Just-in-Time Inventories and Business Cycles*

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Abstract

This paper uses a DSGE model with multi-stage production to evaluate the role of inventories in the business cycle. We examine how inventories may generate and/or propagate cyclical fluctuations and we study how aggregate economic volatility is affected by the introduction of just-in-time (JIT) inventories. We first construct a non-JIT economy where the producers of finished goods hold inventories of finished goods and intermediate materials. Instead, in the JIT economy, inventories of finished goods are held by the producers of finished goods while materials inventories are held by materials producers. In both economies, the higher the input adjustment and stock-out avoidance costs, the larger (smaller) the response of finished goods (materials) inventories to shocks and the smaller the impact on output. Furthermore, the introduction of JIT inventories leads to significant reductions in the volatility of output. We find no evidence that inventories cause business cycles.

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1 Introduction

Inventory research has identified several possible roles for inventories in business cycles. As discussed by Blinder and Maccini (1991, p. 293), early research on inventories established the view that inventories were a destabilizing force in the aggregate economy (e.g., Metzler, 1941). Inventory movements were shown to induce business cycles that otherwise would not exist and so inventories were assigned a causal role in the existence of business cycles. A second viewpoint emerged in subsequent research (e.g., Wilkinson, 1989), typically using the inventory framework by Holt, Modigliani, Muth and Simon (1960), viewing inventories as part of the propagation mechanism associated with business cycles but inventories were not a cause of cycles (Blinder and Maccini 1991, p. 315).[1] More recently, a third possible role for inventories in business cycles has been advanced. It has been suggested that structural changes in inventory management practices have induced stability in the aggregate economy.

Kahn, McConnell, and Perez-Quiros (2002), Herrera and Pesavento (2005) and Camacho, Perez Quiros and Rodríguez Mendizabal (2011) have argued that the information technology (IT) revolution in the 1980s improved information flows to firms, a form of technical progress with implications for the stocks of inventories held by those firms and the stability of the aggregate economy. With better information about expected sales, firms may hold smaller stocks of inventories since future output demand can be more accurately forecasted. An additional aspect of this innovation in the holding of inventories by firms is the development of just-in-time (hereafter JIT) inventories. This change in economic structure means that the users of inventories of intermediate materials no longer hold inventories of these intermediate goods. Rather they take deliveries of materials at the time that they are needed in the production of final output. Inventories of materials may continue to be held in the aggregate economy but they are held by the producers of materials rather than by the buyers of these goods. The studies mentioned above suggest that the adoption of JIT inventories may be one possible cause of the Great Moderation, a period of apparent increased stability of the

[1] Blinder and Maccini (1991) and Ramey and West (1999) provide comprehensive surveys of research on inventory investment.

U.S. economy that began in the 1980s.[2]

This paper examines the connection between inventories and the business cycle in a DSGE context and it does so from two points of view. First, we explore how the introduction of JIT inventories altered the transmission of preference, technology and monetary policy shocks, and how the propagation of shocks interacts with adjustment costs. We do so by comparing the response of key macroeconomic variables (e.g., output, consumption, labor) under two different scenarios. In our benchmark non-JIT economy, inventories of final goods are held by the producers of these goods. The final good producers also hold inventories of intermediate materials, which are used for their production. In the alternative version of the economy, final good producers adopt JIT inventory technology, using intermediate materials delivered from their supplier without holding inventories of their intermediate input. The producers of intermediate materials hold inventories of their own product. Regarding the non-JIT model, we find that the presence of labor and materials adjustment costs, and especially high stock-out avoidance costs, moderates the response of materials inventories and output. On the contrary, such costs exacerbate the dynamic impact on finished goods inventories in the short-run. Once JIT inventories are introduced, the materials producer has an incentive to smooth changes in materials inventories as now it is she –and not the final goods producer– who faces stock-out avoidance costs. Indeed, the higher the cost of avoiding materials stock-outs in the JIT model, the larger the response of labor inputs in the materials sector and the smaller the response of materials orders by the final good sector.

Second, we address the role of JIT inventories in reducing economic fluctuations that originate from shocks that buffet the economy. To better understand the contribution of JIT inventories to business cycles, we compute the variance of the macroeconomic aggregates generated by the DSGE models with and without JIT inventories. More precisely, we

[2]Stock and Watson (2002) discuss and document the Great Moderation although earlier research by a number of authors, including McConnell and Perez-Quiros (2000), suggests that there are other possible explanations for its existence in addition to JIT inventories. Improvements in the conduct of economic policy (see, e.g., Clarida, Galí and Gertler 2000; Boivin and Giannoni 2006) may cause reduced volatility in aggregate economic activity or there may just be fewer shocks buffeting the economy (see, e.g., Ahmed, Levin and Wilson 2004).

generate 10,000 artificial time series with a sample size of 200 (50 years of quarterly data) under two different scenarios. The first scenario is one in which all the structural shocks (productivity, preferences and monetary policy) are taken into consideration. In the second scenario only preference shocks are assumed to hit the economy. The latter setup is aimed at understanding the effect of (pure) demand side innovations in driving inventory dynamics as stressed in the inventory literature. We find that the JIT economy is more stable compared to the non-JIT economy. Simulations of our models reveal a decline in the standard deviations of an array of JIT economic magnitudes compared to their non-JIT counterparts. The finding of a decline in volatility of output is robust to the inclusion of high adjustment and materials holding costs. Thus, our results suggest that the emergence of JIT inventories reduced the volatility of the aggregate economy and thus might have accounted for some of the reduced volatility experienced during the Great Moderation.

Our non-JIT economy also allows us to investigate whether inventories can be considered to be a cause of business cycles. That is, when hit by a shock, the finished goods producer may generate inventory-induced dynamics that result in cyclical fluctuations along the dynamic adjustment path. Thus, conditional on the parameters that we use, we simulate our non-JIT economy and then observe if it produces non-monotonic adjustment paths towards the steady state. If we were to observe cyclical fluctuations in this economy, we would regard these to be business cycles caused by the holding of inventories. However, we find no evidence that inventories are a cause of business cycles.

Our study is related to a number of recent papers that explore the behavior of inventories over the business cycle and the contribution of new inventory holding techniques to the Great Moderation. On one hand, Kahn, McConnell and Perez Quiros (2002) build a general equilibrium model to study the role that changes in inventory behavior stemming from information technology played in reducing the volatility of real output. The main difference between our setup and theirs is that their model does not incorporate stages of production and thus inventories are held by the producer of final goods. Furthermore, the change in inventory behavior stems from improved information regarding future sales, which in turn reduces production volatility.

On the other hand, Iacoviello, Schiantarelli, and Schuh (2011) and Auerenheimer and Trupkin (2014) investigate the role of inventories in DSGE models. Iacoviello, Schiantarelli and Schuh's (2011) study is closer to ours in that they consider a two sector model where one sector holds inventories (goods) and the other (services) does not. In their framework, the emergence of the JIT economy is manifested by changes in the parameters of their DSGE economy and not by a change in inventory holding behavior. In contrast, we abstract from the service sector in our DSGE model but consider how the introduction of JIT inventories – modeled as a shift in who holds inventories, materials or finished goods producers– affects the transmission of shocks. Auerenheimer and Trupkin (2014) also construct a DSGE model to investigate the role of inventories and capacity utilization in the propagation of business cycles. Their model economy has only one good but allows for variable capital utilization. Both studies stress the role of inventories regarding their ability to buffer various shocks to the economy but they include inventories in the utility function of the household. As Auerenheimer and Trupkin (2014, p. 71-72) note, such an approach is a convenient "short-cut" but, as a result, their model lacks a careful microfoundation for the role of inventories in the economy. Our approach has the advantage of using the microfoundations for inventories that are found in most of the inventory literature.

Our paper is organized as follows. The next section describes the structure of our benchmark non-JIT model. Section 3 provides the structure of our JIT economy. Section 4 provides the analysis of the dynamics generated from our non-JIT model while the following section explores the dynamics of the JIT economy and illustrates the stabilizing influence of JIT inventories in the presence of various shocks. Section 6 summarizes results and provides suggestions for future research. An appendix provides analytical results supporting the analysis in the paper.

2 The Benchmark Non-JIT Economy

The benchmark economy is a simple New Keynesian model with price rigidity where there are two types of firms: final good and materials producers. The economy is composed of a representative household, a continuum of final good producers, a representative materials producer, and a monetary authority. The final good producers are monopolistic competitors in their output markets and price-takers in their input markets. Factors of production are labor services and intermediate materials. The final good producers hold inventory stocks of their output and materials. The materials producer is operating in competitive input and output markets. Labor is the only factor of materials production. Materials producers do not hold inventories. As is traditionally done in the inventory literature the model does not consider capital accumulation.

2.1 Household

The representative household carries B_{t-1} units of bonds into period t. In the same period, the household supplies l_t and h_t units of labor services to the final good and the materials producers at a real wage rate of $w_{l,t}$ and $w_{h,t}$, respectively. In addition, the household receives nominal profits from the firms producing final goods ($\Pi_{f,t}$) and materials ($\Pi_{m,t}$). The household uses its income to purchase a consumption bundle (c_t) and bonds (B_t). The nominal cost of the bond purchase is B_t/r_t, where r_t denotes the gross nominal interest rate between period t and $t+1$. The budget constraint of the household is

$$c_t + \frac{B_t/r_t}{p_t} \leq \frac{B_{t-1}}{p_t} + w_{l,t}l_t + w_{h,t}h_t + \frac{\Pi_{f,t}}{p_t} + \frac{\Pi_{m,t}}{p_t}. \tag{1}$$

The household's consumption bundle is defined as a CES aggregate of differentiated final goods

$$c_t = \left[\int_0^1 s_t\left(i\right)^{\frac{\theta-1}{\theta}}\,di\right]^{\frac{\theta}{\theta-1}}, \qquad \theta > 0 \tag{2}$$

where $s_t(i)$ denotes the sales of differentiated final good indexed by $i \in [0,1]$. Cost minimization of the household results in the demand for $s_t(i)$, which is given by

$$s_t(i) = \left[\frac{p_t(i)}{p_t}\right]^{-\theta} c_t, \tag{3}$$

where $p_t(i)$ is the price of a final good indexed by $i \in [0,1]$. The parameter θ represents the elasticity of substitution between the differentiated final goods. The aggregate price level is derived as

$$p_t = \left[\int_0^1 p_t(i)^{1-\theta}\, di\right]^{\frac{1}{1-\theta}}, \tag{4}$$

which is a Dixit-Stiglitz price index.

Given the budget constraint in (1), the household maximizes its lifetime utility

$$\max \mathbb{E}_t \sum_{\tau=t}^{\infty} \beta^{\tau-t} \left\{ z_\tau \ln c_\tau + b \ln (1 - l_\tau - h_\tau) \right\}, \tag{5}$$

where z_t is the preference factor for consumption. We assume the evolution of z_t is given by

$$\ln z_t = \rho_z \ln z_{t-1} + \varepsilon_{z,t}\ , \tag{6}$$

where $\varepsilon_{z,t}$ is an IID shock to the preference factor.

The first order conditions with respect to c_t , l_t , h_t , and B_t are given by

$$\frac{z_t}{c_t} = \lambda_t, \tag{7}$$

$$\frac{b}{1 - l_t - h_t} = w_{l,t}\lambda_t, \tag{8}$$

$$\frac{b}{1 - l_t - h_t} = w_{h,t}\lambda_t, \tag{9}$$

and

$$\frac{\lambda_t / r_t}{p_t} = \beta \mathbb{E}_t \left(\frac{\lambda_{t+1}}{p_{t+1}}\right). \tag{10}$$

Equation (7) defines the shadow price λ_t, which is the marginal utility of consumption. Equations (8) and (9) represent the optimal supply of labor to the final good and materials producers, respectively. In equilibrium, the wage rates, $w_{l,t}$ and $w_{h,t}$, are equalized as the marginal disutilities of labor services are equalized across sectors. Equation (10) represents the typical intertemporal Euler equation.

