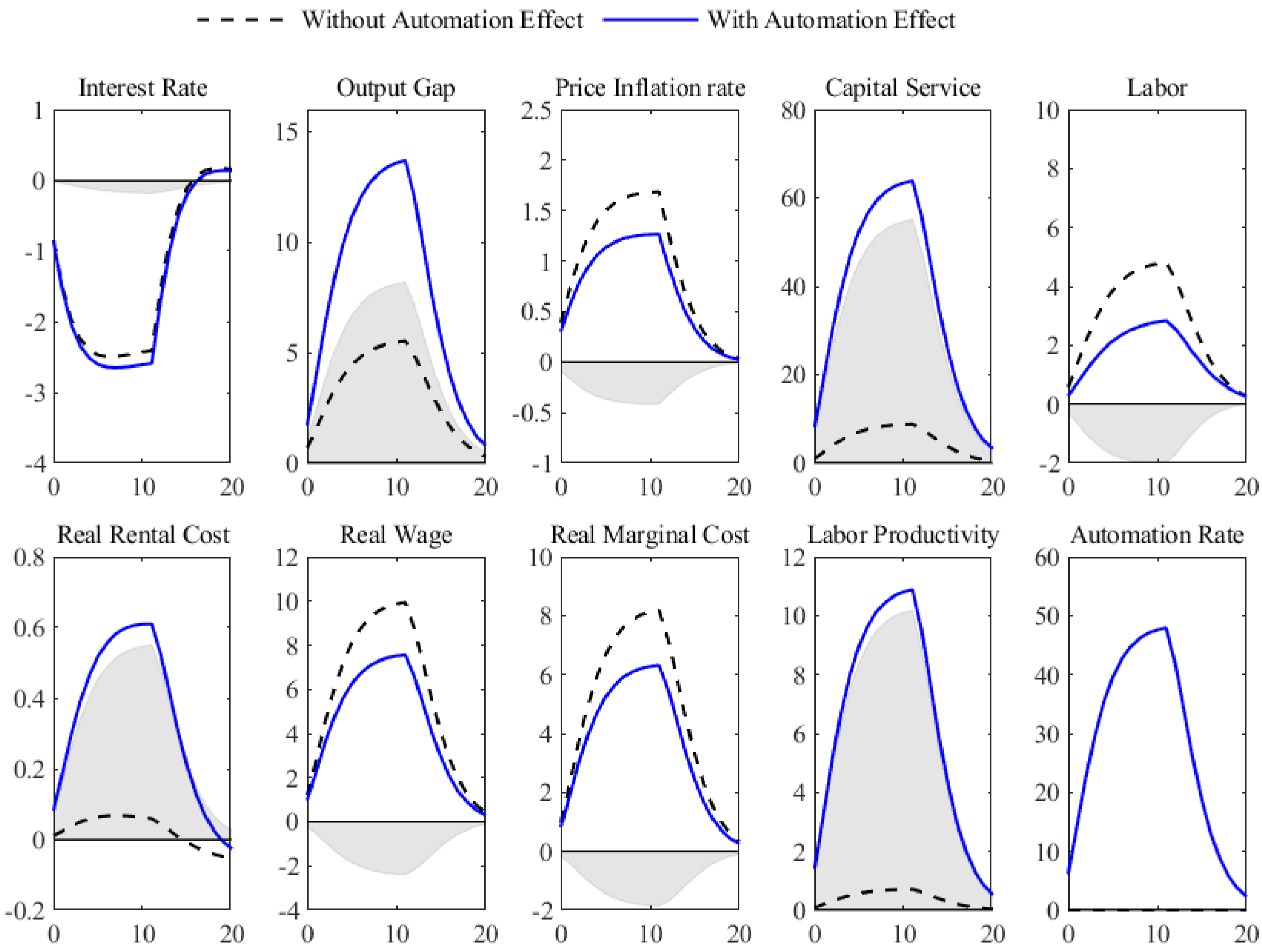
Note: These figures show the percentage deviations of each variable from the steady state value in response to a 1% expansionary monetary policy shock for 12 consecutive terms. The shaded area indicates the impact of automation, which is calculated as the impulse response in the case of With Automation Effect (blue solid lines), and minus the impulse response in the case of Without Automation Effect (black dashed lines).

Figure 3: IRs: Flexible Price and Sticky Wage: Monetary Policy Shock



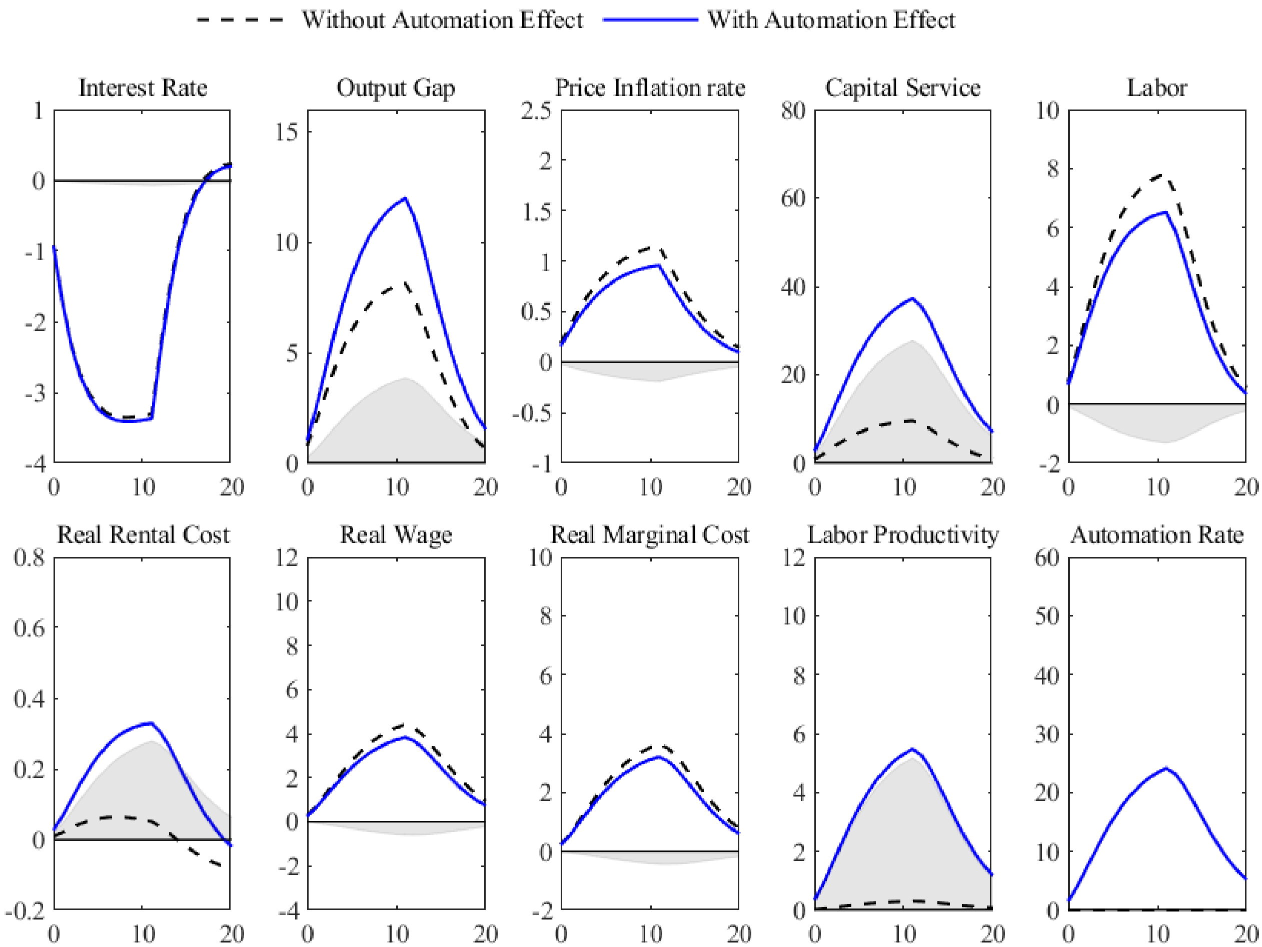
Note: These figures show the percentage deviations of each variable from the steady state value in response to a 1% expansionary monetary policy shock for 12 consecutive terms. The shaded area indicates the impact of automation, which is calculated as the impulse response in the case of With Automation Effect (blue solid lines), and minus the impulse response in the case of Without Automation Effect (black dashed lines).

