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Lumpy investment in sticky information general equilibrium

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Lumpy Investment in

Sticky Information General Equilibrium *

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Abstract

In this paper, I introduce lumpy micro-level capital adjustment into a sticky information general equilibrium model. Lumpy adjustment arises because of inattentiveness in capital investment decisions instead of the more common assumption of non-convex adjustment costs. The model features inattentiveness as the only source of stickiness. I find that the model with lumpy investment yields business cycle dynamics which differ substantially from those of an otherwise identical model with frictionless investment and are much more consistent with the empirical evidence. These results therefore strengthen the case in favour of the relevance of microeconomic investment lumpiness for the business cycle.

Keywords: sticky information, general equilibrium, lumpy investment, business cycle

JEL classification: D83, E10, E22, E32

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1 Introduction

Figure 1 plots output and investment over the US business cycle. The figure shows that aggregate investment is strongly procyclical, very persistent and much more volatile than output. Underlying such smooth aggregate investment dynamics, however, are infrequent and large, or lumpy, capital adjustments at the microeconomic level. Doms and Dunne (1998) show that about 50 % of an average plant's cumulative investment in a 15-year period is concentrated over a period of two to three (contiguous) years.

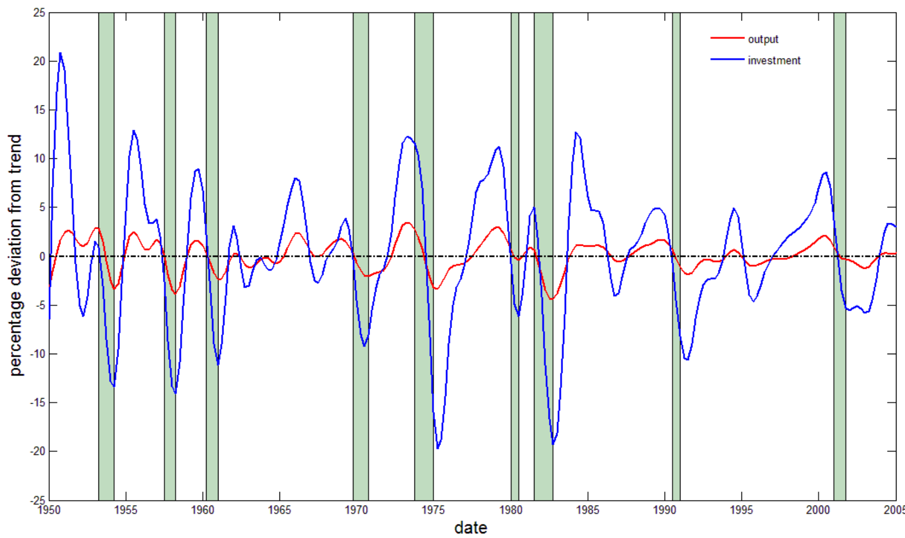

Figure 1: Output and investment over the US business cycle

Note. The figure displays detrended quarterly real GDP and real private domestic investment in the United States over the period from 1950 to 2005. The trends have been computed using the Baxter-King bandpass filter. Red line: output. Blue line: investment. Grey bars denote NBER recessions.

The volatility of investment is a prime contributor to aggregate fluctuations. According to Barro (1997, Table 9.1), private investment accounts for about 93 % of the fluctuations in GDP, and thus "as a first approximation, explaining recessions amounts to explaining the sharp contractions in the private investment components."[1] Notwithstanding the importance of investment in explaining the business cycle (as well as,

[1] Barro's findings are derived from an analysis of the role of investment during five US recessions (namely, those ending in 1961Q1, 1970Q4, 1975Q1, 1982Q4 and 1991Q4).

obviously, in determining long-term economic growth), capital accumulation has been somewhat ignored in canonical versions of the New Keynesian model (see *e.g.* Gali, 2008). However, standard dynamic stochastic general equilibrium (DSGE) models do now feature endogenous capital accumulation (see *e.g.* Levin et al., 2005 and Smets and Wouters, 2007).

Nevertheless, the development of a sound micro-founded model which is able to explain aggregate investment dynamics has been keeping economists busy for years. Standard DSGE models introduce convex investment adjustment costs to reproduce smooth aggregate investment dynamics. In doing so, however, the lumpy nature of plant-level investment is simply brushed away and the micro-foundations of these models for investment behaviour therefore seem rather weak. Some researchers (see *e.g.* Caballero, 1999) try to reconcile this apparent inconsistency by suggesting that such smooth aggregate dynamics may result from the aggregation of asynchronous and lumpy micro-level capital adjustments, which can be easily generated by non-convex (*i.e.* fixed) adjustment costs. In fact, recent micro-founded lumpy investment models (see *e.g.* Khan and Thomas, 2008) provide a good description of aggregate investment.

An important debate running through recent general equilibrium literature is that on the question as to whether micro-level lumpy capital adjustments have important implications for business cycle dynamics. The origin of the debate concerning the (ir)relevance of lumpy investment for aggregate dynamics dates back to Thomas (2002). Previously, partial equilibrium state-dependent lumpy investment models (Caballero et al., 1995, Doms and Dunne, 1998, Caballero and Engel, 1999, Cooper et al., 1999 and Doyle and Whited, 2001) had stressed important amplification and propagatory effects arising from infrequent plant-level investment activities. Thomas (2002) reassessed the impact of lumpy micro-level investment in a general equilibrium framework and concluded that firm-level investment lumpiness does not play an important role for aggregate dynamics. In fact, her lumpy investment model generates business cycle dynamics that are similar to those generated by an otherwise identical model characterised by frictionless investment. According to Thomas (2002, page 508), the irrelevance result arises from the fact that "in general equilibrium, households' preference for relatively smooth consumption profiles offsets changes in aggregate investment demand implied by the introduction of lumpy plant-level investment." Subsequently Gourio and Kashyap (2007), among others, contested Thomas' findings, claiming that lumpy investment is relevant for aggregate fluctuations. In fact, they recalibrated Thomas' model and found that the recalibrated model has properties that differ from those of the standard real business cycle model. This result led them to conclude that the irrelevance result does not stem solely from general equilibrium effects, but is also dependent on the calibration of the model. Currently, there are a number of other studies that support either the relevance or the irrelevance result.[2]

Against this background, this paper evaluates the aggregate significance of lumpy investment in a sticky information DSGE framework. In a related paper, Verona (2013), I demonstrate that time-dependent lumpy capital adjustments arise naturally when a firm faces costs of gathering and processing information. I first show that inattentiveness is the optimal response to such information costs: the firm chooses to update its information and plans only sporadically on optimally chosen dates, and to be inattentive to new information in between adjustment dates. In particular, the firm undertakes small maintenance investment (to compensate for depreciation) when acting inattentively, whereas the stock of capital jumps to its optimal level when the firm updates its information. It is therefore likely to observe large adjustments at those planning dates. I then find that such a partial equilibrium model is successful in fitting quantitative facts on plant-level investment rates.