2.2 The Final Good Producer

A final good producer indexed by $i \in [0,1]$ produces its output to stock. The process obeys the accounting constraint given by

$$f_{t+1}(i) = f_t(i) + \tilde{y}_t(i) - s_t(i), \tag{11}$$

where $f_t(i)$ refers to the stock of final good inventory and $\tilde{y}_t(i)$ is the net flow of final good production.[3] The final good producer uses intermediate materials to produce final goods, accumulating materials inventory according to

$$m_{t+1}(i) = m_t(i) + d_t(i) - u_t(i), \tag{12}$$

where $m_t(i)$ is the stock of materials inventory, $d_t(i)$ represents the deliveries of new materials, and $u_t(i)$ is the use of materials for the production of final goods. Final goods, $y_t(i)$, are produced by the production technology

$$y_t(i) = a_t [l_t(i)]^{\alpha} [u_t(i)]^{\omega}, \tag{13}$$

where the parameters are restricted by $0 < \alpha < 1$, $0 < \omega < 1$, and $0 < \alpha + \omega < 1$ so that the gross production function has positive and diminishing marginal products and is strictly concave in its arguments. Note that it is the usage of materials in production, $u_t(i)$, rather

[3] Because of inventory holding costs, price adjustment costs, and input adjustment costs, net and gross flows of production are different.

than the stock of materials, that appears in the gross production function. The technology factor, a_t, follows an AR(1) process

$$\ln a_t = \rho_a \ln a_{t-1} + \varepsilon_{a,t}, \tag{14}$$

where the technology shock, $\varepsilon_{a,t}$, is an IID innovation to a_t.

Input and output inventories incur holding costs. Following Maccini and Pagan (2013), the cost structure of inventory holding costs are assumed to be the following. Holding costs for final good inventories are

$$FHC_t(i) = \kappa_1 \left[\frac{s_t(i)}{f_t(i)}\right]^{\kappa_2} s_t(i) + \kappa_3 f_t(i), \tag{15}$$

where κ_1, κ_2, and κ_3 are positive parameters. The first term represents the risk of stock-outs, implying that the higher level of sales increases this risk while the higher level of output inventory reduces it. The second term captures inventory holding costs due to storage and/or insurance which are proportional to the level of inventory. Inventory holding costs for materials have a similar structure

$$MHC_t(i) = \psi_1 \left[\frac{y_t(i)}{v_t m_t(i)}\right]^{\psi_2} y_t(i) + \psi_3 v_t m_t(i), \tag{16}$$

where the parameters ψ_1, ψ_2, and ψ_3 are all positive. The relative price of materials is represented by v_t. The first term implies that if the firm decides to increase final good production, then the process is more likely to be disrupted due to a shortage of materials. On the other hand, an increase in materials inventory reduces the likelihood of the disruption. Like output inventory, materials inventory holding incurs costs which are proportional to the level of inventory, as indicated by the second term.

In addition to the inventory holding costs, the firm has to pay a price adjustment cost which is suggested by Rotemberg (1982)

$$PAC_t(i) = \frac{\phi_p}{2}\left[\frac{p_t(i)}{\pi p_{t-1}(i)} - 1\right]^2 c_t, \tag{17}$$

where π is the steady-state inflation rate. Labor and materials input adjustment costs are specified as in Hall (2004)

$$LAC_t(i) = \frac{\phi_l}{2}\left[\frac{l_t(i)}{l_{t-1}(i)} - 1\right]^2 l_{t-1}(i), \tag{18}$$

and

$$MAC_t(i) = \frac{\phi_u}{2}\left[\frac{u_t(i)}{u_{t-1}(i)} - 1\right]^2 u_{t-1}(i). \tag{19}$$

Therefore, the net flow of production is defined to be

$$\tilde{y}_t(i) = y_t(i) - FHC_t(i) - MHC_t(i) - PAC_t(i) - LAC_t(i) - MAC_t(i). \tag{20}$$

The final good producer is assumed to maximize expected profits, represented by

$$\mathbb{E}_t \sum_{\tau=t}^{\infty} \lambda_\tau \beta^{\tau-t}\left\{\left[\frac{p_\tau(i)}{p_\tau}\right] s_\tau(i) - w_{l,\tau} l_t(i) - v_\tau d_\tau(i)\right\}, \tag{21}$$

subject to equations (2), (11), (12), (13), and (20). The first order conditions with respect to $l_t(i)$, $u_t(i)$, $d_t(i)$, $y_t(i)$, $s_t(i)$,$p_t(i)$, $f_{t+1}(i)$, and $m_{t+1}(i)$ are

$$\begin{aligned}\lambda_t w_{l,t} &= \alpha\zeta_t(i)\left[\frac{y_t(i)}{l_t(i)}\right] - \phi_l\eta_t(i)\left[\frac{l_t(i)}{l_{t-1}(i)} - 1\right] \\ &\quad -\beta\mathbb{E}_t\eta_{t+1}(i)\left\{\left(\frac{\phi_l}{2}\right)\left[\frac{l_{t+1}(i)}{l_t(i)} - 1\right]^2 - \phi_l\left[\frac{l_{t+1}(i)}{l_t(i)} - 1\right]\left(\frac{l_{t+1}(i)}{l_t(i)}\right)\right\},\end{aligned} \tag{22}$$

$$\begin{aligned}\xi_t(i) &= \omega\zeta_t(i)\left(\frac{y_t(i)}{u_t(i)}\right) - \phi_u\eta_t(i)\left[\frac{u_t(i)}{u_{t-1}(i)} - 1\right] \\ &\quad -\beta\mathbb{E}_t\eta_{t+1}(i)\left\{\left(\frac{\phi_u}{2}\right)\left[\frac{u_{t+1}(i)}{u_t(i)} - 1\right]^2 - \phi_u\left[\frac{u_{t+1}(i)}{u_t(i)} - 1\right]\left(\frac{u_{t+1}(i)}{u_t(i)}\right)\right\},\end{aligned} \tag{23}$$

$$\lambda_t x_t = \xi_t(i), \tag{24}$$

$$\eta_t(i)\left\{1-\psi_1(1+\psi_2)\left[\frac{y_t(i)}{x_t m_t(i)}\right]^{\psi_2}\right\} = \zeta_t(i), \tag{25}$$

$$\lambda_t\left(\frac{p_t(i)}{p_t}\right) - \eta_t(i)\left\{1+\kappa_1(1+\kappa_2)\left(\frac{s_t(i)}{f_t(i)}\right)^{\kappa_2}\right\} = \mu_t(i)\left(\frac{p_t(i)}{p_t}\right)^{\theta}, \tag{26}$$

$$\begin{aligned} 0 \;=\; & \lambda_t\left(\frac{s_t(i)}{p_t}\right) - \theta\mu_t(i)\left(\frac{p_t(i)}{p_t}\right)^{\theta-1}\left(\frac{s_t(i)}{p_t}\right) - \eta_t(i)\,\phi_p\left(\frac{p_t(i)}{\pi p_{t-1}(i)}-1\right)\left(\frac{c_t}{\pi p_{t-1}(i)}\right) \\ & +\beta\phi_p \mathbb{E}_t \eta_{t+1}(i)\left(\frac{p_{t+1}(i)}{\pi p_t(i)}-1\right)\left(\frac{p_{t+1}(i)\,c_{t+1}}{\pi p_t(i)^2}\right), \end{aligned} \tag{27}$$

$$\eta_t(i) = \beta \mathbb{E}_t \eta_{t+1}(i)\left\{1+\kappa_1\kappa_2\left[\frac{s_{t+1}(i)}{f_{t+1}(i)}\right]^{\kappa_2+1} - \kappa_3\right\}, \tag{28}$$

and

$$\xi_t(i) = \beta\mathbb{E}_t\left\{\xi_{t+1}(i) + \psi_1\psi_2\eta_{t+1}(i)\left[\frac{y_{t+1}(i)}{x_{t+1}m_{t+1}(i)}\right]^{\psi_2+1} x_{t+1} - \psi_3\eta_{t+1}(i)\,x_{t+1}\right\}. \tag{29}$$

The Lagrange multipliers $\mu_t(i)$, $\zeta_t(i)$, $\eta_t(i)$, and $\xi_t(i)$ represent the shadow prices of aggregate demand, gross output, output inventory, and materials inventory, respectively. Equations (22) and (23) combined with (24) indicate the typical profit maximization conditions that equate a factor price and the value of its marginal product. Equation (25) shows the optimal choice of production. If the firm considers a marginal increase in output, then it has to pay an additional cost of $\zeta_t(i)$. At the optimal level of production, the cost $\zeta_t(i)$ equals the increased value of output inventory, $\eta_t(i)$, net of the cost due to the risk of disruption $(\eta_t(i)\,\psi_1(1+\psi_2)\,[y_t(i)\,/\,(v_t m_t(i))]^{\psi_2})$. If holding materials inventory is not costly ($\psi_1 = \psi_2 = \psi_3 = 0$), then the value of output inventory should be equal to the cost of production, in equilibrium. Since the final good producer is monopolistically competitive in its output market, it can control its sales level by adjusting the price of the final good. Equation (26) indicates that the value of additional sales ($\mu_t(i)\,[p_t(i)\,/p_t]^{\theta}$) should be equal to the value of marginal revenue ($\lambda_t(p_t(i)\,/p_t)$) net of the value of inventory ($\eta_t(i)$) and the value of marginal output inventory holding costs $(\eta_t(i)\,\kappa_1(1+\kappa_2)[s_t(i)/f_t(i)]^{\kappa_2})$. If output inventory holding is not costly ($\kappa_1=\kappa_2=\kappa_3=0$), then the value of sales is equalized to the value of real profit. The equation (27) describes the pricing principle of the firm. A marginal increase in the price will generate additional revenue $(\lambda_t[s_t(i)/p_t])$. The firm will consider the value of reduced sales due to the price increase and the value of price adjustment cost to decide the new price level. Equations (28) and (29) describe the optimal choice of output and materials inventory. When the firm chooses the inventory level for the next period, the firm will equate the cost (the value of inventory in the current period) and the benefit (the the value of the inventory in next period net of the value of marginal inventory holding cost).

2.3 The Materials Producer

The materials producer uses labor services, h_t, to produce its output, d_t. The technology of materials production is described by

$$d_t = a_t h_t^{\gamma}, \tag{30}$$

where $0<\gamma<1$. The firm does not hold any inventory, thus its production is the same as the delivery to (or orders by) the final good producer. The profit maximizing condition of the firm is simply

$$w_{h,t} = \gamma v_t \left(\frac{d_t}{h_t}\right). \tag{31}$$

2.4 The Monetary Authority

The monetary authority adjusts the nominal interest rate, r_t, in response to deviations of detrended output, and inflation rate $\pi_t = p_t/p_{t-1}$ from their respective steady-state values, according to the policy rule

$$\ln(r_t/r) = \rho_r \ln(r_{t-1}/r) + \rho_y \ln(y_t/y) + \rho_\pi \ln(\pi_t/\pi) + \varepsilon_{r,t}, \tag{32}$$

where r, y, and π, are the steady-state values of r_t, y_t, and π_t. A monetary policy shock is represented by $\varepsilon_{r,t}$, which is an IID innovation.

3 The Just-in-Time Inventory Economy

To evaluate the role of JIT inventories, we modify our model in the following way. We still consider a continuum of final good producers and a continuum of materials producers but the crucial difference between this JIT model and the non-JIT one above is that here materials inventories are held by the materials producer, rather than by the final good producer. As a result, the materials producer's profit maximization problem becomes a dynamic one since it now holds a stock of materials. Both producers are monopolistic competitors in their output markets and price-takers in their input markets. The specifications of the household and monetary authority are the same as those in the benchmark model.