Figure 4: IRs: Sticky Price and Flexible Wage: Monetary Policy Shock



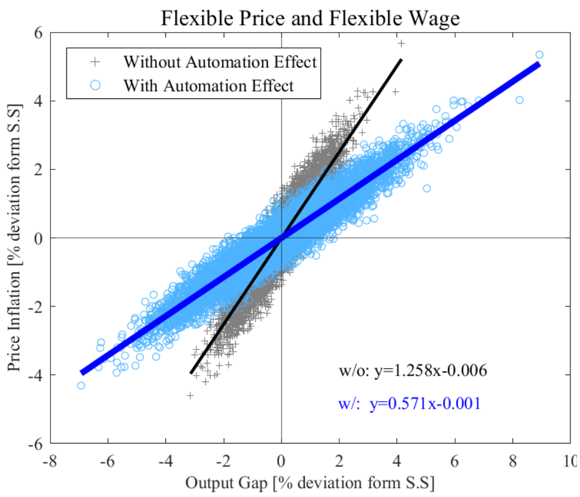
Note: These figures show the percentage deviations of each variable from the steady state value in response to a 1% expansionary monetary policy shock for 12 consecutive terms. The shaded area indicates the impact of automation, which is calculated as the impulse response in the case of With Automation Effect (blue solid lines), and minus the impulse response in the case of Without Automation Effect (black dashed lines).

Figure 5: IRs: Sticky Price and Sticky Wage: Monetary Policy Shock

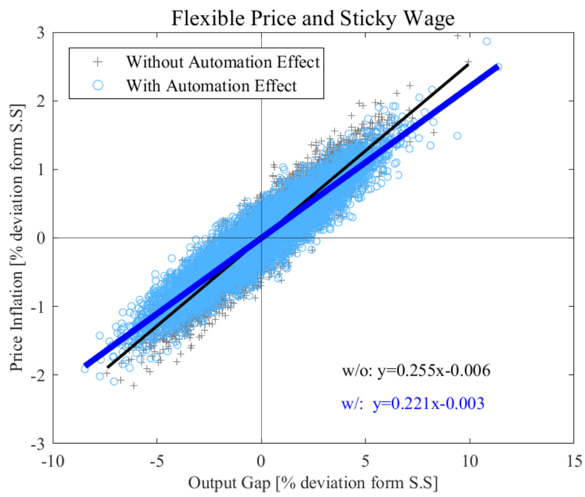


Note: These figures show the percentage deviations of each variable from the steady state value in response to a 1% expansionary monetary policy shock for 12 consecutive terms. The shaded area indicates the impact of automation, which is calculated as the impulse response in the case of With Automation Effect (blue solid lines), and minus the impulse response in the case of Without Automation Effect (black dashed lines).

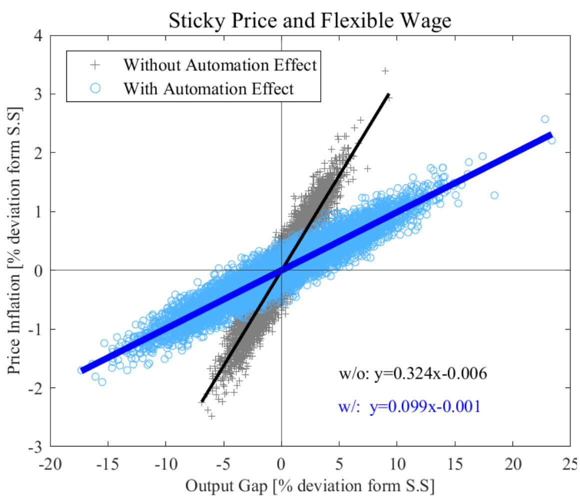
Figure 6: Price Phillips Curve: Monetary Policy Shocks



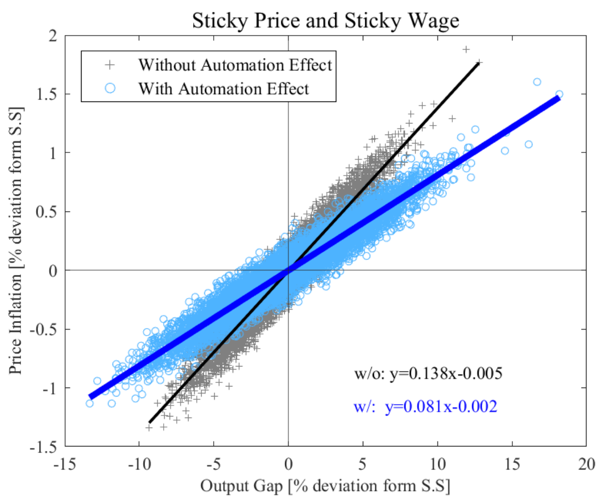
Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	1.258	0.571	▲54.6
Std. Error	(0.005)	(0.002)	—



Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.255	0.221	▲13.5
Std. Error	(0.001)	(0.001)	—



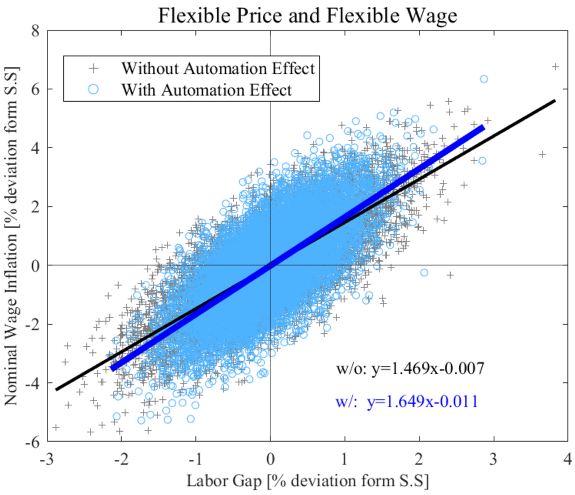
Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.324	0.099	▲69.4
Std. Error	(0.001)	(0.000)	—



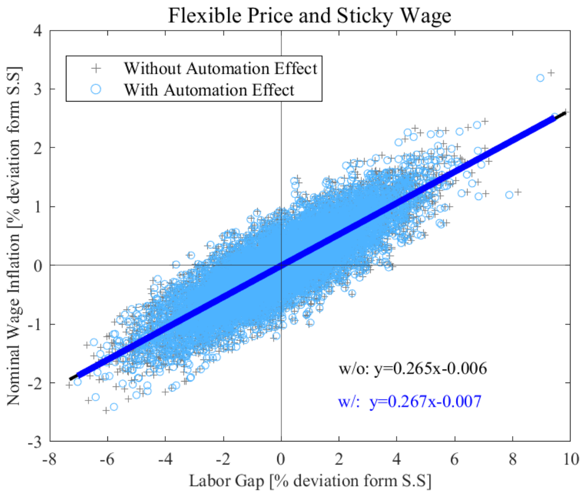
Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.138	0.081	▲41.4
Std. Error	(0.000)	(0.000)	—

Note: These figures are derived using 10,000 randomly generated monetary policy shocks and removing the first 1,000 samples to eliminate the influence of initial values.

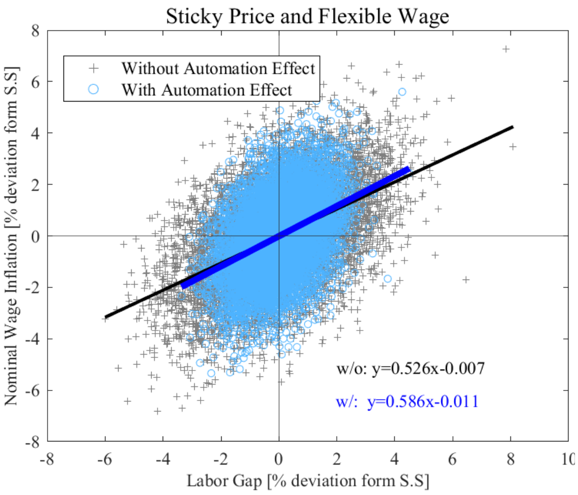
Figure 7: Wage Phillips Curve: Monetary Policy Shocks



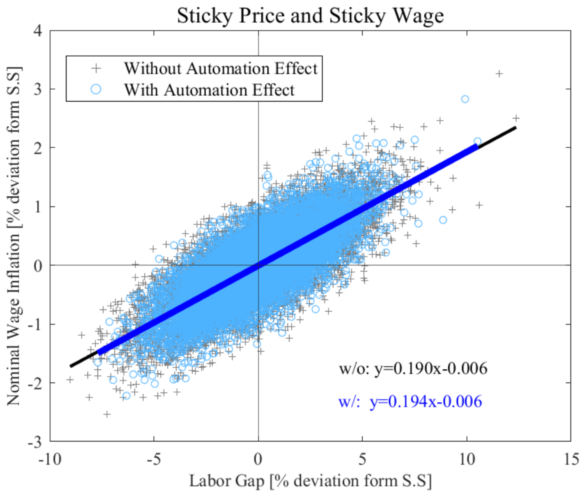
Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	1.469	1.649	12.3
Std. Error	(0.013)	(0.018)	—



Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.265	0.267	0.7
Std. Error	(0.002)	(0.002)	—



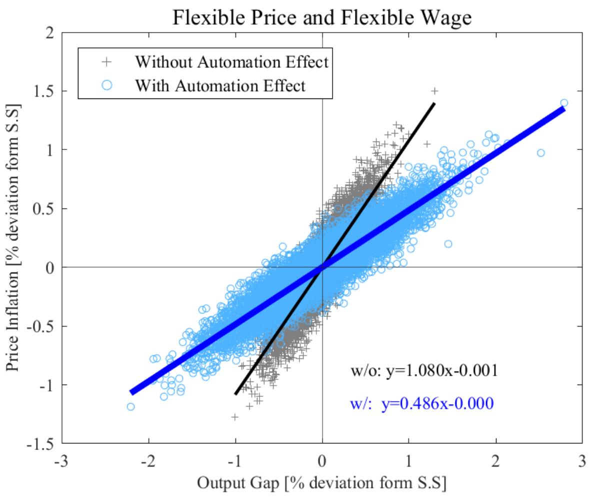
Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.526	0.586	11.3
Std. Error	(0.010)	(0.014)	—

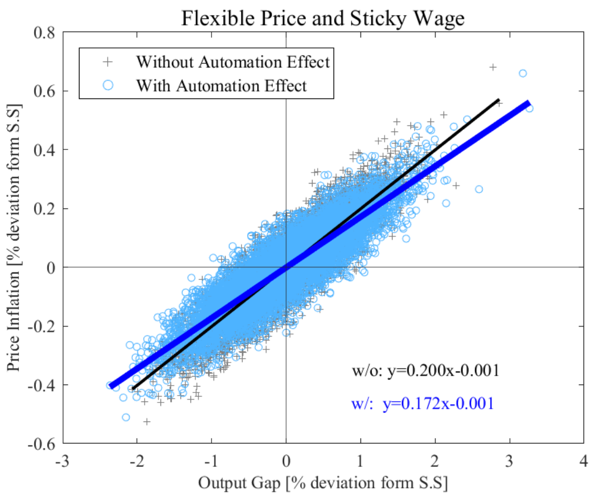


Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.190	0.194	1.7
Std. Error	(0.002)	(0.002)	—

Note: These figures are derived using 10,000 randomly generated monetary policy shocks and removing the first 1,000 samples to eliminate the influence of initial values.