In this paper, I embed that theoretical framework into the sticky information general equilibrium (SIGE) model developed by Mankiw and Reis (2006, 2007). Specifically, I augment the SIGE model with a set of firms that make capital investment decisions in an inattentive manner. In the capital-augmented version of the SIGE model, inattentiveness is the only source of stickiness and it is pervasive to all decisions: consumption, wages, prices and capital investment decisions are all based, to a certain degree, on outdated information.

This paper consequently provides two main contributions.

First, incorporating lumpy investment, which is consistently micro-founded on inattentiveness in capital investment decisions, into the SIGE model reconciles general equilibrium modelling with recent developments in the microeconomic theory of investment. Such a model allows a further contribution to be made to the debate on the (ir)relevance of lumpy investment for macroeconomic dynamics.

[2] Papers supporting the relevance result include Bayer (2006), Sveen and Weinke (2007), Iacoviello and Pavan (2007), Bachmann et al. (2013) and Fiori (2011). Khan and Thomas (2003, 2008) and House (2008) in turn provide additional evidence in favour of the irrelevance result. A similar irrelevance result has been obtained by Veracierto (2002), who analyses the role of plant-level irreversibilities in investment for aggregate fluctuations.

Second, enhancing the SIGE model by means of capital and investment overcomes one of its weaknesses, which was pointed out by Reis (2009b). Such an improvement narrows the gap between the sticky information DSGE approach and the workhorse sticky prices DSGE framework (*e.g.* Smets and Wouters, 2003 and Christiano et al., 2005), which has included capital and investment from the beginning. I therefore provide a fully fledged micro-founded DSGE model that relies on just one rigidity – inattentiveness – to mimic the inertia found in macroeconomic data, rather than on a large set of nominal and real rigidities as put forth by the sticky prices approach, *e.g.* staggered price and wage setting with partial indexation, habit persistence in consumption, investment (or capital) adjustment costs and variable capital utilization. Using the model, it is therefore possible to analyse how and to what extent inattentiveness alone shapes business cycle dynamics.[3]

The paper is organized as follows. Section 2 describes the capital-augmented sticky information general equilibrium (SIGEK) model, and Section 3 presents the key log-linearised equations. Section 4 analyses the business cycle implications of lumpy investment in general equilibrium and discusses the findings in the context of the previous literature. Finally, Section 5 concludes.

2 The capital-augmented sticky information general equilibrium model

There are three sets of agents: firms, households and the government.

Within the firms sector, there are two types of firms, intermediate and final-goods firms, and there is a continuum of each indexed by i and f, respectively, in the unit interval. Each of the monopolistic competitive intermediate-goods firms has two departments: an attentive hiring department, which decides on how much of each labour variety to hire, and an inattentive pricing department, which produces the intermediate good and chooses a plan for current and future prices for its good. Perfectly competitive final-goods firms also have two departments: the attentive purchasing department, which chooses how much of each variety of intermediate goods to buy, and the inattentive producing department, which produces the final good by combining its firm-specific capital with a Dixit-Stiglitz aggregator of varieties of intermediate goods. The producing department chooses a plan for current and future capital adjustments.

[3] Mackowiak and Wiederholt (2011) develop a DSGE model with rational inattention (by households and firms) *à la* Sims (2003).

Households are made up of consumers and workers and there is a continuum of each type of individual indexed by j and k, respectively, in the unit interval. Consumers consume, save and borrow by trading bonds between themselves. Each worker provides differentiated labour services to intermediate-goods firms. Both consumers and workers are inattentive and make optimal decisions only sporadically. In particular, consumers choose a plan for current and future consumption, and workers choose a plan for current and future wages.

Finally, monetary and fiscal policies follow exogenous rules and close the model.

Figure 2 sketches the structure of the model. In contrast to the original SIGE model, the SIGEK model features a new agent, the sector comprising competitive final-goods firms.[4] I will begin this section by describing the market clearing conditions and policy processes and then define the agents' problems.

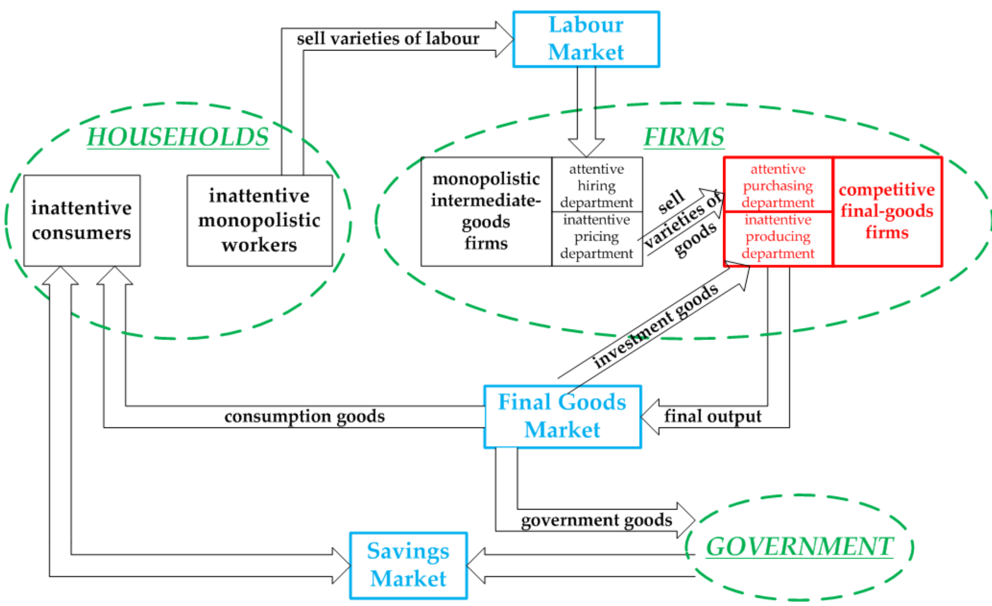

Figure 2: Structure of the model

[4] I separate final goods production from intermediate goods production for three main reasons. First, it is common to separate them so as to have the Dixit-Stiglitz aggregation occurring in production rather than in consumption and it is irrelevant which method is chosen. Second, the separation allows me to have an agent to be inattentive about the new decision, capital. Third, and more important, if prices and capital decisions are made within the same agent, then one possible problem is that if one obtains an estimate of the sticky information parameter related to those decisions, it will be hard to understand whether it is the pricing or the capital decision that is driving the estimation result.