3.1 The Final Good Producer

The specification of final good producer shares the same structure as the benchmark model, except for the feature that the firm does not hold materials inventory. A final good producer indexed by $i \in [0, 1]$ uses a CES technology to combine the differentiated materials

$$u_t(i) = \left[\int_0^1 d_t(j)^{\frac{\tau-1}{\tau}} dj \right]^{\frac{\tau}{\tau-1}}, \qquad \tau > 0. \tag{33}$$

where $d_t(j)$ denote the order of differentiated materials indexed by $j \in [0, 1]$. Cost minimization of the firm results in the demand for type j materials as

$$d_t(j) = \left[\frac{\tilde{v}_t(j)}{\tilde{v}_t} \right]^{-\tau} u_t(i), \tag{34}$$

where $\tilde{v}_t(j)$ is the price of type j materials. The parameter τ represents the elasticity of substitution between differentiated materials. The aggregate materials price level is

$$\tilde{v}_t = \left[\int_0^1 \tilde{v}_t\left(j\right)^{1-\tau} dj\right]^{\frac{1}{1-\tau}}. \tag{35}$$

The net flow of final good production is defined as

$$\tilde{y}_t\left(i\right) = y_t\left(i\right) - FHC_t\left(i\right) - PAC_t\left(i\right) - LAC_t\left(i\right) - MAC_t\left(i\right), \tag{36}$$

where $FHC_t\left(i\right)$, $PAC_t\left(i\right)$, $LAC_t\left(i\right)$, and $MAC_t\left(i\right)$ are defined as in equations (15), (17), (18), and (19), respectively. The first order conditions with respect to $l_t\left(i\right)$, $u_t\left(i\right)$, $y_t\left(i\right)$, $s_t\left(i\right)$, $p_t\left(i\right)$, and $f_{t+1}\left(i\right)$ are as follows:

$$\begin{aligned} \lambda_t w_{l,t} &= \alpha\zeta_t\left(i\right)\left(\frac{y_t\left(i\right)}{l_t\left(i\right)}\right) - \phi_l\eta_t\left(i\right)\left[\frac{l_t\left(i\right)}{l_{t-1}\left(i\right)} - 1\right] \\ &\quad -\beta\mathbb{E}_t\eta_{t+1}\left(i\right)\left[\left(\frac{\phi_l}{2}\right)\left[\frac{l_{t+1}\left(i\right)}{l_t\left(i\right)} - 1\right]^2 - \phi_l\left[\frac{l_{t+1}\left(i\right)}{l_t\left(i\right)} - 1\right]\left(\frac{l_{t+1}\left(i\right)}{l_t\left(i\right)}\right)\right], \end{aligned} \tag{37}$$

$$\begin{aligned} \lambda_t\left(\frac{v_t}{p_t}\right) &= \omega\zeta_t\left(i\right)\left(\frac{y_t\left(i\right)}{u_t\left(i\right)}\right) - \phi_u\eta_t\left(i\right)\left[\frac{u_t\left(i\right)}{u_{t-1}\left(i\right)} - 1\right] \\ &\quad -\beta\mathbb{E}_t\eta_{t+1}\left(i\right)\left[\left(\frac{\phi_u}{2}\right)\left[\frac{u_{t+1}\left(i\right)}{u_t\left(i\right)} - 1\right]^2 - \phi_u\left[\frac{u_{t+1}\left(i\right)}{u_t\left(i\right)} - 1\right]\left(\frac{u_{t+1}\left(i\right)}{u_t\left(i\right)}\right)\right], \end{aligned} \tag{38}$$

$$\eta_t\left(i\right) = \zeta_t\left(i\right), \tag{39}$$

$$\lambda_t\left(\frac{p_t\left(i\right)}{p_t}\right) - \eta_t\left(i\right)\left\{1 + \kappa_1\left(1+\kappa_2\right)\left(\frac{s_t\left(i\right)}{f_t\left(i\right)}\right)^{\kappa_2}\right\} = \mu_t\left(i\right)\left(\frac{p_t\left(i\right)}{p_t}\right)^{\theta}, \tag{40}$$

$$\begin{aligned} 0 &= \lambda_t\left(\frac{s_t\left(i\right)}{p_t}\right) - \theta\mu_t\left(i\right)\left(\frac{p_t\left(i\right)}{p_t}\right)^{\theta-1}\left(\frac{s_t\left(i\right)}{p_t}\right) - \eta_t\left(i\right)\phi\left(\frac{p_t\left(i\right)}{\pi p_{t-1}\left(i\right)} - 1\right)\left(\frac{c_t}{\pi p_{t-1}\left(i\right)}\right) \\ &\quad +\beta\phi\mathbb{E}_t\eta_{t+1}\left(i\right)\left(\frac{p_{t+1}\left(i\right)}{\pi p_t\left(i\right)} - 1\right)\left(\frac{p_{t+1}\left(i\right)c_{t+1}}{\pi p_t\left(i\right)^2}\right), \end{aligned} \tag{41}$$

and

$$\eta_t(i) = \beta \mathbb{E}_t \eta_{t+1}(i) \left\{ 1 + \kappa_1 \kappa_2 \left(\frac{s_{t+1}(i)}{f_{t+1}(i)} \right)^{\kappa_2 + 1} - \kappa_3 \right\}. \tag{42}$$

3.2 The Materials Producer

A materials producer indexed by $j \in [0,1]$ obeys the accounting constraint for materials inventory

$$m_{t+1}(j) = m_t(j) + \tilde{n}_t(j) - d_t(j), \tag{43}$$

where $m_t(j)$ refers to the stock of materials and $\tilde{n}_t(j)$ is the net flow of materials production. The gross production of materials is a function of labor input $h_t(j)$

$$n_t(j) = a_t [h_t(j)]^{\gamma}, \qquad 0 < \gamma < 1. \tag{44}$$

Like the final good producer, the materials producer incurs inventory holding costs and price adjustment costs. These costs are measured in units of materials. Therefore, the net flow of production is defined as

$$\tilde{n}_t(j) = n_t(j) - MHC_t(j) - VAC_t(j) \tag{45}$$

where $MHC_t(i)$ and $VAC_t(i)$ represent materials inventory holding cost and materials price adjustment cost, respectively. The materials inventory holding cost is represented as

$$MHC_t(j) = \psi_1 \left(\frac{d_t(j)}{m_t(j)} \right)^{\psi_2} d_t(j) + \psi_3 m_t(j), \tag{46}$$

where ψ_1, ψ_2, and ψ_3 are positive parameters. The materials price adjustment cost is specified as

$$VAC_t(j) = \frac{\chi}{2} \left[\frac{\tilde{v}_t(j)}{\pi \tilde{v}_{t-1}(j)} - 1 \right]^2 u_t. \tag{47}$$

The objective of the firm is to maximize its expected real market value, equal to

$$\mathbb{E}_t \sum_{\tau=t}^{\infty} \beta^{\tau-t} \lambda_\tau \left[\left(\frac{\tilde{v}_\tau (j)}{p_\tau} \right) d_\tau (j) - w_{h,\tau} h_\tau (j) \right]$$

subject to equations (34), (43), and (44). The first order conditions with respect to $h_t (j)$, $n_t (j)$, $d_t (j)$, $\tilde{v}_t (j)$, and $m_{t+1} (j)$ are

$$\lambda_t w_{h,t} = \gamma \varkappa_t (j) \left(\frac{n_t (j)}{h_t (j)} \right), \tag{48}$$

$$\varkappa_t (j) = \varrho_t (j), \tag{49}$$

$$\lambda_t \left(\frac{v_t (j)}{p_t} \right) - \varrho_t (j) \left\{ 1 + \psi_1 (1 + \psi_2) \left(\frac{d_t (j)}{m_t (j)} \right)^{\psi_2} \right\} = \varsigma_t (j) \left[\frac{v_t (j)}{v_t} \right]^{\tau}, \tag{50}$$

$$\begin{aligned} 0 \;=\; & \lambda_t \left(\frac{d_t (j)}{p_t} \right) - \tau \varsigma_t (j) \left(\frac{\tilde{v}_t (j)}{\tilde{v}_t} \right)^{\tau-1} \left(\frac{d_t (j)}{\tilde{v}_t} \right) - \varrho_t (j) \chi \left(\frac{\tilde{v}_t (j)}{\pi \tilde{v}_{t-1} (j)} - 1 \right) \left(\frac{u_t}{\pi \tilde{v}_{t-1} (j)} \right) \\ & + \beta \chi \mathbb{E}_t \varrho_{t+1} (j) \left(\frac{\tilde{v}_{t+1} (j)}{\pi \tilde{v}_t (j)} - 1 \right) \left(\frac{\tilde{v}_{t+1} (j) u_{t+1}}{\pi \tilde{v}_t (j)^2} \right), \end{aligned} \tag{51}$$

$$\varrho_t (j) = \beta \mathbb{E}_t \varrho_{t+1} (j) \left\{ 1 + \psi_1 \psi_2 \left(\frac{d_{t+1} (j)}{m_{t+1} (j)} \right)^{\psi_2 + 1} - \psi_3 \right\}, \tag{52}$$

where the Lagrange multipliers $\varsigma_t (j)$, $\varkappa_t (i)$, and $\varrho_t (i)$ represent the shadow prices of materials demand, gross materials production, and materials inventory, respectively.

4 Inventories: Propagation mechanism or source of business cycles?

The goal of this section is to explore, in the context of a New Keynesian model, whether inventories are a source of cycles or whether they only act as a propagation mechanism. We evaluate the role that inventories play in the propagation of shocks, computing the responses of a variety of economic magnitudes to three shocks of interest in the business cycle literature: technology, preferences, and monetary policy innovations. Our simulations use, for the most part, parameter values drawn from earlier studies (see Appendix B, Tables 1 - 2 for parameter values and references). The only exceptions are a set of cost parameters used to demonstrate how different adjustment costs and inventory holding costs may lead us to infer a different role for inventories in the economy.

4.1 Interactions with labor and materials input adjustment costs

The model in this paper includes several real and nominal frictions: labor and input adjustment costs, and monopolistic competition in the market for final goods and materials. As is common in recent New Keynesian models, these rigidities smooth the responses of economic magnitudes to shocks so as to better match the behavior observed in the data.

Figures 1-3 depict the response to shocks in the benchmark inventory model where the final good producers hold the inventories of their final goods and materials. To better grasp the role that different rigidities play in this model, we plot impulse response functions with different levels of adjustment costs. The dashed line represents the responses of the variables of interest when the benchmark parameters are used. The solid line illustrates the response when high labor and materials input adjustment costs are turned on. In both scenarios we set the cost of adjusting inventories to the parameter values estimated by Maccini and Pagan (2013).

In general, final good (F) and materials (M) inventories increase after a favorable productivity shock (Figure 1). Since the productivity shock increases the marginal products of labor and materials, firms can produce more output with less input, resulting in a decline in materials use and a build-up of materials inventory. As the household gets more purchasing power due to a higher real wage rate and lower inflation rate, consumption expenditures (sales) increase. However, the increase in consumption is restricted since the income effect makes the household expand leisure time (and provide less labor supply) as well. As a result, sales (consumption) do not increase as fast as net output, which causes the accumulation of final goods inventory. Notice that the difference between the responses to a productivity shock with low and high adjustment costs is negligible for all variables at long horizons. Yet, some differences are evident during the first two years or so. In particular, when high labor and materials input adjustment costs are turned on, the reduction in labor and materials input is somewhat smaller. In contrast, a positive productivity shock entails a larger accumulation of final good inventories and an initial liquidation of materials inventories. Since inputs in production respond less due to the high adjustment costs, final good inventory accumulates faster while materials inventory does more slowly. The difference becomes insignificant in the long run.[4]

Figure 2 depicts the dynamics generated by a preference shock. The shock increases the marginal utility of consumption over leisure time. To increase consumption, the household is willing to supply more labor services, resulting in a decline in the wage rate. Since firms produce more final goods to meet the increased demand, materials input increases while materials inventory is exhausted. Because the increase in the net output of final goods does not keep up with the sharp increase in sales, a liquidation of final good inventory follows. Consider now how input adjustment costs affect the response to an innovation in the preference for consumption. Here again differences in the long-run responses with low and high adjustment costs are negligible for all variables. Yet, in the short run the high input adjustment costs smooth the responses of labor and materials usage. As a result,

[4]Impulse responses not reported here reveal a similar picture when only labor or only material input adjustment costs are turned on.

the fluctuation in final good production is relatively smaller while the liquidation of final good inventories is more substantial, implying that the greater real rigidity makes inventory investment more volatile. By comparison, materials inventories initially move in the opposite direction with an accumulation taking place when adjusting labor and materials inputs is highly costly. From the second quarter until about a year after the shock, materials inventories are liquidated at a faster rate in the benchmark scenario.

Lastly, as shown in Figure 3, a positive monetary policy shock reduces the incentive to save, generating a sales increase. Because of a higher wage rate and materials price, labor and materials inputs do not respond sharply to increased demand. Therefore, firms meet demand by reducing their inventory level. The presence of high input adjustment costs smooths the short-run effect of a monetary policy shock on output, labor, materials input, and materials inventories. Instead, we observe that the shock leads to a larger decline in final good inventories. Since the adjustment of final good production is more costly, the firms liquidate more of their output inventory. As is the case for the other two shocks, the difference between the two scenarios is negligible in the long run.

In brief, as input adjustment becomes more costly, final good producer's factor inputs respond passively to a shock, resulting in a greater fluctuation of final good inventory. Those quantitative differences are large for the first year, especially in response to a monetary policy shock, however they dissipate about a year and a half after the shocks.

4.2 High stock-out avoidance costs

Now consider what happens when the final good producer faces a high cost of incurring materials stock-outs. The crucial difference between the benchmark and JIT models is the holder of materials inventory. Therefore, different values of the parameter ψ_2, which has an important effect on the level of materials inventory, are used for the analysis. We set the value of ψ_2, which controls the rate at which marginal materials holding cost rise with the stock of materials, at seven because the model does not have a unique and stable solution for larger parameter values.[5] The dotted lines in Figures 1-3 depict the responses when in addition to turning on high labor and materials input adjustment costs, the cost of incurring in materials stock-out (ψ_2) is high.