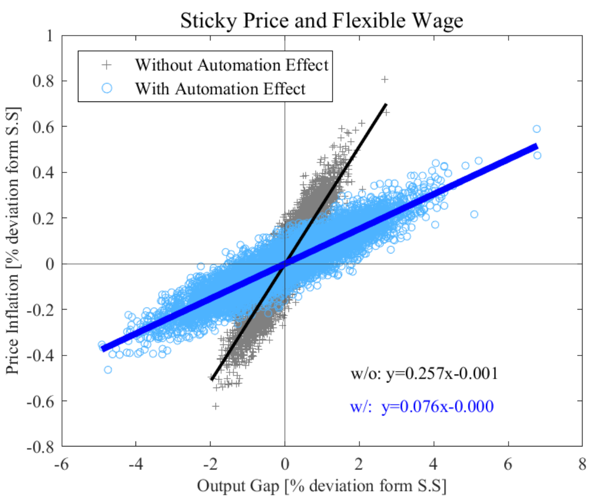
Figure 8: Price Phillips Curve: Preference Shocks

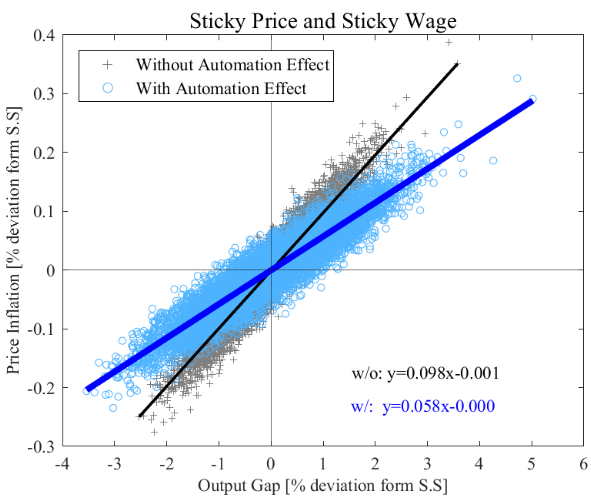




Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	1.080	0.486	▲55.0
Std. Error	(0.006)	(0.002)	—

Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.200	0.172	▲14.0
Std. Error	(0.001)	(0.001)	—



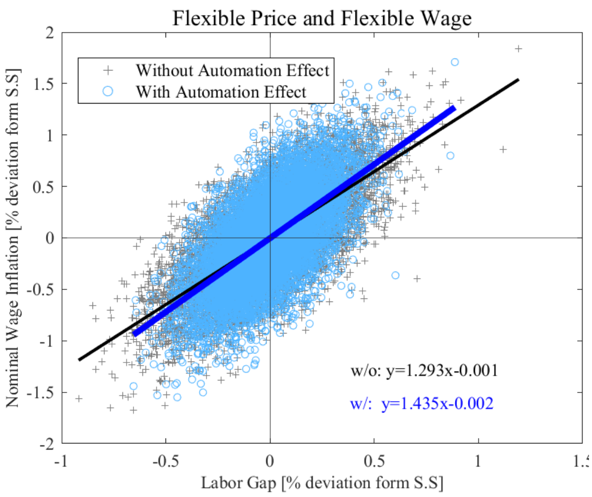


Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.257	0.076	▲70.4
Std. Error	(0.001)	(0.000)	—

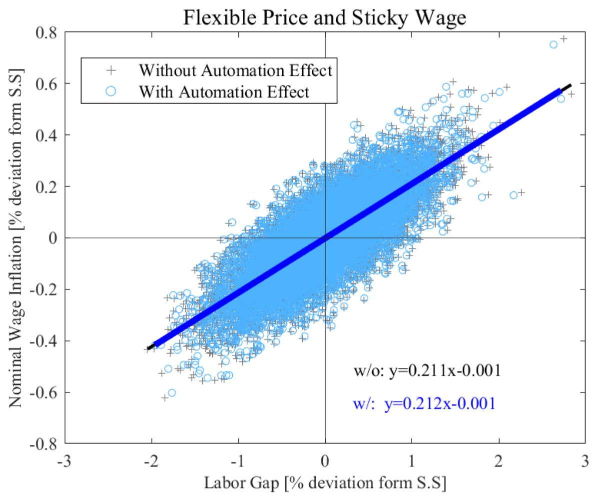
Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.098	0.058	▲41.5
Std. Error	(0.000)	(0.000)	—

Note: These figures are derived using 10,000 randomly generated preference shocks and removing the first 1,000 samples to eliminate the influence of initial values.

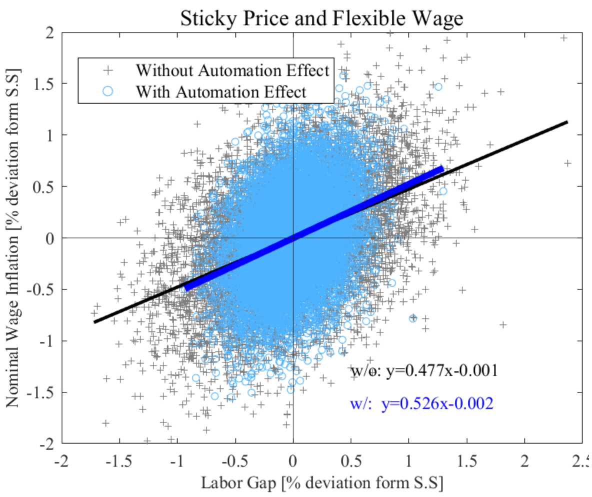
Figure 9: Wage Phillips Curve: Preference Shocks