2.1 Market clearing conditions and policy processes

The total output produced by final-goods firms, Y_t^{FIN}, is divided into consumption, investment and government goods. Market clearing in the final goods market requires that:

$$Y_t^{FIN} = G_t \left(C_t + INV_t \right) \quad , \tag{1}$$

where $1 - 1/G_t$ is the fraction of output consumed by the government, and $C_t = \int_0^1 C_{t,j} dj$ and $INV_t = \int_0^1 INV_{t,f} df$ represent total consumption of consumers and total investment of final-goods firms, respectively. Government consumption G_t is financed by lump-sum taxes to households that keep the budget balanced at all times. The fraction G_t is stochastic, and shocks to it can be interpreted as aggregate demand shocks. The central bank sets the nominal interest rate i_t according to:

$$i_t \equiv \log \left[E_t \left(\Pi_{t+1} P_{t+1} / P_t \right) \right] = \phi_\pi \log \left(\frac{P_t}{P_{t-1}} \right) - \varepsilon_t \quad , \tag{2}$$

where P_t denotes the price level, Π_{t+1} the real interest rate between t and $t+1$, and ε_t a discretionary monetary policy shock. The definition of the nominal interest rate follows the Fisher equation, whereas the nominal interest rate is set according to a Taylor-type rule which responds to inflation.

There is an intermediate goods market for each variety i, in which all final-goods firms f are buyers and the seller is the intermediate-goods firm which has the monopoly over its variety i . In equilibrium:

$$Y_{t,i}^{INT} = \int_0^1 Y_{t,f}^{INT} \left(i \right) df \quad , \tag{3}$$

where $Y_{t,i}^{INT}$ is the total production of intermediate good i at time t, and $Y_{t,f}^{INT}(i)$ is the demand by final-goods firm f of variety i at time t.

There is a labour market for each variety of labour k. Intermediate-goods firms i demand labour, which is supplied by the household k, which has the monopoly over its labour services. Market clearing requires:

$$L_{t,k} = \int_0^1 N_{t,i} \left(k \right) di \quad , \tag{4}$$

where $L_{t,k}$ is the total labour supply of variety k at time t, and $N_{t,i}(k)$ is the labour demand by the intermediate-goods firm i of variety k at time t. Total output and labour are defined by aggregating across all varieties: $Y_t^{FIN} = \int_0^1 Y_{t,f}^{FIN} df$ and $L_t = \int_0^1 L_{t,k} dk$.

Finally, nominal bonds are in zero net supply so the condition for the bond market to clear is $\int_0^1 B_{t,j} dj = 0$.

2.2 Final-goods firms

2.2.1 Attentive purchasing departments[5]

The purchasing department of the f-th firm buys a continuum of varieties i of intermediate goods in the amount $Y_{t,f}^{INT}(i)$ at price $P_{t,i}$, and combines them into a final input $Y_{t,f}$ according to a Dixit-Stiglitz aggregator with time-varying stochastic elasticity of substitution $\hat{v}_t$. Each department solves the following problem, with current prices and a total desired amount of inputs $Y_{t,f}$ being taken as given:

$$\min_{\left\{Y_{t,f}^{INT}(i)\right\}_{i\in[0,1]}} \quad \int_0^1 P_{t,i} Y_{t,f}^{INT}(i)\, di$$

$$\textit{subject to} \quad Y_{t,f} = \left[\int_0^1 Y_{t,f}^{INT}(i)^{\frac{\hat{v}_t-1}{\hat{v}_t}} di\right]^{\frac{\hat{v}_t}{\hat{v}_t-1}} .$$

Optimal behaviour implies that the demand for each variety i by firm f is $Y_{t,f}^{INT}(i) = Y_{t,f}\left[P_{t,i}/P_t\right]^{-\hat{v}_t}$, where $P_t = \left[\int_0^1 {P_{t,i}}^{1-\hat{v}_t} di\right]^{\frac{1}{1-\hat{v}_t}}$ is the aggregate price index. Integrating over the continuum of departments f and using the market clearing condition (3) gives the total demand for the intermediate-goods of variety i:

$$Y_{t,i}^{INT} = \left(\frac{P_{t,i}}{P_t}\right)^{-\hat{v}_t} Y_t \ , \tag{5}$$

where $Y_t \equiv \int_0^1 Y_{t,f} df$.

[5] The problem solved by these agents is equivalent to the problem of final-goods firms in standard DSGE models (see *e.g.* Smets and Wouters, 2003).

2.2.2 Inattentive producing departments

The final good is the composite of two inputs, a homogeneous input Y_t, resulting from a Dixit-Stiglitz aggregator of varieties of intermediate goods, and the installed firm-specific capital, $K_{t-1,f}$. The producing department of the f-th firm produces the final good $Y_{t,f}^{FIN}$ according to the following technology:

$$Y_{t,f}^{FIN} = Z_t Y_t^{1-\alpha} K_{t-1,f}^{\alpha} \quad , \tag{6}$$

where $\alpha < 1$ represents the share of capital in the firm's production function and Z_t an aggregate productivity shock. The timing in (6) implies that capital becomes productive with a one-period delay. As in Verona (2013), I assume that the firm can buy or sell capital instantly and without any adjustment costs, at a constant price normalised to one. When the price of capital is constant, the Jorgensonian user cost of capital (*i.e.* the opportunity cost of holding one unit of capital for a period) is simply the sum of the discount rate of the firm and the depreciation rate.

Let me consider the problem faced by the producing department that last updated its information τ periods ago. Following the SIGE tradition, I assume that, in each period, a fraction η of departments, randomly drawn from the population, update their information, so there are $\eta (1-\eta)^{\tau}$ departments in this situation.[6] Each of these departments chooses the stock of capital $K_{t,\tau}$ to maximise expected real profits:

$$\max_{K_{t,\tau}} \qquad E_{t-\tau}\left[Y_{t,\tau}^{FIN} - (\Pi_t + \rho) K_{t-1,\tau}\right]$$

$$\textit{subject to} \qquad Y_{t,\tau}^{FIN} = Z_t Y_t^{1-\alpha} K_{t-1,\tau}^{\alpha} \qquad ,$$

where ρ is the real depreciation rate and $(\Pi_t + \rho)$ represents the user cost of capital. The first-order condition is

$$E_{t-\tau}\left[\alpha Z_{t+1} Y_{t+1}^{1-\alpha} K_{t,\tau}^{\alpha-1}\right] = E_{t-\tau}\left(\Pi_{t+1} + \rho\right) \quad .$$

If the firm observed all variables, this condition would state that the firm accumulates capital up to the point

[6] Bernoulli's method for modelling investment lumpiness was originally proposed by Kiyotaki and Moore (1997).

where the marginal product of capital equals the user cost of capital. After some rearrangements, the desired stock of capital becomes

$$K_{t,\tau} = \left[E_{t-\tau}\left(\frac{\Pi_{t+1}+\rho}{\alpha}\right)\right]^{-\frac{1}{1-\alpha}} \left[E_{t-\tau}\left(Z_{t+1}Y_{t+1}^{1-\alpha}\right)\right]^{\frac{1}{1-\alpha}} \quad . \tag{7}$$