Notice that, regardless of the shock in question, inventories of materials react considerably less than in the alternative scenarios. Consider first the response to a productivity shock (Figure 1). Notice that when we increase the cost of avoiding stock-outs, materials inventory increases but the magnitude is relatively limited. Similar patterns are observed in response to a preference shock and a monetary policy shock (Figure 2 and 3).

To understand the reason, consider the log-linearized version of materials inventory accumulation equation

$$m\hat{m}_{t+1} = m\hat{m}_t + d\hat{d}_t - u\hat{u}_t, \tag{53}$$

where $\hat{m}$, $\hat{d}$, and $\hat{u}$ denote the log deviations from the steady state values of materials inventory, materials order, and materials use, respectively. Corresponding steady state values are represented by m, d, and u. When the cost of a materials stock-out is at the benchmark level ($\psi_2 = 0.015$), the steady state level of materials inventory is very small ($m = 0.0229$). However, as the stock-out costs increase significantly ($\psi_2 = 7$), m grows up to 1.5929 while steady state values of materials orders and materials use are intact ($d = u = 0.3008$). Because a high stock-out cost results in a high level of m, the responses of materials orders and materials use have limited impact on inventory accumulation. Intuitively, when a stock-out incurs a small cost, firms hold less materials inventory and thus a greater fluctuation of materials inventory results compared to the steady state level. However, if the stock-out of materials inventory becomes more costly to firms, then more inventory is held by firms, resulting in a very sluggish fluctuation of the inventory relative to the steady state level.

In addition, we present results in the Appendix revealing that cyclical fluctuations in the dynamic adjustment path of final output and other economic variables can occur when the stock-producing firm holds materials inventories along with a stock of finished goods. Yet,

[5] Klein (2000, 1418) provides stability conditions for models of the type that we study in this paper.

our analysis shows that this property of dynamic adjustment paths only occurs when the marginal adjustment costs on materials inventories rise very rapidly in the stock of materials. In contrast, even when ψ_2 is very high, a unique and stable steady state exists for the JIT economy and no fluctuations appear in the adjustment path. In other words, for the values of ψ_2 considered in our analysis inventories do not cause business cycles to exist. Instead, the function of inventories in both the benchmark and the JIT model is to propagate business cycles.

5 The Implications of Just-in-Time Inventories

This section explores, in the context of our JIT model, how different assumptions regarding labor, materials input, and inventory adjustment and holding costs alter the model's predictions regarding the effect of technology, preferences, and monetary policy shocks. Recall that our JIT model differs from the benchmark model in a crucial aspect: materials inventories are held by the materials producer rather than the final good producer. This assumption corresponds to the inventory strategy where the final good producer receives materials only as they are needed in the production process, which in turn reduces inventory holding costs. In other words, inventories of materials are held by the materials producer until they are required downstream.

5.1 JIT inventories with input adjustment costs

The aim of this section is to evaluate whether the role played by labor and materials adjustment costs in smoothing the impulse responses is affected by the introduction of JIT inventories. Figures 4, 5, and 6 illustrate the responses to productivity, preferences and monetary policy shocks, respectively. The dashed lines represent the responses in the JIT model where the benchmark parameters are used. The solid lines illustrate the responses when high labor and materials input adjustment costs are turned on. To better grasp the implications of introducing JIT inventories, we use the same parameter values for each scenario as in the benchmark model. As earlier, we set the cost of adjusting inventories to the parameter values estimated by Maccini and Pagan (2013).

Comparing the responses to a productivity shock in the benchmark and the JIT models (dashed lines in Figures 1 and 4, respectively) reveals almost no differences for the behavior of final goods. In fact, inventories, labor input, wages, output and sales exhibit virtually the same path in both models. Similarly, the differences between the benchmark and the JIT models are mostly insignificant when comparing the responses of the final good producer to a preference shock (Figures 2 and 5) and a monetary policy shock (Figures 3 and 6). The differences are noticeable in the dynamics of materials inventory. When JIT technology is utilized, materials inventory fluctuates less in response to productivity and preference shocks. On the other hand, the response of materials inventory to a monetary policy shock is relatively greater in the JIT model.

As is the case in the non-JIT benchmark model, adding high adjustment costs smooths out the response of labor input, materials orders, and materials output to a productivity shock in the JIT model (Figure 4). As a result, more of the adjustment is done through greater variation in final good inventory. The presence of high adjustment costs in the JIT model leads to an initial liquidation followed by a smaller accumulation of materials inventories and a larger buildup of final goods inventories. The difference between the response of final good production in the JIT model and the JIT with high adjustment costs is quite small.

In contrast, high adjustment costs do smooth the response of final good production to preference (Figure 5) and monetary policy shocks (Figure 6). On the one hand, a higher preference for consumption induces a smaller increase in the demand for inputs while it results in larger declines in wages and the real price of materials in the JIT model with high adjustment costs. In other words, high adjustment costs amplify the response of relative prices to a preference shock. On the other hand, expansionary monetary policy has a muted effect on relative prices when high adjustment costs are turned on in the JIT model.

5.2 JIT inventories as a stabilizing force

5.2.1 Dynamic Responses to Shocks

Does the introduction of JIT inventories represent a stabilizing force in the economy? And if so, how? To answer these questions let us first take a look at what happens in the JIT model when the cost of incurring in materials stock-outs, ψ_2, is high.

Consider what happens when we introduce JIT inventories. The dotted lines in Figures 4, 5, and 6 represent, respectively, the responses to productivity, preferences, and monetary policy shocks in the JIT model with high adjustment costs and high inventory holding costs. First, notice how the responses in the JIT model where high adjustment costs are turned on are almost identical for output, inventories, and wages in the final good sector, regardless of the magnitude of ψ_2. Moreover, in this framework the materials producer has an incentive to smooth out changes in materials inventories as it is she – and not the final good producer – who faces the high stock-out avoidance costs. Second, the higher the cost of avoiding materials stock-outs in the JIT model, the larger the response of labor inputs in the materials sector and the smaller the response of materials orders by the final good sector.

As we saw in the benchmark case, inventories of materials react considerably less when a high stock-out cost is imposed. The reason is not different from the benchmark case. Since a stock-out of inventory becomes very costly to the materials producer, the materials inventory holding increases so as to reduce the probability of a stock-out. Therefore, the fluctuation of materials inventory becomes very limited.

5.2.2 JIT Inventories and Volatility

To better understand the impact of JIT inventories on business cycles, we conduct simulations by computing the standard deviations generated by the two models. More precisely, we generate 10,000 artificial time series with a sample size of 200 (50 years of quarterly data) under two different scenarios. The first scenario is one in which all the structural shocks (productivity, preferences and monetary policy) are taken into consideration. In the second scenario only preference shocks are assumed to hit the economy. The latter setup is aimed at understanding the effect of (pure) demand side innovations in driving inventory dynamics.

Standard deviations for the variables of interest (output, consumption, final goods inventories, materials inventories, and inflation rate) are reported in Tables 3 - 4. Note that, in order to evaluate the robustness of the simulation results to the key parameter – the materials inventory stock-out cost, ψ_2 – we compute second moments for parameters in the neighborhood of the benchmark value, $\psi_2 = 0.015$.

Table 3 shows the scenario where all the shocks are taken into consideration. The second and third column report the standard deviation for the simulated variables whereas the fourth column records the percentage change. Let us focus on the third panel, which corresponds to the results for the baseline calibration, $\psi_2 = 0.015$. Note that as JIT inventories are introduced, the standard deviation of all the reported variables but materials inventory decrease. In fact, the standard deviation of materials inventory increases by 28 percent whereas that of final good inventory decreases by about 19 percent. As for the other variables, the standard deviation of inflation declines by 14 percent and output and consumption become less volatile (about an 8 percent reduction in the standard deviation). Though the simulation results across the different values of ψ_2 are qualitatively consistent, they reveal two insights. First, the higher the stock-out avoidance cost, ψ_2, the less responsive final goods and materials inventories are to shocks. Second, when materials inventories are held by the final good producer (i.e., benchmark model) an increase in ψ_2 leads to a slight reduction in output volatility. On the contrary, when materials inventories are held by the materials producer (i.e., JIT model), higher ψ_2 results in slightly larger output volatility.

Let us now turn our attention to the scenario with only preference shocks (Table 4). Note that, as in the previous case, the introduction of JIT inventories reduces the volatility of output and consumption. Yet, when technology and monetary policy shocks are turned off two important differences are observed. First, final goods inventory is more volatile in the JIT model but less volatile in the benchmark model. Second, output volatility exhibits a slight increase – instead of a decrease – as the stock-out cost, ψ_2, rises.

To better understand the reason for these differences it is useful to compare the steady state values in both models. Four implications for the steady state values in the JIT model relative to the benchmark model are apparent from Figure 7.

1. Gross output in the JIT economy is smaller.

2. Net output in the JIT economy is larger.

3. Final good inventory is larger in the JIT economy.

4. Materials inventory is smaller in the JIT economy.

As a result, the ratio of final good inventory to gross output is larger in the JIT model, whereas that of materials inventory to gross output is smaller. Because materials inventory declines substantially, total inventory holding is smaller in the JIT model. This result is consistent with the findings of Kahn, McConnell, and Perez-Quiros (2002) that the total amount of inventory has declined since 1984. Notice that, when the JIT technology is introduced, it is optimal for the final good producer to hold more final good inventories and produce less as she forgoes the cost of holding materials inventory. This greater stock of final good inventory allows the producer to smooth production over the business cycle. Therefore, gross output and consumption volatility decline.

In brief, the simulation results suggest that the introduction of JIT technology leads to a reduction in the volatility of the economy. In particular, new inventory management techniques aid in reducing the impact of shocks and thus contribute to the dampening of economic fluctuations. Yet, a caveat must also be made here. Our model does not speak to the role of other mechanisms such as improved policy or "good luck" in diminishing the volatility of output; however, it indicates that the introduction of new inventory holding techniques could be one of the possible causes for the Great Moderation.

6 Conclusion

Previous research has suggested that inventories cause business cycles, that they only serve as a part of the propagation mechanism for business cycles and, more recently, that inventories may have increased the stability of aggregate economies due to the emergence of just-in-time (JIT) inventories. In order to investigate these possible roles for inventories in the business cycle, a DSGE model is an attractive framework since we can be quite explicit regarding the structural changes that occur when constructing our aggregate economies. In this paper, we construct two DSGE models, one with and one without JIT inventories. We use these models to determine if inventories cause business cycles and if the JIT economy is more stable in response to several sources of economic shocks.

Using a baseline set of parameter values drawn from earlier studies, we simulate our models and find that there are no high-frequency fluctuations in the aggregate economy in response to shocks to preferences, productivity, and monetary policy. Identical findings emerge when we add costs of adjustment to intermediate materials and labor and when there are high marginal materials holding costs. Thus we conclude that in our economies, inventories are not a source of business cycles since we observe no cyclical fluctuations in the adjustment path to the steady state in either of our economies. We then construct standard deviations for a variety of economic magnitudes in response to preference, productivity, and monetary policy shocks and we find that there are indeed reduced standard deviations evident in the JIT economy. Thus we conclude that the emergence of the JIT economy may be partly responsible for the increased stability apparent in aggregate economies by moderating the responses of various economic magnitudes to economic shocks.

There are a number of additional issues that might be pursued in future research on this topic. We omit capital stocks and its associated utilization rate in our analysis as is traditional in the inventory investment literature. These extensions to our models introduce an additional propagation mechanism into the economy that can affect the dynamics displayed by the model in response to shocks. Further it would be of interest to estimate the parameters of our models to see how well they fit aggregate macroeconomic data. We used parameter values drawn from earlier studies but our economies differ substantially from those used in previous research. This empirical evidence would be useful in providing more evidence on the role of inventories in the business cycle.

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A Appendix: Inventories as a Cyclical Source

In this Appendix, a model of a stock-producing firm is set out which reveals that, for a firm holding inventories of finished goods and materials, transition equations that arise from optimizing behavior may involve oscillations in state variables as they approach the steady state. Once the model is described and its optimality criteria given, we derive the characteristic roots that arise in the model and show that those roots may be complex numbers. Further, we are also able to show how we can induce complex roots by the choice of parameters.

The firm is assumed to produce entirely to stock. It produces its output into a stock of finished goods, using intermediate materials in production and so it also holds a stock of intermediate materials inventories. Inventories obey the accounting constraints

$$\dot{f}(t) = y(t) - s, f(0) = f_0 \tag{54a}$$

$$\dot{m}(t) = d(t) - u(t), m(0) = m_0 \tag{54b}$$

where f refers to finished goods, y is the flow of output produced, s denotes sales, m is the stock of intermediate materials, d is deliveries of new intermediate materials, u is the rate at which materials are withdrawn from the stock of materials and used up in production.