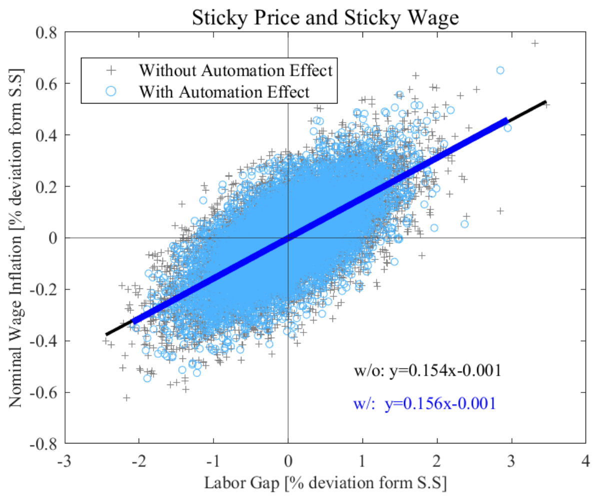
Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	1.293	1.435	11.0
Std. Error	(0.014)	(0.018)	—



Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.211	0.212	0.5
Std. Error	(0.002)	(0.002)	—



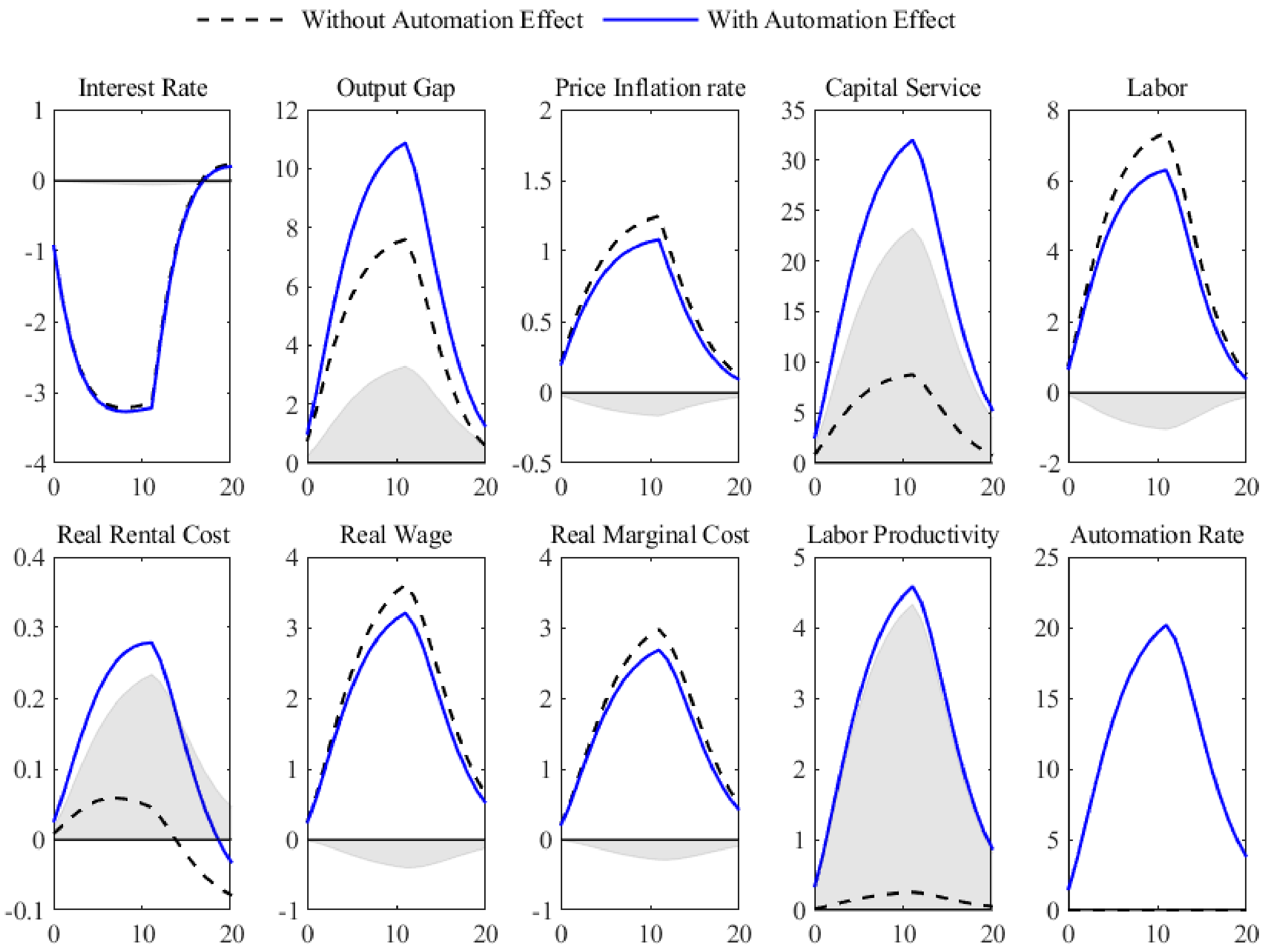
Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.477	0.526	10.4
Std. Error	(0.010)	(0.016)	—



Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.154	0.156	1.8
Std. Error	(0.002)	(0.002)	—