To attain the stock $K_{t,\tau}$ in period $t+1$, the firm demands the quantity $INV_{t,\tau}$ of the final good in period t given by

$$INV_{t,\tau} = K_{t,\tau} - (1-\rho) K_{t-1,\tau} \quad . \tag{8}$$

2.3 Intermediate-goods firms

2.3.1 Attentive hiring departments[7]

Each of the intermediate-goods firms has a department that hires a continuum of labour varieties in the amount $N_{t,i}(k)$ at price $W_{t,k}$. Labour services are combined into the labour input $N_{t,i}$ according to a Dixit-Stiglitz function with time-varying stochastic elasticity of substitution $\hat{\gamma}_t$. The hiring department of the i-th firm solves the following problem, with current wages and a total desired amount of inputs $N_{t,i}$ being taken as given:

$$\begin{aligned} &\min_{\{N_{t,i}(k)\}_{k\in[0,1]}} && \int_0^1 W_{t,k} N_{t,i}(k)\, dk \\ &\textit{subject to} && N_{t,i} = \left[\int_0^1 N_{t,i}(k)^{\frac{\hat{\gamma}_t-1}{\hat{\gamma}_t}}\, dk\right]^{\frac{\hat{\gamma}_t}{\hat{\gamma}_t-1}} \quad . \end{aligned}$$

The solution to this problem is $N_{t,i}(k) = N_{t,i}\left(W_{t,k}/W_t\right)^{-\hat{\gamma}_t}$, where $W_t = \left[\int_0^1 W_{t,k}{}^{1-\hat{\gamma}_t} dk\right]^{\frac{1}{1-\hat{\gamma}_t}}$ is the aggregate wage index. Summing over all firms i and using the market clearing condition (4) gives the total demand for labour of variety k:

$$L_{t,k} = \left(\frac{W_{t,k}}{W_t}\right)^{-\hat{\gamma}_t} N_t \quad , \tag{9}$$

where $N_t \equiv \int_0^1 N_{t,i} di$.

[7] This agent is equivalent to the "employment agency" typically introduced in the DSGE literature (see *e.g.* Erceg et al., 2000).

2.3.2 Inattentive pricing departments

Let me now consider the problem faced by the pricing department of an intermediate-good firm that last updated its information τ periods ago. In each period, a randomly drawn fraction of departments λ update their information, so there are $\lambda (1-\lambda)^{\tau}$ departments in this situation. They choose a nominal price $P_{t,\tau}$ to maximise expected real profits:

$$\max_{P_{t,\tau}} \quad E_{t-\tau}\left[\frac{P_{t,\tau}Y_{t,\tau}^{INT}}{P_t} - \frac{W_t N_{t,\tau}}{P_t}\right]$$

$$\textit{subject to} \qquad Y_{t,\tau}^{INT} = A_t N_{t,\tau}^{\beta} \tag{10}$$

$$Y_{t,\tau}^{INT} = \left(\frac{P_{t,\tau}}{P_t}\right)^{-\hat{v}_t} Y_t$$

Equation (10) is the production function, where β measures the degree of returns to scale and productivity A_t is stochastic. The second constraint is the total demand for the firm's product in (5). The first order condition is:

$$P_{t,\tau} = \frac{E_{t-\tau}\left[\hat{v}_t W_t N_{t,\tau}/P_t\right]}{E_{t-\tau}\left[\beta\left(\hat{v}_t - 1\right) Y_{t,\tau}^{INT}/P_t\right]} \quad . \tag{11}$$

If the firm observed all the variables on the right-hand side, this condition would state that the nominal price charged is a mark-up, $\hat{v}_t/\left(\hat{v}_t - 1\right)$, over nominal marginal costs, which correspond to the cost of an extra unit of labour, W_t, divided by its marginal product, $\beta Y_{t,\tau}^{INT}/N_{t,\tau}$.

2.4 Households

Households live forever and discount future utility by a factor $\xi \in (0,1)$. They obtain utility in each period from consumption and leisure according to:

$$U\left(C_{t,j}, L_{t,k}\right) = \ln C_{t,j} - \frac{\chi L_{t,k}^{1+1/\psi}}{1+1/\psi} \quad ,$$

where $C_{t,j}$ is consumption by consumer j at date t, $L_{t,k}$ is the labour supplied by worker k on date t, ψ is the Frisch elasticity of labour supply and χ captures relative preferences for consumption versus leisure.

On each date t, the household faces the following budget constraint:

$$A_{t+1} = \Pi_{t+1} \left(A_t - C_{t,j} + \frac{W_{t,k} L_{t,k} + T_t}{P_t} \right) \ ,$$

where A_t denotes the real wealth at the beginning of period t and T_t are lump-sum transfers. These transfers comprise the profits received from intermediate-goods firms, lump-sum taxes paid to the government and payments for an insurance contract that households sign at the beginning of each period so that they begin each period with the same wealth.

In the savings market, consumers face a probability δ of revising their plans every period, which means that in each period there are $\delta (1-\delta)^{\tau}$ of consumers in this situation. They choose a plan for current and future consumption, $\{C_{t+\tau,\tau}\}_{\tau=0}^{\infty}$, where $C_{t,\tau}$ is the time-t expenditure of a consumer who last updated her information τ periods ago. The optimality conditions for consumers are:[8]

$$\frac{1}{C_{t,0}} = \xi E_t \left[\Pi_{t+1} \frac{1}{C_{t+1,0}} \right] \tag{12}$$

and

$$\frac{1}{C_{t,\tau}} = E_{t-\tau} \left[\frac{1}{C_{t,0}} \right] \ .$$

The first equation is the Euler equation for an attentive consumer. It states that the marginal utility of consuming today equals the expected discounted return on savings multiplied by the marginal utility of consuming tomorrow. The second equation states that the marginal utility of consumption for inattentive consumers is equal to the marginal utility they would expect if full information were available.

In the labour market, a randomly drawn fraction of workers ω update their plans each period, so that in each period there are $\omega (1-\omega)^{\tau}$ of workers in this situation. They choose a plan for current and future wages, $\{W_{t+\tau,\tau}\}_{\tau=0}^{\infty}$, where $W_{t,\tau}$ is the time-t wage set by a worker who last updated her information τ periods ago.

[8] The dynamic problem solved by consumers and workers is more complicated than those solved by firms. I refer the reader to Verona (2011, Appendix A) for details.