Net output is produced according to the production function

$$y(t) = y(\ell(t), u(t)) - h(m(t), s) \tag{55}$$

where ℓ measures labor services in production. As in much of the inventory investment literature, the firm's capital stock is assumed to be fixed. The gross production function, $y(\ell(t),\ u(t))$, has positive ($y_\ell > 0,\ y_u > 0$) and diminishing ($y_{\ell\ell} < 0,\ y_{u.u} < 0$) marginal products and it is assumed to be strictly concave in its arguments ($y_{\ell\ell}y_{uu} - y_{\ell u}^2 > 0$). It will also be assumed that $y_{\ell u} > 0$. Notice that gross output produced depends upon withdrawals from the stock of materials as in Humphreys, Maccini and Schuh (2001); it does not depend upon the stock of materials. Since output is a flow, withdrawals from the stock of materials (or utilized materials), rather than the stock of materials, should appear as an argument of the production function.[6] Labor services and withdrawals from the stock of materials are always positive.

The gross production function has subtracted from it a holding cost term designed to capture the benefits and costs attached to holding a stock of materials. As Mack (1967) suggested, there are benefits in production that accrue to the firm by holding a stock of intermediate materials inventories. Production can occur more efficiently when an inventory of intermediate goods is held but there are also costs attached to materials inventories, such as the insurance, maintenance, obsolescence, labor, and physical capital costs incurred by the firm in holding an inventory of intermediate materials for use in production. Thus it will be assumed that the holding cost term is U-shaped in the stock of materials. At low levels of materials stocks, holding costs fall as the stock of materials rises. This is the range where the benefits in production dominate the inventory holding costs of the firm but, eventually, materials holding costs rise as the stock of materials grows, growing larger than the efficiency gains in production. These holding costs are also assumed to be convex in the stock of materials inventories ($h_{mm} > 0$). Mack (1967) also suggested that materials are held with an eye towards the level of sales and so the holding cost term subtracted from the gross production function also includes the level of sales (more will be said below about the role of sales in this holding cost function). There is a given initial stock of finished goods.

Equation (54b) is an accounting relationship for the stock of materials. Materials rise with deliveries of new materials and, for simplicity, there are no delivery lags associated with orders of new intermediate materials. A new order for a unit of materials is therefore identical to the delivery of a new unit of materials (see the concluding section of this paper for further discussion of this issue). Deliveries are unrestricted in sign; if $d < 0$, the firm is selling off excess materials in second-hand markets. Materials used up in production reduce the stock of

[6] Ramey (1989) assumes that a constant fraction of the stock of materials is used up in production. Here we allow the firm to choose, in effect, the rate at which it withdraws materials as well as the stock of materials that it wishes to hold.

materials. Utilized materials must obey the restriction $0 < u < m$; this restriction on utilized materials is assumed to hold without formally imposing the constraint in the optimization problem just as will be done for the restriction that labor services must be positive. The stock of materials could also decline due to depreciation, breakage, or obsolescence that could be captured by subtracting exponential decay in the stock of materials. This possibility is also ignored for the sake of simplicity. Finally, there is a given initial stock of materials.

The firm wishes to maximize

$$J(t) = \int_0^\infty R(t)e^{-rt}dt \tag{56a}$$

$$R(t) = s - w\ell(t) - c(f(t), s) - v[d(t) + i(d(t) - u(t))] \tag{56b}$$

where $R(t)$ is the firm's real cash flow, w is the real wage (the firm's output price is normalized to unity), v is the real purchase price of materials, and r is the discount rate ($r > 0$). Cash flow is given by the difference between real sales and costs where the latter is comprised of payments for labor services and the costs attached to inventories.

The firm operates in perfect input markets so that factor input prices are parametric to the firm. The wage bill is given by the product of the real wage and labor services used in production. The firm pays for intermediate materials at the time of delivery and there are installation (adjustment) costs attached to net changes in the stock of intermediate materials, costs measured in units of materials. These costs have the standard curvature properties used in the adjustment cost literature.[7]

$$i'(\dot{m}) \gtreqless 0, \dot{m} \gtreqless 0, i''(\dot{m}) > 0$$

If the firm is to hold finished goods inventories, there must be benefits as well as costs attached to doing so. Inventories could be productive for sales as in Bils and Kahn (2000)

[7] Note that there would still be adjustment costs attached to the stock of finished goods even without this assumption. With a strictly concave gross production function, the cost of adding current production to the stock of finished goods would rise at the margin as output increases and so there would still be adjustment costs attached to the stock of finished goods.

but a more commonly used assumption, and one that is used here, is that these benefits are embodied in a cost function such as the one in (56b). For example, it is frequently assumed that inventory holding costs contain a component that is linear in the stock of inventories and that costs also depend upon the gap between actual and desired inventories where the latter is proportional to the level of sales (see Moore, Maccini and Schaller (2004) as an example). The cost function in the cash flow equation embodies these ideas. It is also possible, and we assume this to be the case, that this cost function is U-shaped so that the firm's costs decline initially as the stock of finished goods inventories rises, then increasing after reaching a minimum point. At low levels of finished goods inventories, there are benefits to the firm, such as the avoidance of stock-outs, that cause the firm's planned cash flow to rise with the level of inventories. Eventually these benefits are exhausted and the firm's holding costs begin to rise due to the insurance, maintenance and other costs of holding finished goods inventories. It is further assumed that this cost function is convex in the level of inventories ($c_{ff} > 0$). Higher sales provide benefits to the firm by reducing the marginal holding costs of finished goods inventories ($c_{fs} < 0$), a traditional assumption in the inventory investment literature.[8]

A.1 Optimality Conditions

The firm's optimality criteria may be found by using (54a-54b), (55) and (56b) to form the Hamiltonian

$$H = s - w\ell - c(f,s) - v[d + i(d-u)] + \lambda[y(\ell,u) - h(m,s) - s] + \vartheta[d-u]$$

where the time notation has been suppressed. In this expression, λ and ϑ are adjoint variables measuring the values, imputed by the firm, to inventory stock accumulation. The

[8] This is the implication of the standard quadratic approximation where inventory costs depend upon the square of the gap between inventories and their desired level where the latter is proportional to the level of sales.

following conditions describe optimal behavior by the firm.[9]

$$\begin{aligned}
w &= \lambda y_\ell(\ell, u) && \text{(57a)}\\
\vartheta &= \lambda y_u(\ell, u) + vi'(d-u) && \text{(57b)}\\
\vartheta &= v[1 + i'(d-u)] && \text{(57c)}\\
\dot{\lambda} &= c_f(f, s) + r\lambda && \text{(57d)}\\
\dot{\vartheta} &= \lambda h_m(m, s) + r\vartheta && \text{(57e)}\\
\dot{f} &= y(\ell, u) - h(m, s) - s && \text{(57f)}\\
\dot{m} &= d - u && \text{(57g)}\\
0 &= \lim_{t\longrightarrow\infty} \lambda(t)e^{-rt}f(t) = \lim_{t\longrightarrow\infty} \vartheta(t)e^{-rt}m(t) && \text{(57h)}
\end{aligned}$$

Each of these optimality criteria may be readily interpreted.

Labor services and materials withdrawals are variable factor inputs in production (there are no adjustment costs attached to either of them) so standard static conditions describe the optimal choices of these inputs. Expression (57a) is such a marginal productivity condition for the optimal choice of labor. Combine (57b) and (57c) to give

$$v = \lambda y_u(\ell, u)$$

which is a conventional marginal productivity condition for the materials withdrawn from the stock of materials and used in production. As in the ordinary static theory of the firm, the ratio of the marginal products of variable factor inputs is equal to the factor input price ratio. The firm uses the shadow value of finished goods inventory accumulation in evaluating the marginal productivities of its variable factor inputs because it produces its output into a stock of finished goods inventories rather than selling its output directly to final consumers.

Expression (57c) shows that there is a measure of Tobin's marginal q (Hayashi 1982)

[9] The maximized Hamiltonian is easily shown to be strictly concave in the state variables given the maintained assumptions regarding functional forms. An optimal path will exist in this case and it will be unique. These optimality criteria are thus sufficient to determine an optimal path.

associated with the stock of materials. Marginal q ($q = \vartheta/v$) lies above or below unity as the firm accumulates or decumulates materials. Equations (57d-57e) can be integrated to show that the imputed values of inventories measure the discounted marginal benefits attached to inventories. (57f) and (57g) are repetitions of accounting relationships while the expressions in (57h) are transversality conditions implying that the imputed values of inventory accumulation recede to zero as time grows arbitrarily large.

These conditions will now be used to describe the behavior of the firm along the path to the steady state.

A.2 Dynamics

The transition equations that describe the evolution of the firm's state and costate variables are given below. The transition equations may be derived by eliminating the instruments using the optimality criteria in (57a)-(57c). These are given by

$$\begin{aligned}
u &= \widehat{u}(\lambda, w, v), \ell = \widehat{\ell}(\lambda, w, v), d - u = \widehat{g}(\vartheta/v) && \text{(58a)} \\
\frac{\partial u}{\partial \lambda} &= \frac{y_\ell y_{\ell u} - y_{\ell\ell} y_u}{\lambda\left(y_{\ell\ell} y_{uu} - y_{\ell u}^2\right)} > 0, \frac{\partial u}{\partial w} = \frac{-y_{\ell u}}{\lambda\left(y_{\ell\ell} y_{uu} - y_{\ell u}^2\right)} < 0 && \text{(58b)} \\
\frac{\partial u}{\partial v} &= \frac{y_{\ell\ell}}{\lambda\left(y_{\ell\ell} y_{uu} - y_{\ell u}^2\right)} < 0, \frac{\partial \ell}{\partial \lambda} = \frac{y_u y_{\ell u} - y_{uu} y_\ell}{\lambda\left(y_{\ell\ell} y_{uu} - y_{\ell u}^2\right)} > 0, && \text{(58c)} \\
\frac{\partial \ell}{\partial w} &= \frac{y_{uu}}{\lambda\left(y_{\ell\ell} y_{uu} - y_{\ell u}^2\right)} < 0, \frac{\partial \ell}{\partial v} = \frac{-y_{\ell u}}{\lambda\left(y_{\ell\ell} y_{uu} - y_{\ell u}^2\right)} < 0, && \text{(58d)} \\
\widehat{g}'(\vartheta/v) &= i''(d-u)^{-1} > 0. && \text{(58e)}
\end{aligned}$$

These relationships lead to the transition equations below.

$$\dot{\lambda} = c_f(f, s) + r\lambda \tag{59}$$

$$\dot{\vartheta} = \lambda h_m(m, s) + r\vartheta \tag{60}$$

$$\dot{f} = y(\widehat{\ell}(\lambda, w, v), \widehat{u}(\lambda, w, v)) - h(m, s) - s \tag{61}$$

$$\dot{m} = \widehat{g}(\vartheta/v) \tag{62}$$

Defining $\widetilde{\lambda}(t) = \lambda(t) - \lambda^*, \widetilde{\vartheta}(t) = \vartheta(t) - \vartheta^*, \widetilde{f}(t) = f(t) - f^*, \widetilde{m}(t) = m(t) - m^*,$ the linear approximation to the transition equations is

$$\begin{bmatrix} \dot{\widetilde{\lambda}}(t) \\ \dot{\widetilde{\vartheta}}(t) \\ \dot{\widetilde{f}}(t) \\ \dot{\widetilde{m}}(t) \end{bmatrix} = \begin{bmatrix} r & 0 & \Delta_{13} & 0 \\ \Delta_{21} & r & 0 & \Delta_{24} \\ \Delta_{31} & 0 & 0 & \Delta_{34} \\ 0 & \Delta_{42} & 0 & 0 \end{bmatrix} \begin{bmatrix} \widetilde{\lambda}(t) \\ \widetilde{\vartheta}(t) \\ \widetilde{f}(t) \\ \widetilde{m}(t) \end{bmatrix} \tag{63}$$

where the coefficients in (63), evaluated in the steady state, are defined as

$$\Delta_{13} = c_{ff} > 0, \Delta_{21} = h_m(m,s) < 0, \Delta_{24} = \lambda h_{mm}(m,s) > 0, \tag{64}$$

$$\Delta_{31} = \frac{2y_{\ell u}y_\ell y_u - y_{uu}y_\ell^2 - y_{\ell\ell}y_u^2}{\lambda\left(y_{\ell\ell}y_{uu} - y_{\ell u}^2\right)} > 0, \Delta_{34} = -\Delta_{21}, \Delta_{42} = \frac{1}{vi''(d-u)} > 0. \tag{65}$$

It can be shown that $|\Delta| = \Delta_{13}\Delta_{42}(\Delta_{21}^2 + \Delta_{31}\Delta_{24}) = \upsilon_1\upsilon_2\upsilon_3\upsilon_4 > 0$ where υ_i denotes the characteristic roots in this system. These characteristic roots are found by forming $|\Delta - \upsilon I_4| = 0$ where I_4 refers to an identity matrix of order four. The roots are assumed to be distinct (a slight perturbation of underlying parameters in the optimization problem can induce distinct roots) and the roots are given by

$$\upsilon_i = \frac{r}{2} \pm \sqrt{\frac{r^2}{4} + \frac{\Delta_{13}\Delta_{31} + \Delta_{24}\Delta_{42}}{2} \pm \sqrt{(\frac{\Delta_{13}\Delta_{31} - \Delta_{24}\Delta_{42}}{2})^2 - \Delta_{13}\Delta_{42}\Delta_{21}^2}}\ .$$

The roots may be complex because $((\Delta_{13}\Delta_{31} - \Delta_{24}\Delta_{42})/2)^2 - \Delta_{13}\Delta_{42}\Delta_{21}^2$ can be negative. If the roots are complex, they will occur in conjugate pairs. The roots are thus symmetric about r/2 with two stable roots having negative real parts and two unstable roots with positive real parts. Whether or not the roots are real or complex, it is true that $\upsilon_1 + \upsilon_2 < 0$ and $\upsilon_1\upsilon_2 > 0$ with $\upsilon_{1,2}$ denoting the stable roots.