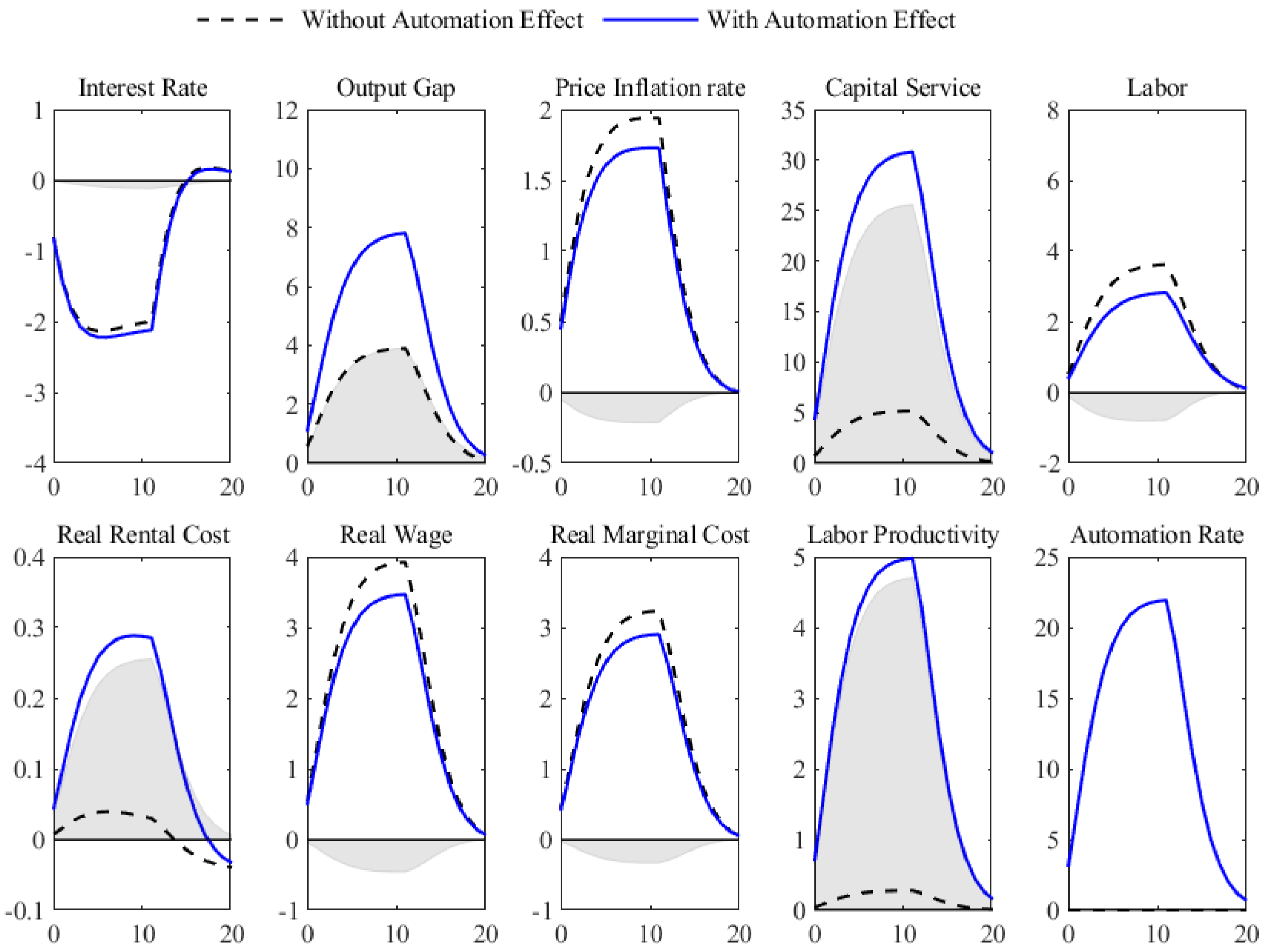
Note: These figures are derived using 10,000 randomly generated preference shocks and removing the first 1,000 samples to eliminate the influence of initial values.

Figure 10: IRs: U.S: Monetary Policy Shock



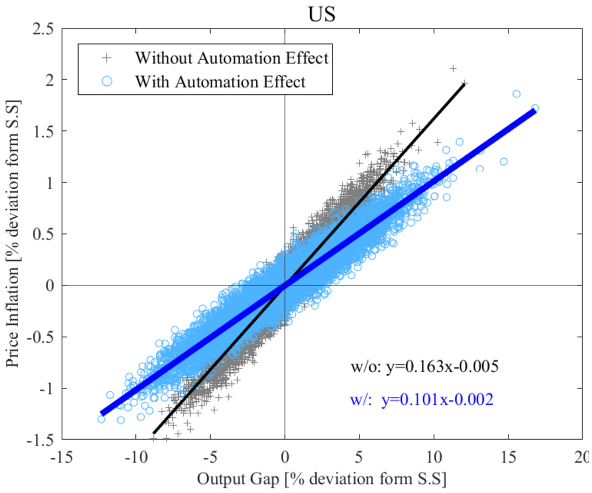
Note: These figures show the percentage deviations of each variable from the steady state value in response to a 1% expansionary monetary policy shock for 12 consecutive terms. The shaded area indicates the impact of automation, which is calculated as the impulse response in the case of With Automation Effect (blue solid lines), and minus the impulse response in the case of Without Automation Effect (black dashed lines).

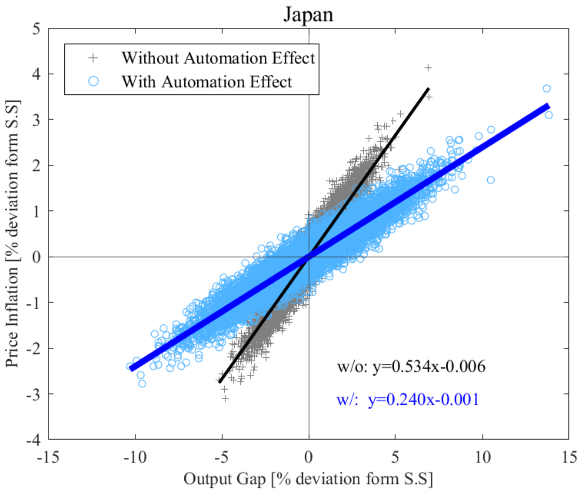
Figure 11: IRs: Japan: Monetary Policy Shock



Note: These figures show the percentage deviations of each variable from the steady state value in response to a 1% expansionary monetary policy shock for 12 consecutive terms. The shaded area indicates the impact of automation, which is calculated as the impulse response in the case of With Automation Effect (blue solid lines), and minus the impulse response in the case of Without Automation Effect (black dashed lines).

Figure 12: Price Phillips Curve: US (left) and Japan (right): Monetary Policy Shock



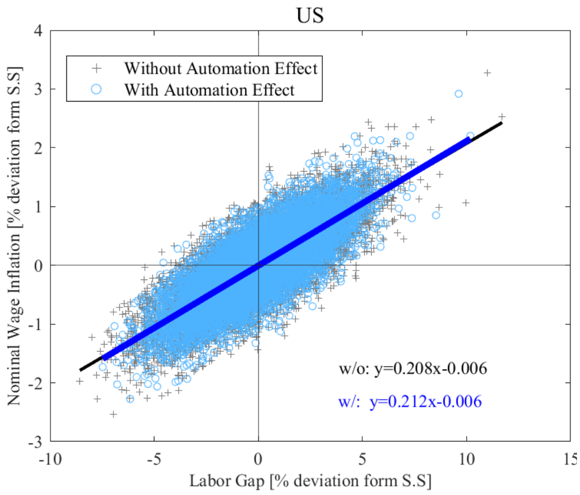


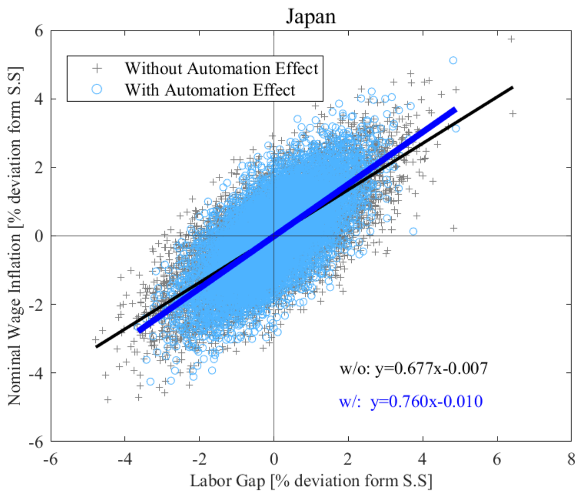
Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.163	0.101	▲37.6
Std. Error	(0.001)	(0.000)	—

Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.534	0.240	▲55.1
Std. Error	(0.002)	(0.001)	—

Note: These figures are derived using 10,000 randomly generated monetary policy shocks and removing the first 1,000 samples to eliminate the influence of initial values.