The optimality conditions for workers are:

$$\frac{\hat{\gamma}_t}{\hat{\gamma}_t - 1}\frac{P_t L_{t,0}^{1/\psi}}{W_{t,0}} = \xi E_t \left[\Pi_{t+1}\frac{\hat{\gamma}_{t+1}}{\hat{\gamma}_{t+1} - 1}\frac{P_{t+1} L_{t+1,0}^{1/\psi}}{W_{t+1,0}}\right] \tag{13}$$

and

$$W_{t,\tau} = \frac{E_{t-\tau}\left[\hat{\gamma}_t L_{t,\tau}^{1+1/\psi}\right]}{E_{t-\tau}\left[\hat{\gamma}_t L_{t,\tau} L_{t,0}^{1/\psi}/W_{t,0}\right]} \quad .$$

The first equation is the intertemporal labour supply Euler equation for an attentive worker. If $\hat{\gamma}_t$ were constant, the equation would state that the marginal disutility of supplying labour today ($L_{t,0}^{1/\psi}$) divided by the real wage ($W_{t,0}/P_t$) is equal to the discounted real interest rate multiplied by the marginal disutility of working tomorrow ($L_{t+1,0}^{1/\psi}$) divided by the corresponding real wage ($W_{t+1,0}/P_{t+1}$). With a time-varying $\hat{\gamma}_t$, the Euler equation takes into account the change in the mark-up charged by monopolistic workers. The second condition states that inattentive workers set wages so that their expected disutility from working equals the disutility from working expected by attentive workers.

3 The sticky information equilibrium

The detailed presentation of the model log-linearisation is presented in Verona (2011, Appendix A). In this section I discuss the key reduced-form relations. I log-linearise the equilibrium conditions around the non-stochastic steady state. Lower case variables denote the log-deviations of the respective upper case variable from this steady state, with the exceptions of: v_t and γ_t, which are the log-deviations of $\hat{v}_t$ and $\hat{\gamma}_t$, respectively; r_t, which is the log-deviation of the short real interest rate $E_t\left[\Pi_{t+1}\right]$; and R_t, which is the log-deviation of the long real interest rate defined as $\lim_{T\to\infty} E_t\left[\bar{\Pi}_{t,t+1+T}\right]$, where $\bar{\Pi}_{t+l,t+1+k} = \prod_{z=t+l}^{t+k}\Pi_{z+1}$ is the compound return between two dates. Lower case letters with no subscript denote parameters or steady-state values.

The aggregate capital stock is:

$$k_t = \eta\sum_{\tau=0}^{\infty}(1-\eta)^{\tau} E_{t-\tau}\left[\frac{1}{1-\alpha}y_{t+1}^{FIN} - \frac{\alpha}{1-\alpha}k_t - \frac{r}{(r+\rho)(1-\alpha)}r_t\right] \quad . \tag{14}$$

The three determinants of the stock of capital (k_t) are split into the three terms on the right-hand side. First, higher expected future output (y_{t+1}^{FIN}) increases the current stock of capital. Second, the higher the current level of capital stock, the lower the capital stock accumulated today because of decreasing return to scale in production ($\alpha < 1$). Third, the lower the real interest rate (r_t), the lower the opportunity cost of holding capital and, therefore, the higher the incentive to increase the stock of capital. If many firms are informed (η is high), capital is instantly responsive to changes in these determinants, whereas, otherwise, capital adjusts gradually over time.

Aggregate investment (inv_t) is:

$$inv_t = \frac{1}{\rho} k_t - \frac{1-\rho}{\rho} k_{t-1} \quad . \tag{15}$$

The Phillips curve is:

$$p_t = \lambda \sum_{\tau=0}^{\infty} (1-\lambda)^{\tau} E_{t-\tau} \left[p_t + \frac{\beta (w_t - p_t) + (1-\beta) y_t - a_t}{\beta + v(1-\beta)} - \frac{\beta}{(v-1)[\beta + v(1-\beta)]} v_t \right] \quad . \tag{16}$$

This equation notes that the price level (p_t) depends on past expectations of its current value, real marginal costs and the desired mark-up. Real marginal costs are higher with (i) higher real wages paid to workers ($w_t - p_t$), (ii) higher output (y_t), because of decreasing returns to scale ($\beta < 1$), and (iii) lower productivity (a_t). The desired mark-up increases whenever the elasticity of substitution across the goods varieties (v_t) decreases. The higher the value of λ, the greater the number of informed price-setting firms that respond immediately to shocks.

The IS curve is:

$$c_t = \delta \sum_{\tau=0}^{\infty} (1-\delta)^{\tau} E_{t-\tau} (c_t^n - R_t) \quad , \tag{17}$$

where $c_t^n = \lim_{\tau \to \infty} E_t c_{t+\tau}$ is a measure of consumers' wealth and $R_t = \sum_{\tau=0}^{\infty} (i_{t+\tau} - \Delta p_{t+1+\tau})$ is the long real interest rate. Higher expected future wealth encourages current consumption, while higher expected interest rates encourage savings and therefore postpone consumption. Unexpected shocks to any of these variables only raise current consumption by δ because only this fraction of consumers is aware of the news.

The wage curve is:

$$w_t = \omega \sum_{\tau=0}^{\infty} (1-\omega)^{\tau} E_{t-\tau} \left[p_t + \frac{\gamma}{\gamma+\psi}(w_t - p_t) + \frac{l_t}{\gamma+\psi} + \frac{\psi}{\gamma+\psi}(c_t^n - R_t) - \frac{\psi}{(\gamma+\psi)(\gamma-1)}\gamma_t \right] \quad . \tag{18}$$

Current wages (w_t) are higher: (i) the higher the price level is, since workers care about real wages, (ii) the higher real wages are in the economy as these push up the demand for a particular labour variety through substitution, (iii) with higher employment (l_t), because of an increasing marginal disutility of working, (iv) with higher wealth, because of the income effect, (v) with lower interest rates, since the return on savings is lower and the incentive to work in order to save is also lower, and (vi) the lower the elasticity of substitution across labour varieties (γ_t) is, since the desired mark-up of workers is then higher. As ω increases, many workers are informed, so wages become more responsive to changes in these determinants.

The aggregate resource constraint is

$$y_t^{FIN} = \alpha_c c_t + \alpha_i inv_t + g_t \quad , \tag{19}$$

where $\alpha_c = c/(c+inv)$ and $\alpha_i = inv/(c+inv)$.

The policy rules are

$$r_t = i_t - E_t(\Delta p_{t+1}) \tag{20}$$

and

$$i_t = \phi_\pi \Delta p_t - \varepsilon_t \quad . \tag{21}$$

Finally, intermediate output and labour are given by

$$y_t = \frac{y_t^{FIN} - z_t - \alpha k_{t-1}}{1-\alpha} \tag{22}$$

and

$$l_t = \frac{y_t - a_t}{\beta} \quad , \tag{23}$$

respectively.