Using the expression that determines the existence of complex roots, it is easily seen that the larger is the term Δ_{21} , the more likely it is that complex roots will exist. This term is given by the marginal holding costs for materials which leads us to choose the parameters in the materials holding cost function when attempting to induce business cycles in our DSGE model.

In the case of just-in-time inventories, we do not provide any analytical results here because the dynamics arising from the firms holding inventories is straightforward. In each model, there is one inventory state variable that is held by each firm and, with the usual concavity restrictions that are made, maximized Hamiltonians will be strictly concave in the state variables, and saddlepaths arise that describe the path to the steady state. The transition equations will have real characteristics roots so that no oscillations in stocks will arise. All of these features of the JIT inventory problems are standard in macroeconomic research.

B Calibration

Calibration parameters and their values are summarized in Tables 1 and 2. The baseline parameter values are set as follows: assuming a two percent real interest rate and a two percent economic growth in the steady state, the discount factor β is set at 0.99. The share of labor (α) and materials (ω) in final good production are imposed according to Petrin and Levinsohn (2003). The share of labor in materials production (γ) is set at 0.6667. Baseline parameters for output inventory holding costs (κ_1 , κ_2 , κ_3) and those for materials inventory holding costs (ψ_1, ψ_2, ψ_3) are imposed according to Maccini and Pagan (2013). Elasticities of substitution between different goods (θ) and between different materials (τ) are set at 6 so that the steady state markups will be 1.2. Using Ireland's (2001) estimation result, price adjustment cost parameter values for final good (ϕ) and materials (χ) are set to 50. Labor input (ϕ_l) and materials input (ϕ_m) adjustment cost parameters are set according to the estimates of Hall (2004). Given that the time endowment is normalized to unity, the steady state labor supply is assumed to be 0.33, which means that the household spends a third of its time for market activity. Since the steady state wage rates are equal for the production of final good and materials, steady state labor supply to the final good firm (l) is set to 0.165. Considering the historical average of the U.S. inflation rate, our steady state inflation rate (π) is assumed to be 1.006, which implies that about 2.4 percent of annual inflation rate. Following the standard empirical analysis, the Taylor rule parameters are set as follows: the persistence of the interest rate (ρ_r) is set at 0.5. The sensitivities of the interest rate to the output gap (ρ_y) and inflation gap (ρ_π) are set at 0.5 and 1.5, respectively, which are consistent with the Taylor Principle. Since the model variables are assumed to be stationary, the steady state productivity shock (a) and preference shock (z) are normalized to unity. The persistence of the productivity shock (ρ_a) and the preference shock (ρ_z) are set at 0.7 so that the repercussions of those shocks last for a while. Finally, the magnitude of economic shocks (σ_a, σ_z, σ_r) are set at 0.1.

Table 1. Description of parameters

Parameter	Description
β	Discount rate
α	Share of labor in final good production
ω	Share of materials in final good production
γ	Share of labor in materials production
κ_1	Parameter for output inventory costs
κ_2	Parameter for output inventory costs
κ_3	Parameter for output inventory costs
ψ_1	Parameter for materials inventory costs
ψ_2	Parameter for materials inventory costs
ψ_3	Parameter for materials inventory costs
θ	Elasticity of substitution for different goods
ϕ_p	Parameter for price adjustment costs
ϕ_l	Parameter for labor input adjustment costs
ϕ_u	Parameter for materials input adjustment costs
χ	Parameter for materials price adjustment costs
τ	Elasticity of substitution for different materials
l	Steady state supply of labor to final good producer
π	Steady state inflation rate
ρ_r	Taylor rule parameter for r_{t-1}/r
ρ_y	Taylor rule parameter for y_t/y
ρ_π	Taylor rule parameter for π_t/π
ρ_a	Persistence of productivity shock
ρ_z	Persistence of preference shock
σ_a	Magnitude of productivity shock
σ_z	Magnitude of preference shock
σ_r	Magnitude of monetary policy shock

Table 2. Calibration

Parameter	Benchmark/JIT	High Cost	Source
β	0.9900		
α	0.2500		Levinsohn and Petrin (2003)
ω	0.3750		Levinsohn and Petrin (2003)
γ	0.6667		
κ_1	0.1000		Maccini and Pagan (2013)
κ_2	0.0260		Maccini and Pagan (2013)
κ_3	0.0400		Maccini and Pagan (2013)
ψ_1	0.1000		Maccini and Pagan (2013)
ψ_2	0.0150	7	Maccini and Pagan (2013)
ψ_3	0.0700		Maccini and Pagan (2013)
θ	6.0000		Rotemberg and Woodford (1992)
ϕ_p	50.000		Ireland (2001)
ϕ_l	0.0750	1.5	Hall (2004)
ϕ_u	0.0500	1.5	Hall (2004)
χ	50.000		Ireland (2001)
τ	6.0000		Rotemberg and Woodford (1992)
l	0.1650		
π	1.0060		
ρ_r	0.5000		
ρ_y	0.5000		
ρ_π	1.5000		
ρ_a	0.7000		
ρ_z	0.7000		
σ_a	0.1000		
σ_z	0.1000		
σ_r	0.1000		

Table 3. Standard Deviations of Simulated Variables - All Shocks

Variable	Benchmark	JIT	Change (%)
($\psi_2 = 0.005$)			
Output	0.1456	0.1334	-8.41
Consumption	0.1406	0.1293	-8.04
Final Good Inventory	1.7962	1.4072	-21.66
Materials Inventory	1.1061	1.3680	23.67
Inflation Rate	0.0742	0.0635	-14.43
($\psi_2 = 0.01$)			
Output	0.1452	0.1335	-8.06
Consumption	0.1406	0.1293	-8.04
Final Good Inventory	1.7528	1.4016	-20.04
Materials Inventory	1.0394	1.3102	26.05
Inflation Rate	0.0741	0.0635	-14.22
($\psi_2 = 0.015$)			
Output	0.1448	0.1335	-7.76
Consumption	0.1407	0.1294	-8.03
Final Good Inventory	1.7160	1.3963	-18.63
Materials Inventory	0.9843	1.2600	28.00
Inflation Rate	0.0739	0.0636	-14.00
($\psi_2 = 0.05$)			
Output	0.1428	0.1340	-6.18
Consumption	0.1408	0.1298	-7.81
Final Good Inventory	1.5526	1.3666	-11.98
Materials Inventory	0.7490	1.0248	36.83
Inflation Rate	0.0729	0.0639	-12.37
($\psi_2 = 0.1$)			
Output	0.1409	0.1345	-4.55
Consumption	0.1404	0.1303	-7.22
Final Good Inventory	1.4356	1.3376	-6.82
Materials Inventory	0.5827	0.8415	44.40
Inflation Rate	0.0716	0.0642	-10.30

Table 4. Standard Deviations of Simulated Variables - Preference Shock

Variable	Benchmark	JIT	Change (%)
($\psi_2 = 0.005$)			
Output	0.0402	0.0370	-7.97
Consumption	0.0474	0.0450	-5.06
Final Good Inventory	0.4248	0.4686	10.32
Materials Inventory	0.2104	0.1415	-32.75
Inflation Rate	0.0067	0.0051	-22.89
($\psi_2 = 0.01$)			
Output	0.0403	0.0370	-8.14
Consumption	0.0474	0.0450	-5.04
Final Good Inventory	0.4181	0.4681	11.95
Materials Inventory	0.1998	0.1386	-30.63
Inflation Rate	0.0067	0.0051	-22.85
($\psi_2 = 0.015$)			
Output	0.0403	0.0370	-8.31
Consumption	0.0474	0.0450	-5.03
Final Good Inventory	0.4123	0.4675	13.39
Materials Inventory	0.1906	0.1359	-28.72
Inflation Rate	0.0067	0.0051	-22.90
($\psi_2 = 0.05$)			
Output	0.0408	0.0370	-9.30
Consumption	0.0474	0.0450	-5.18
Final Good Inventory	0.3868	0.4643	20.05
Materials Inventory	0.1476	0.1204	-18.41
Inflation Rate	0.0067	0.0051	-24.40
($\psi_2 = 0.1$)			
Output	0.0412	0.0369	-10.28
Consumption	0.0475	0.0449	-5.46
Final Good Inventory	0.3708	0.4610	24.31
Materials Inventory	0.1142	0.1047	-8.27
Inflation Rate	0.0069	0.0050	-27.02

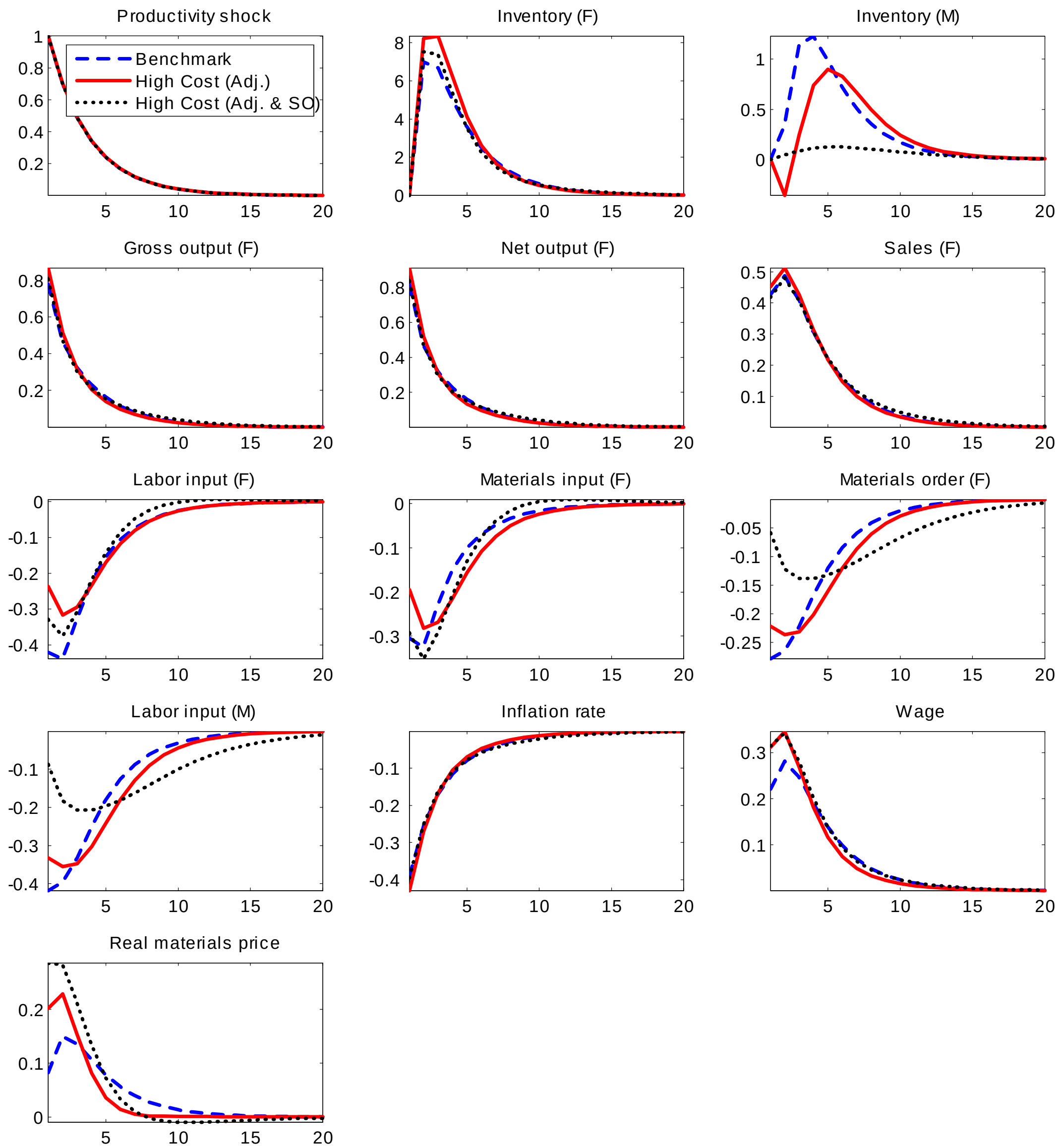

Figure 1. Impulse Responses to a Productivity Shock: Benchmark Model

N.B.: dashed lines represent the responses computed using the benchmark parameters, solid lines represent the responses when high labor and materials input adjustment costs are turned on, dotted lines denote the responses when high labor and materials input costs are turned on and stock-out avoidance costs are high.