Figure 13: Wage Phillips Curve: US (left) and Japan (right): Monetary Policy Shock



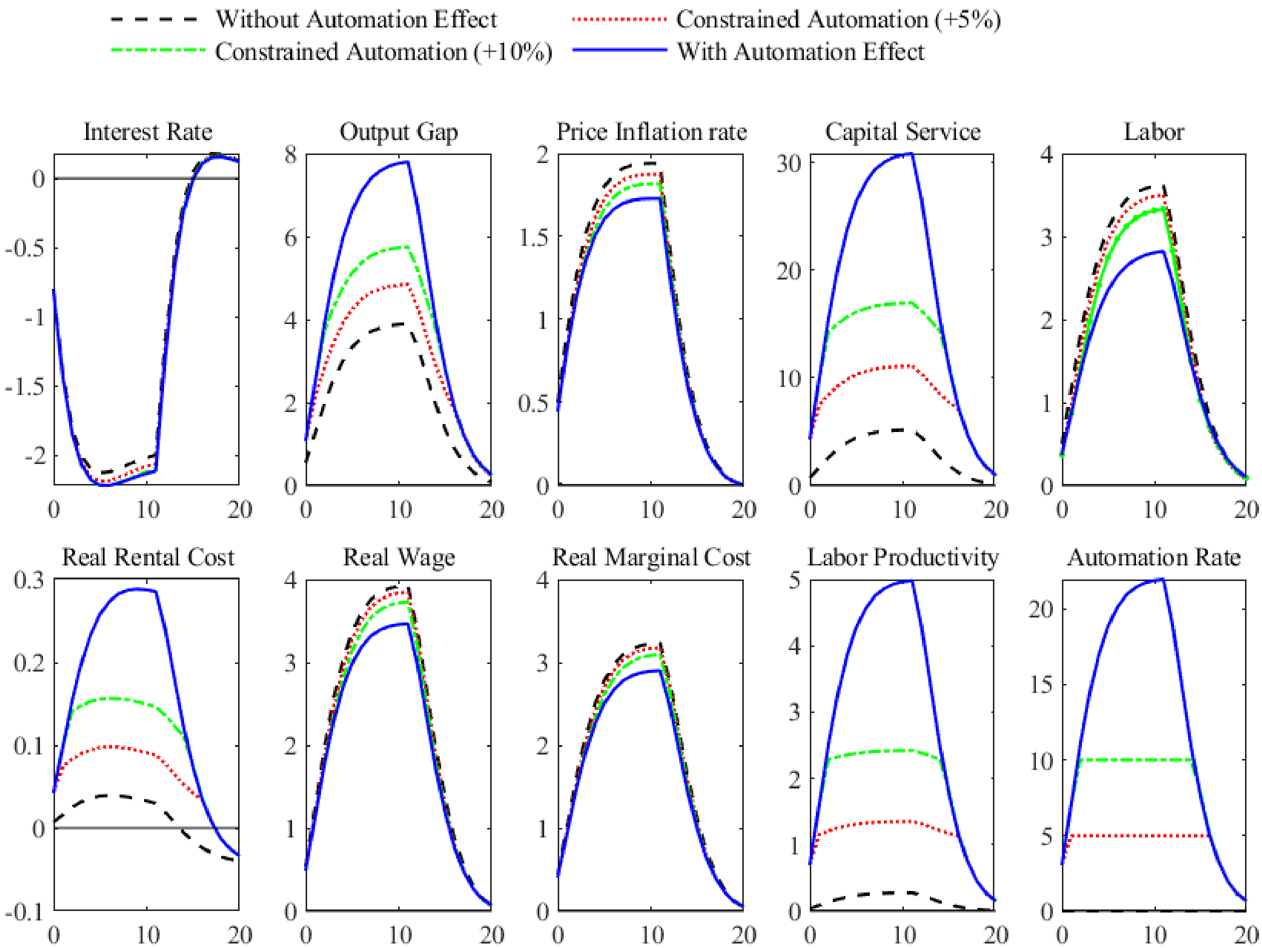


Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.208	0.212	2.0
Std. Error	(0.002)	(0.002)	–

Slope of Phillips Curve			
OLS estimation	(1) Without Automation Effect	(2) With Automation Effect	(1)⇒(2) (%)
Coefficient	0.677	0.760	12.3
Std. Error	(0.007)	(0.008)	–