Equations (14) to (23) characterise the equilibrium for y_t^{FIN} (final output), c_t (consumption), w_t (wages), p_t (prices), inv_t (investment), k_t (stock of capital), r_t (real interest rate), i_t (nominal interest rate), y_t (intermediate output) and l_t (labour) given exogenous shocks to ε_t (monetary policy), Δa_t (aggregate intermediate-goods productivity growth), g_t (aggregate demand), v_t (intermediate-goods mark-up), γ_t (labour mark-up) and z_t (aggregate final-goods productivity). Each of these shocks follows an independent $AR(1)$ process: $\varepsilon_t = \rho_\varepsilon \varepsilon_{t-1} + e_t^\varepsilon$, $\Delta a_t = \rho_{\Delta a} \Delta a_{t-1} + e_t^{\Delta a}$, $g_t = \rho_g g_{t-1} + e_t^g$, $v_t = \rho_v v_{t-1} + e_t^v$, $\gamma_t = \rho_\gamma \gamma_{t-1} + e_t^\gamma$ and $z_t = \rho_z z_{t-1} + e_t^z$, where the shocks $e_t^s \sim N\left(0\,,\,\sigma_s^2\right)$ are i.i.d. with $E\left[e_t^s e_{t+k}^s\right] = 0$ for $k \neq 0$ and $E\left[e_t^s e_t^{s'}\right] = 0$ for $s \neq s'$.

For the purpose of this study, I calibrate the model assuming that the length of a period corresponds to one quarter. The key parameter is that driving the degree of inattentiveness in capital decisions η, which is set to 0.1. This value lies within the empirically plausible range for the lumpiness parameter indicated by Sveen and Weinke (2007) and implies that final-goods firms are, on average, inattentive for ten quarters.[9] The share of consumption in total output α_c is assumed to be 0.85 and, accordingly, the share of investment is $\alpha_i = 1 - \alpha_c = 0.15$. The steady-state real depreciation rate and real interest rate, ρ and r, are set to 0.035 and 0.01, respectively, which implies a user cost of capital of 18 % per year, which is in line with the value used by Abel and Eberly (2005). The share of capital in the final-goods firm's production function α is assumed to be 0.33. The serial correlation and the standard deviation of the final-goods productivity shock, ρ_z and σ_z, are set to 0.75 and 0.5, respectively. The values for the remaining parameters are taken from Table 2 in Reis (2009b) and have been obtained from the estimation of the SIGE model on post-1986 US data. Table 3 summarises the baseline parameterisation for the SIGEK model.

4 Lumpy investment and the business cycle

Having presented the model's key relations, I now study the impact of lumpy micro-level investment on the business cycle. In this section, I analyse and contrast the dynamic behaviour of four models:

1. the SIGEK model with pervasive inattentiveness (also called the lumpy investment model);

[9] After analysing the micro evidence reported by Doms and Dunne (1998), Sveen and Weinke (2007) suggest that η should take values between 0.06 and 0.12.

2. the SIGEK model with frictionless investment, which is obtained setting η to 1;
3. the SIGEK model when all agents are attentive, which is obtained by setting $\eta = \lambda = \omega = \delta = 1$ (also called the classical model since there are no rigidities in this model economy);
4. the Mankiw and Reis SIGE model.

Before analysing the results, let me recall that Thomas' irrelevance conclusion arises from the fact that, in her model, business cycle dynamics (impulse responses and second moments) are virtually indistinguishable between an economy with non-convex capital adjustment costs and one with frictionless investment. Accordingly, a comparison of the first two models allows me to gauge the role of lumpy investment consistently micro-founded on inattentiveness in shaping the business cycle. Model 3 is used here as the simplest benchmark with which all models with some source of informational inertia could be compared. Finally, comparing the results from model 1 with those from model 4 allows for assessing whether the inclusion of capital and investment in the original SIGE model modifies the performance of the sticky information general equilibrium approach.[10,11]

In what follows, I first analyse the impulse responses to the various structural shocks and then investigate the models' ability to match some second-order moments of US aggregate data.

4.1 Impulse response functions

Figures 5 to 10 plot the impulse response functions to one-standard-deviation impulses to the six shocks. In all the figures presented, variables are reported as a percentage deviation from their steady-state values and the horizontal axis represents time on a quarterly scale. Blue-circle and blue-diamond lines represent the responses of models 1 and 2, respectively, while red-cross lines represent the responses of model 4. For the sake of clarity, I do not report the impulse responses of the classical model, which are far too large and

[10] All simulations were conducted with Dynare version 4 using the procedure described in Verona and Wolters (2013). The results for the SIGE model were obtained by simulating the Reis (2009a) model using the calibration in Table 3. In order to make the results comparable with those of other models, the simulation of the SIGE model was conducted by setting $\alpha_y = 0$ in the monetary policy rule, *i.e.* by dropping the interest rate response to the output gap, so that the nominal interest rate only responds to inflation.

[11] I leave the task of comparing the SIGEK model with other DSGE models (*e.g.* Smets and Wouters, 2007, Khan and Thomas, 2008 and Mackowiak and Wiederholt, 2011) for future research.

essentially have no persistence. I first describe the dynamics of model 1 and then compare these with the dynamics of the other models.

Figure 5 plots the effects of a positive (expansionary) monetary policy shock. The SIGEK model predicts that, in the short run, output, consumption, investment, capital, hours worked, real wages and inflation all increase in response to a monetary expansion, and then they converge rapidly to their steady-state levels. The fast reaction of macroeconomic variables to monetary policy is due to the fact that the policy shock is short-lived ($\rho_\varepsilon = 0.29$).

Figure 6 shows the effects of a positive wage mark-up shock (which corresponds to a fall in the desired mark-up). Real wages decrease and there is an expansion in output, hours worked, consumption and investment. The fall in wages induces a drop in prices, with the result that inflation declines and the central bank cuts the nominal interest rate to gradually push inflation back to its steady-state value. Noticeably, the responses of most variables are hump-shaped and delayed. Figure 7 displays the effects of a positive intermediate-goods mark-up. The shock makes the economy more competitive (the desired price mark-up decreases) and inflation consequently falls, while output, consumption and investment increase on impact. As for the policy shock, all variables respond quickly because the goods mark-up shock is also quite short-lived ($\rho_\nu = 0.28$).

Turning to the aggregate demand (government spending) shock, Figure 8 shows that a positive innovation to aggregate demand increases inflation, output and hours worked. While increasing investment significantly, this shock has a negative wealth effect that causes consumption to fall.

Figure 9 displays the responses to a positive intermediate-goods productivity shock. By construction, this technology shock has a permanent impact on output, consumption, investment and real wages. Finally, Figure 10 displays the responses to a positive final-goods productivity shock. Although the effect of this shock is transitory, the dynamics are qualitatively similar to those of the intermediate-goods productivity shock.

For the purpose of this study, it is worth noting that there are visible differences between the responses of the model with frictionless investment and those of the model with lumpy investment. In particular, the main quantitative difference is that the responses of some variables, especially those of capital and investment, are much larger when attentive final-goods firms make their capital investment decisions every period, as they react instantly to the shocks. More specifically, and in contrast to Thomas' findings, the impulse response analysis indicates that lumpy investment may be relevant for business cycle dynamics.