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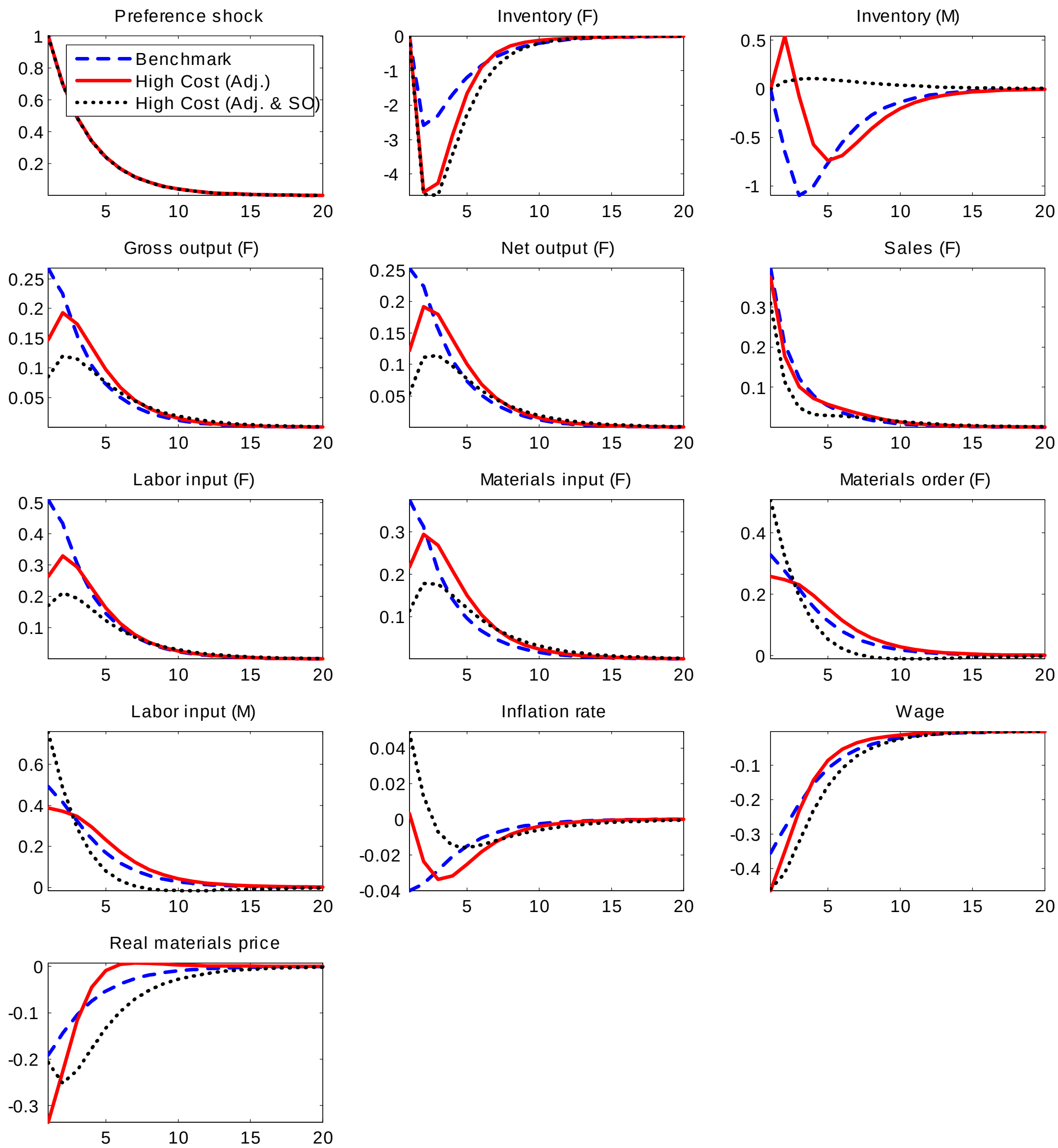

Figure 2. Impulse Responses to a Preference Shock: Benchmark Model

N.B.: dashed lines represent the responses computed using the benchmark parameters, solid lines represent the responses when high labor and materials input adjustment costs are turned on, dotted lines denote the responses when high labor and materials input costs are turned on and stock-out avoidance costs are high.

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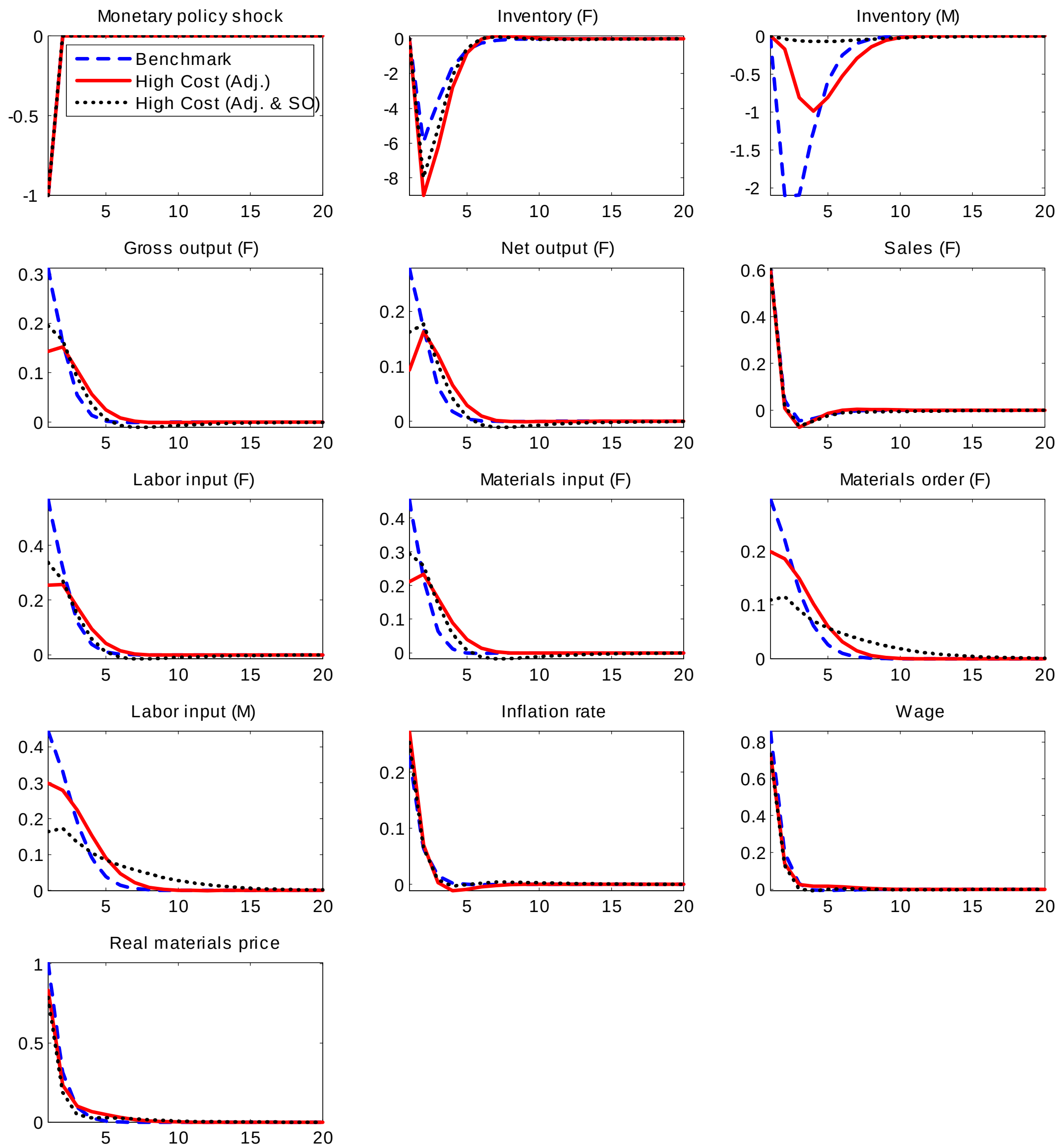

Figure 3. Impulse Responses to a Monetary Policy Shock: Benchmark Model

N.B.: dashed lines represent the responses computed using the benchmark parameters, solid lines represent the responses when high labor and materials input adjustment costs are turned on, dotted lines denote the responses when high labor and materials input costs are turned on and stock-out avoidance costs are high.

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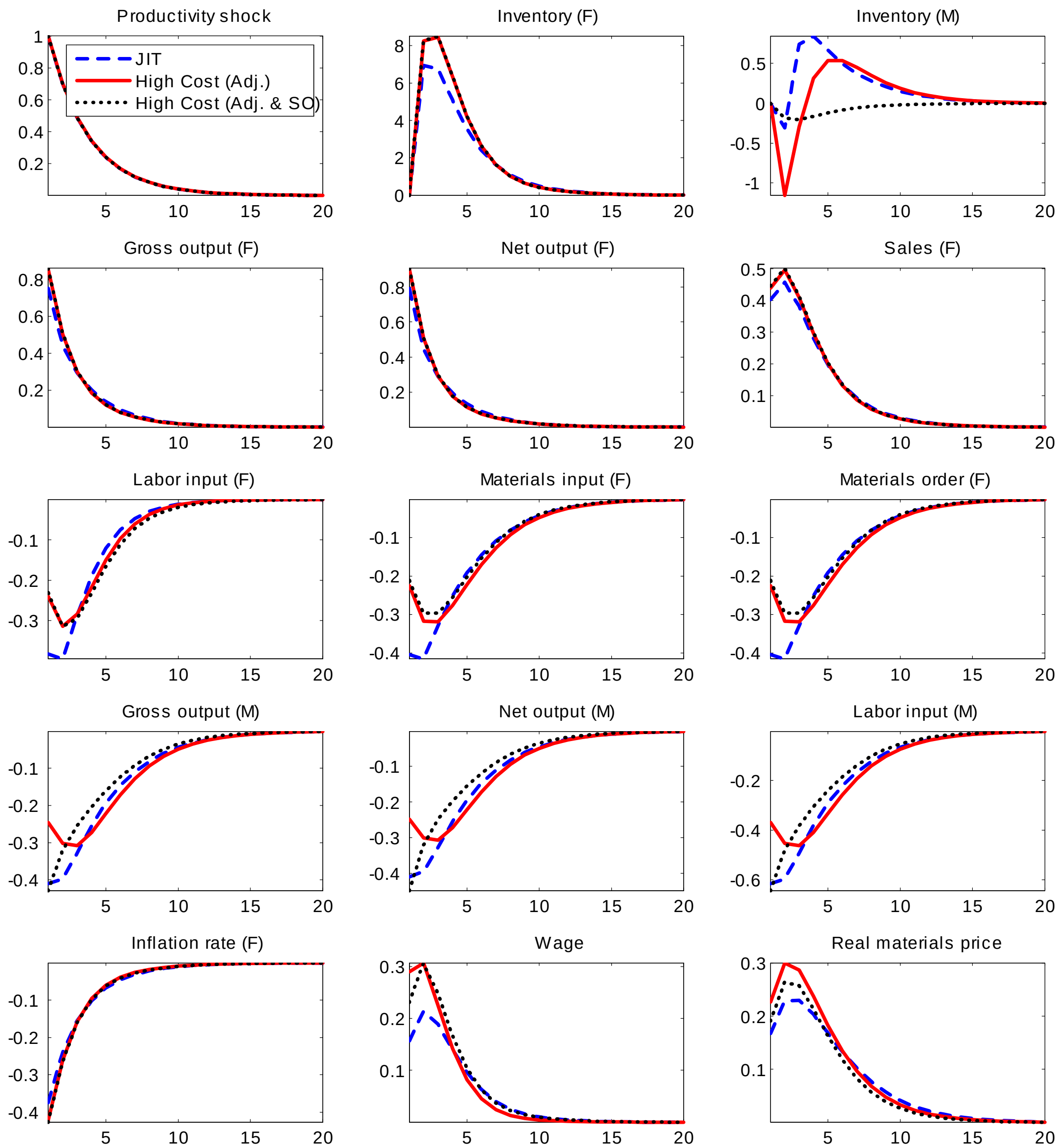

Figure 4: Impulse Responses to a Productivity Shock: JIT Model

N.B.: dashed lines represent the responses computed using the benchmark parameters, solid lines represent the responses when high labor and materials input adjustment costs are turned on, dotted lines denote the responses when high labor and materials input costs are turned on and stock-out avoidance costs are high.