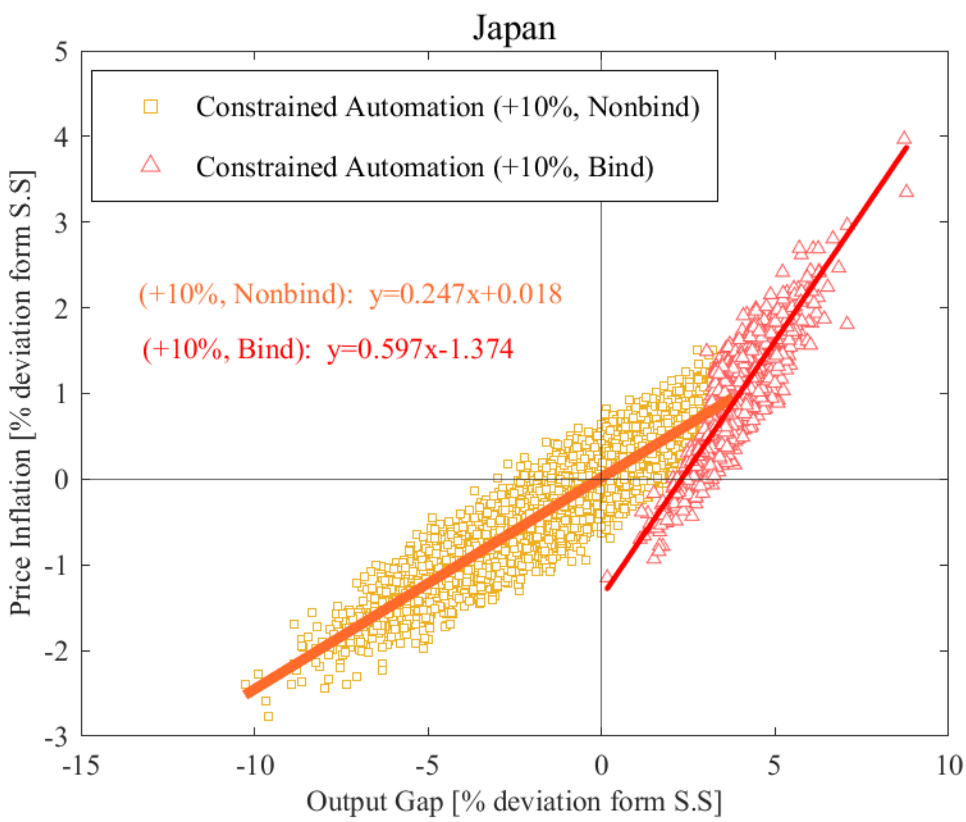
Note: These figures are derived using 10,000 randomly generated monetary policy shocks and removing the first 1,000 samples to eliminate the influence of initial values.

Figure 14: IRs: Japan: Constrained Automation: Monetary Policy Shock



Note: These figures show the percentage deviations of each variable from the steady state value in response to a 1% expansionary monetary policy shock for 12 consecutive terms. Constrained Automation (+5%) (red dotted lines) denotes the impulse responses when the automation rate can increase to the 5% upper limit relative to the steady state level. Constrained Automation (+10%) (green dash-dotted lines) denotes the impulse responses when the automation rate can increase to the 10% upper limit relative to the steady state level.

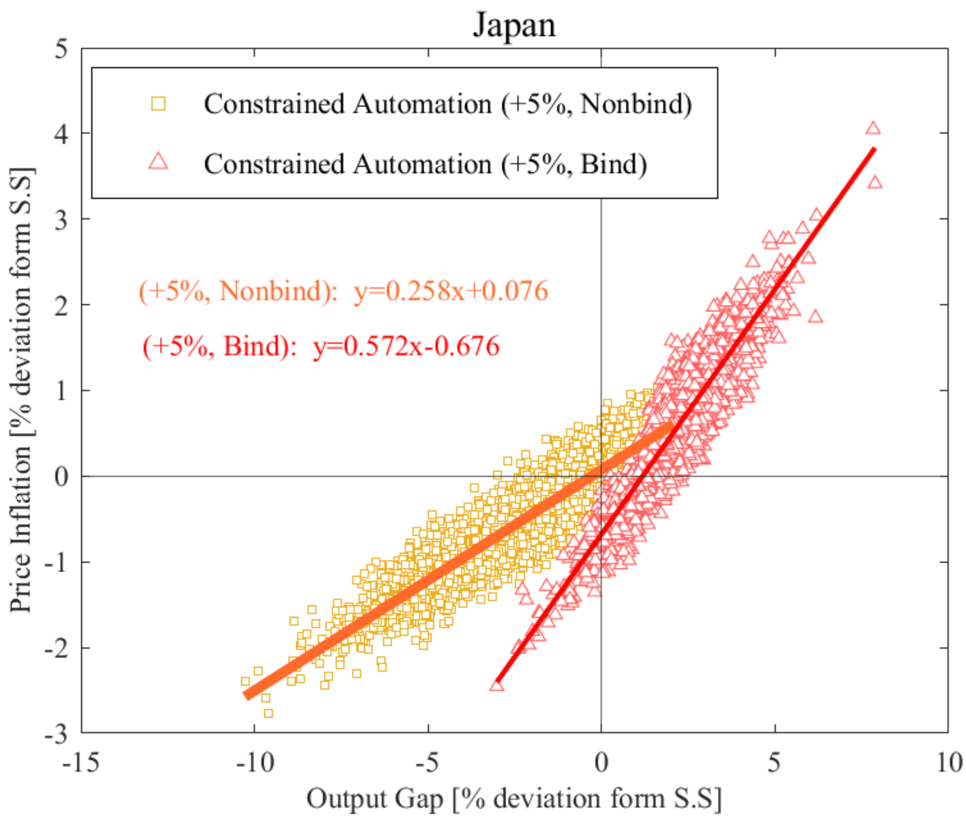
Figure 15: Kinked Price Phillips Curve: Japan: Constrained Automation $(+10\%)$



Slope of Phillips Curve		
OLS estimation	(1) Constrained Automation (+10%, Nonbind)	(2) Constrained Automation (+10%, Bind)
Coefficient	0.247	0.597
Std. Error	(0.001)	(0.009)

Note: This figure shows the price Phillips curve in the case of Constrained Automation (+10%) which is derived using 10,000 randomly generated monetary policy shocks and removing the first 1,000 samples to eliminate the influence of initial values. Constrained Automation (+10%, Bind) (red triangles) denotes the sets of price inflation rate and output gap when the automation rate reaches the 10% upper limit. Constrained Automation (+10%, Nonbind) (yellow squares) denotes the sets of price inflation rate and output gap when the automation rate does not reach the 10% upper limit.

Figure 16: Kinked Price Phillips Curve: Japan: Constrained Automation (+5%)



Slope of Phillips Curve		
OLS estimation	(1) Constrained Automation (+5%, Nonbind)	(2) Constrained Automation (+5%, Bind)
Coefficient	0.258	0.572
Std. Error	(0.001)	(0.004)

Note: This figure shows the price Phillips curve in the case of Constrained Automation (+5%) which is derived using 10,000 randomly generated monetary policy shocks and removing the first 1,000 samples to eliminate the influence of initial values. Constrained Automation (+5%, Bind) (red triangles) denotes the sets of price inflation rate and output gap when the automation rate reaches the 5% upper limit. Constrained Automation (+5%, Nonbind) (yellow squares) denotes the sets of price inflation rate and output gap when the automation rate does not reach the 5% upper limit.

Figure 17: Reduction of Nominal Adjustment Costs by Automation

Note: These figures show the nominal adjustment costs, (sum of the level of price and wage adjustment costs) in the case of With Automation Effect and minus those costs in the case of Without Automation Effect, calculated with impulse responses against a 1% expansionary monetary policy shock for 12 consecutive periods.