Figures 5 to 9 also report the impulse responses of the SIGE model. Overall, the dynamics do not change significantly when the SIGE model is augmented by a micro-founded lumpy investment model. The impulse responses of the SIGE model are, in fact, qualitatively, and, in most cases, also quantitatively similar to those of the SIGEK model with pervasive inattentiveness.

4.2 Second moments: models versus US aggregate data

I now examine whether the models yield empirically reasonable aggregate dynamics by comparing their predictions with some second-order moments characterising the post-1986 US economy. In particular, I focus on the volatility and autocorrelations of output, investment, consumption, hours, real wages and inflation, as well as on the cross-correlation of output with the other variables.[12,13]

Panel A in Table 1 displays output and investment moments in the US data, as well as the predictions of the models. The main features of the data are well known. Both output and investment are very persistent, with a first order serial correlation above 0.9. Investment is procyclical, with no phase shift, and is about 5 times as volatile as output.

The classical model overestimates the volatility of output and investment and underestimates their persistence. In addition, it does not perform well when it comes to fitting the lead-lag relation with output. The model with frictionless investment ($\eta = 1$) does not perform much better than the classical model. Even though investment is only slightly more volatile than in the data, its persistence is almost zero at all lags. Furthermore, the contemporaneous correlation with output is close to that observed in the data, but all cross-correlations at lags other than zero are low or close to zero. Pervasive inattentiveness, however, brings the model more in line with observed data on output and investment. Output is less volatile and more persistent than in the other models. Although the model predicts that investment is only about two-and-a-half times as volatile as output, it improves promisingly as regards fitting investment autocorrelations (even at

[12] All data were taken from the FRED database available through the Federal Reserve Bank of St. Louis. The cyclical components of each series were obtained by applying the Baxter-King bandpass filter.
[13] I do not report the moments of the SIGE model since they are similar to those of the SIGEK model with lumpy investment.

Table 1: Aggregate variables, models versus data in the post-1986 US

Series		standard deviation	autocorrelation coefficients (order)				correlation ($\mathbf{X_t}$, $\mathbf{output_{t+k}}$)				
			1	2	3	4	$k=-2$	$k=-1$	$k=0$	$k=1$	$k=2$
Panel A: output and investment											
output	**data**	**0.90**	**0.93**	**0.76**	**0.52**	**0.29**					
	classical	3.16	0.60	0.51	0.48	0.46					
	SIGEK($\eta = 1$)	4.34	0.35	0.30	0.29	0.29					
	SIGEK	2.67	0.90	0.83	0.79	0.75					
invest-ment	**data**	**4.84**	**0.93**	**0.75**	**0.51**	**0.27**	**0.61**	**0.82**	**0.91**	**0.9**	**0.78**
	classical	7.78	0.14	0.01	-0.01	-0.01	-0.02	0.07	0.71	0.33	0.22
	SIGEK($\eta = 1$)	5.39	0.05	0.00	0.00	0.01	-0.01	0.04	0.86	0.22	0.12
	SIGEK	2.40	0.71	0.56	0.46	0.40	0.31	0.41	0.61	0.56	0.52
Panel B: other macroeconomic variables											
consump-tion	**data**	**0.88**	**0.95**	**0.81**	**0.61**	**0.41**	**0.75**	**0.86**	**0.89**	**0.81**	**0.65**
	classical	0.98	0.56	0.45	0.41	0.38	0.05	0.04	-0.39	-0.26	-0.25
	SIGEK($\eta = 1$)	0.45	0.94	0.89	0.83	0.79	-0.05	-0.01	-0.03	-0.11	-0.15
	SIGEK	0.75	0.95	0.89	0.85	0.80	-0.13	-0.08	-0.03	-0.1	-0.16
hours	**data**	**1.55**	**0.96**	**0.86**	**0.70**	**0.52**	**0.82**	**0.87**	**0.83**	**0.75**	**0.62**
	classical	2.03	0.43	0.32	0.29	0.27	0.33	0.42	0.94	0.72	0.63
	SIGEK($\eta = 1$)	2.18	0.22	0.16	0.16	0.15	0.18	0.23	0.97	0.52	0.43
	SIGEK	2.00	0.83	0.73	0.65	0.60	0.7	0.78	0.91	0.88	0.85
real wages	**data**	**1.11**	**0.91**	**0.69**	**0.44**	**0.25**	**-0.19**	**-0.1**	**0.01**	**0.08**	**0.12**
	classical	0.70	0.44	0.31	0.27	0.26	-0.31	-0.37	-0.79	-0.68	-0.61
	SIGEK($\eta = 1$)	0.33	0.86	0.72	0.63	0.57	-0.36	-0.23	-0.22	-0.64	-0.67
	SIGEK	0.59	0.88	0.77	0.69	0.63	-0.68	-0.68	-0.63	-0.69	-0.72
inflation	**data**	**0.26**	**0.65**	**0.58**	**0.58**	**0.57**	**0.35**	**0.33**	**0.27**	**0.19**	**0.11**
	classical	0.64	0.23	0.08	0.04	0.03	-0.2	-0.15	0.42	0.1	0.02
	SIGEK($\eta = 1$)	0.22	0.37	0.39	0.39	0.36	-0.15	-0.3	0.45	0.06	-0.01
	SIGEK	0.26	0.88	0.81	0.74	0.67	0.15	0.16	0.22	0.18	0.16

Note. The moments for US data (in bold) were obtained by applying the Baxter-King bandpass filter to the logarithm of the original series, with a band of 6 to 32 quarters. The standard deviation of investment is relative to the standard deviation of output. The correlation refers to the cross-correlation of the cyclical component of the respective variable with the $K-$quarter lag of the cyclical component of output.

high lags) and the overall shape of the cross-correlation curve. Overall, panel A clearly shows that the lumpy investment model's implied second moments of output and investment differ significantly from those of the model with frictionless investment and are much more consistent with the empirical evidence.

Panel B in Table 1 allows for analysing whether the quantitative differences in the models' output and investment moments extend to other macroeconomic variables. It reports the second moments of consumption, hours, real wages and inflation. The results still exhibit interesting quantitative differences between the lumpy and the frictionless investment models. Moreover, the model that overall best captures these moments is the model with pervasive inattentiveness (even though some moments, especially the cross-correlations of consumption and real wages with output, seem hard to replicate).

This analysis therefore confirms that the business cycle is clearly affected by investment lumpiness at the micro-level, and that pervasive stickiness improves the model's ability to replicate the overall dynamics of macroeconomic variables.

How sensitive are the second-order moments of investment to changes in the degree of information stickiness η?