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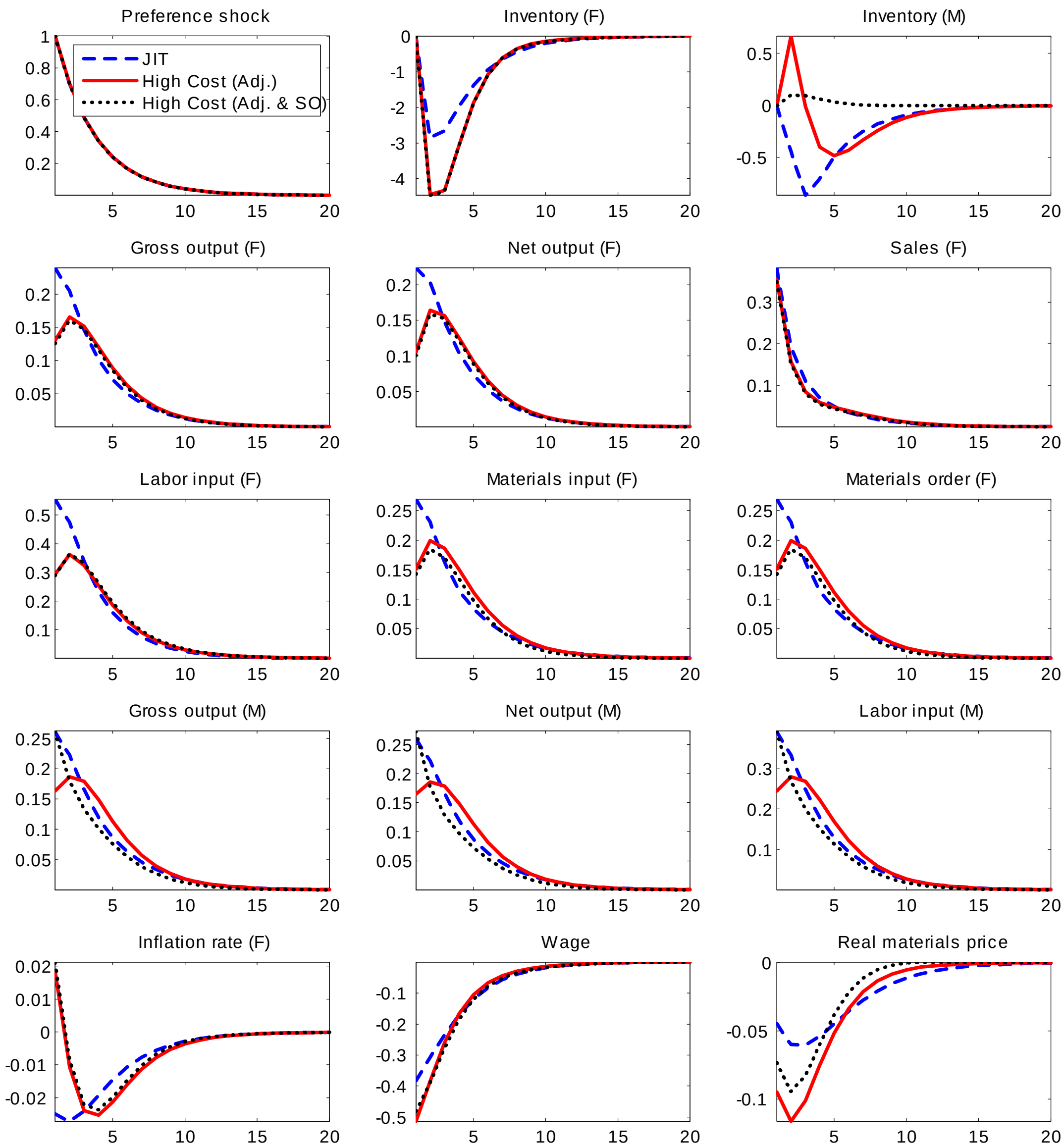

Figure 5: Impulse Responses to a Preference Shock: JIT Model

N.B.: dashed lines represent the responses computed using the benchmark parameters, solid lines represent the responses when high labor and materials input adjustment costs are turned on, dotted lines denote the responses when high labor and materials input costs are turned on and stock-out avoidance costs are high.

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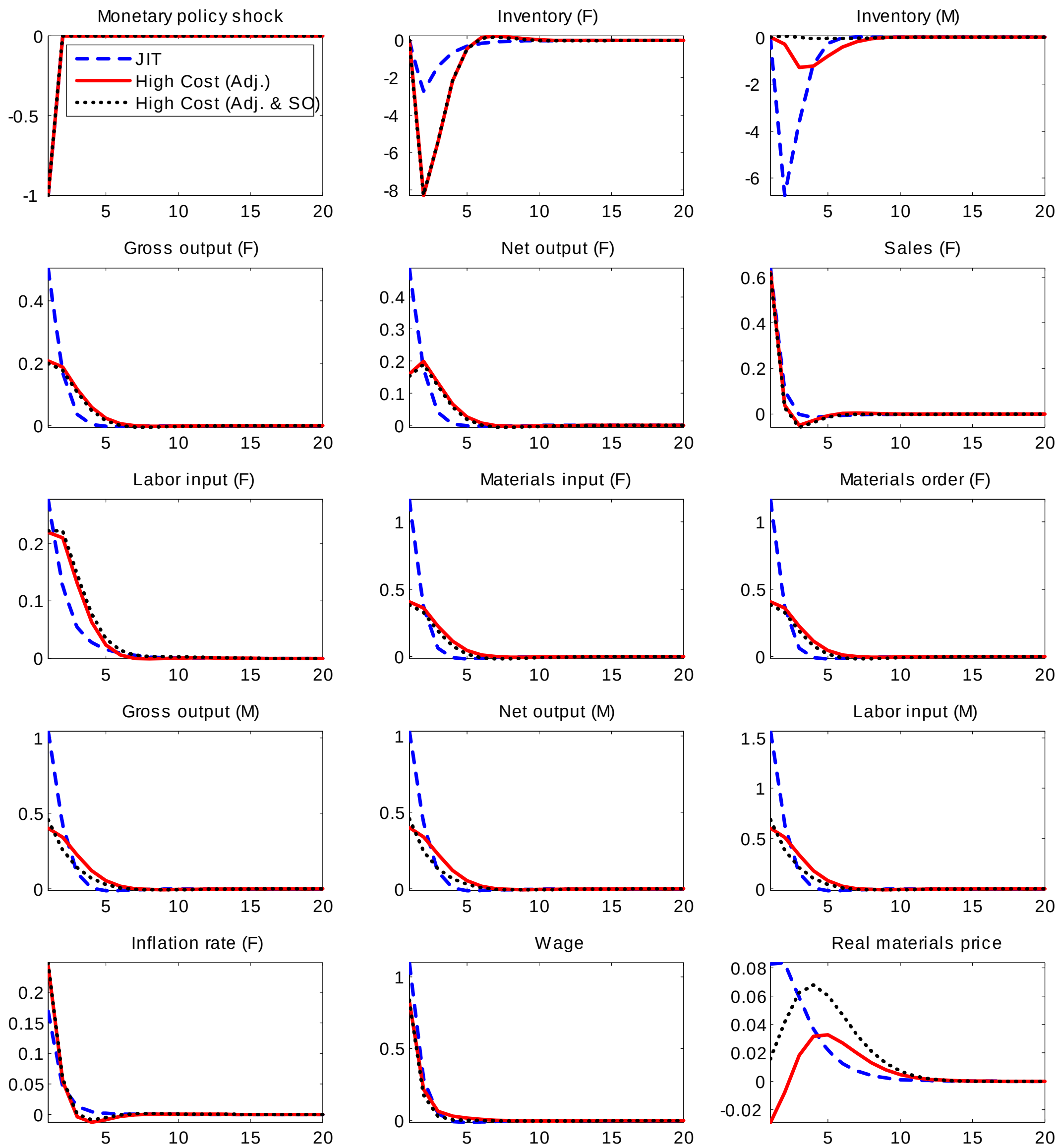

Figure 6: Impulse Responses to a Monetary Policy Shock: JIT Model

N.B.: dashed lines represent the responses computed using the benchmark parameters, solid lines represent the responses when high labor and materials input adjustment costs are turned on, dotted lines denote the responses when high labor and materials input costs are turned on and stock-out avoidance costs are high.

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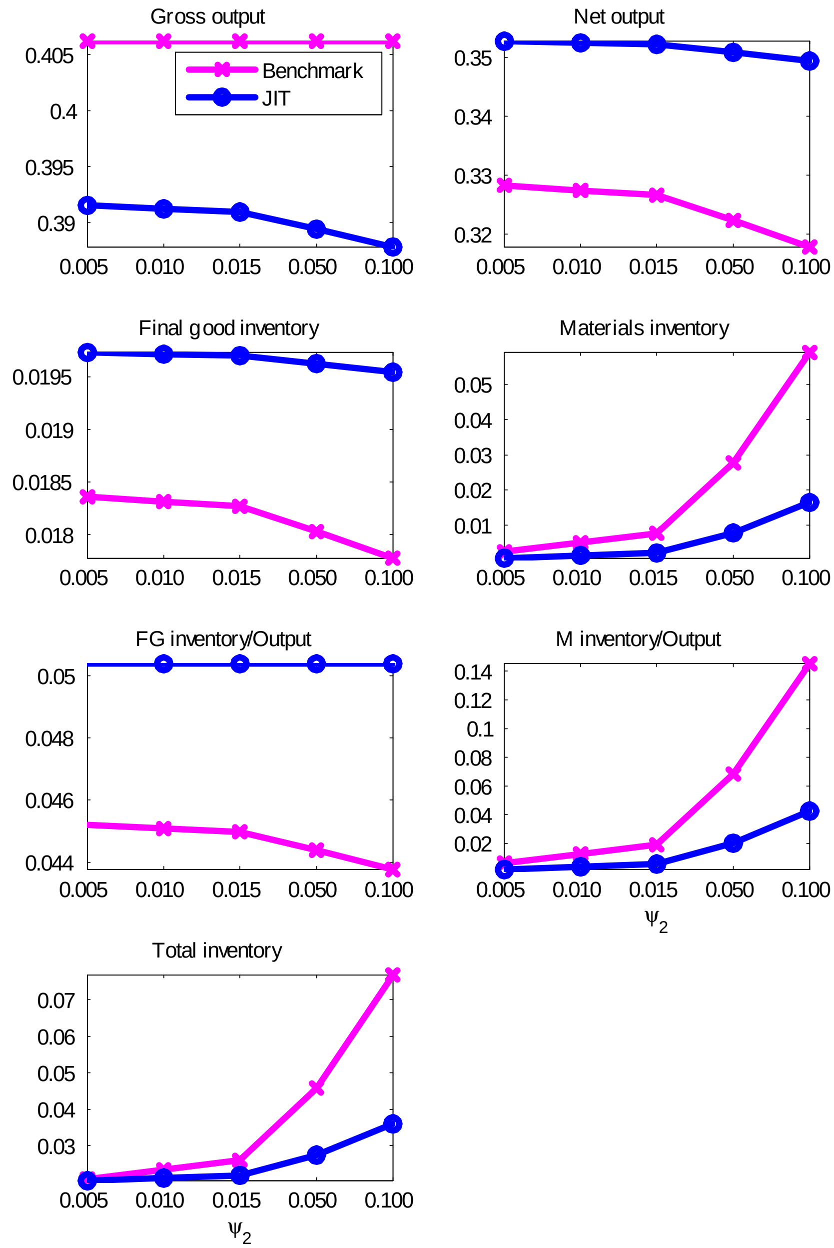

Figure 7: Steady State Values for Different ψ_2