The previous results were obtained by setting the degree of information stickiness η to 0.10 for final-goods firms in line with the value suggested by Sveen and Weinke (2007). To check for robustness, Figures 3 and 4 contrast the SIGEK model's investment moments for different values of the parameter η with their empirical counterparts. Let me recall that the smaller the value of η, the smaller the fraction of updating firms and the smaller the impact of the shocks on capital and investment. Therefore, as η decreases, investment should become less volatile and more persistent.

Figure 3 confirms this conjecture: the standard deviation decreases and autocorrelations increase as η declines. The figure further shows that the model has difficulties in simultaneously replicating the volatility and the persistence of investment. On the one hand, the model matches the volatility of investment observed in the data only when firms are often attentive, on average updating their information once every eight months ($\eta \simeq 0.4$). On the other hand, a high degree of information stickiness ($\eta < 0.1$) is required to match the high persistence of investment.

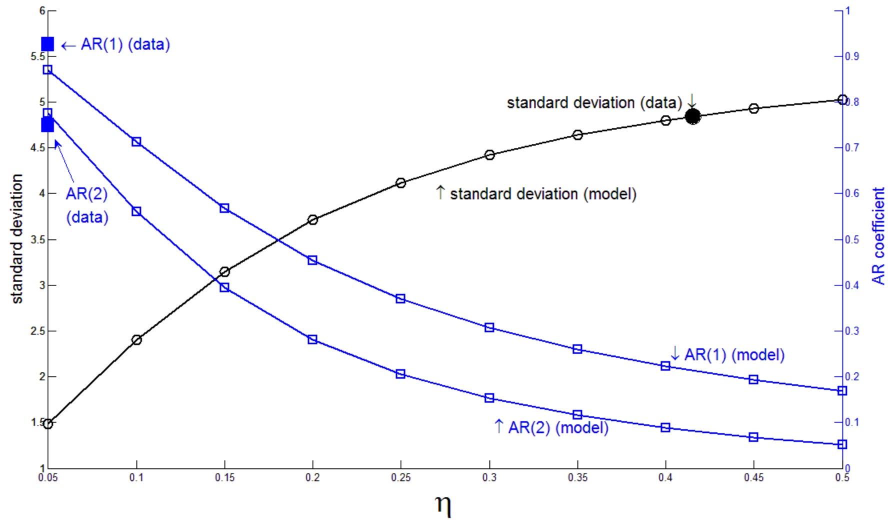

Figure 3: Standard deviation and autocorrelation of investment at lags 1 and 2 (sensitivity analysis for different values of η)

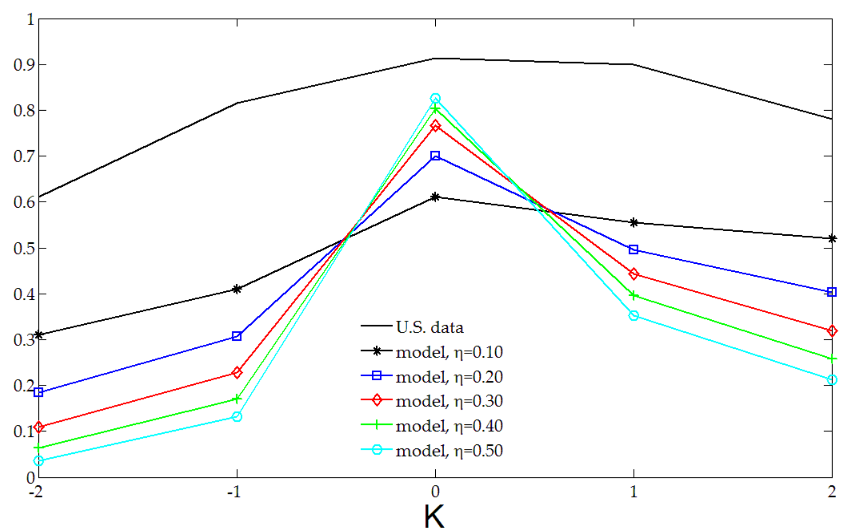

Figure 4: Cross-correlation of investment with output at lag K, $K = \{-2, -1, 0, 1, 2\}$ (sensitivity analysis for different values of η)

Note. US data: black line. SIGEK model ($\eta = 0.1$): black-asterisk line. SIGEK model ($\eta = 0.2$): blue-square line. SIGEK model ($\eta = 0.3$): red-diamond line. SIGEK model ($\eta = 0.4$): green-plus line. SIGEK model ($\eta = 0.5$): cyan-circle line. Other parameters than η: see Table 3.

Figure 4 plots the cross-correlation of investment with output at different leads and lags. As η increases, the model becomes better at matching the contemporaneous correlation with output, but performs worse when it comes to matching cross-correlations at lags other than zero. Small values of η (*i.e.* high degrees of inattentiveness) in turn improve the model's ability to fit the overall lead-lag relation of investment with output.

While it is true that the SIGEK model with pervasive inattentiveness is superior to the alternatives studied here in terms of fitting the dynamic behaviour of investment, it suffers from a trade-off between fitting the volatility and the persistence of investment. It seems difficult to solve this trade-off by just fine-tuning one parameter, namely the degree of information stickiness η in the economy.

Aggregate investment rate: partial versus general equilibrium models with lumpy investment

In Verona (2013), I show that lumpy capital adjustments arise naturally when firms face costs of gathering and processing information. I find that such a partial equilibrium model is successful in fitting quantitative facts on plant-level investment rates. I then aggregate the behaviour of many inattentive firms in order to derive some aggregate predictions and find that the performance at the aggregate level is not as successful as at the plant-level. Columns 2 and 3 of Table 2 are taken from Verona (2013, Table 3) and show the serial correlation and the standard deviation of the aggregate investment rate in the data (annual values), as well as the respective moments implied by the partial equilibrium model with lumpy investment. In that model, the aggregate investment rate is less persistent and far more volatile than in the data, meaning that the model does not fit well the aggregate data.

Columns 4 and 5 report the moments in the data (quarterly values) and the respective moments implied by the SIGEK model with pervasive inattentiveness. The general equilibrium model matches these moments much better than the partial equilibrium lumpy investment model. In fact, the persistence of the aggregate investment rate increases sharply (although it still remains lower than in the data) and its excessive volatility is virtually eliminated when lumpy investment is included in general equilibrium.[14] Intuitively, aggregation

[14] In this paper, the distribution of inattentiveness is exponential, while in the partial equilibrium model, I consider the uniform distribution (to keep the computational burden manageable). The results of the partial equilibrium model would be qualitatively similar using the exponential distribution.

helps to smoothen investment spikes, but not sufficiently, and general equilibrium effects move the model further in the direction of fitting these moments of the aggregate investment rate.[15]

Table 2: Aggregate investment rate, models versus US data

	annual data 1984-2005[a,b]	**partial equilibrium model** [b]	**quarterly data post-1986**[c]	**SIGEK model** [d]
serial correlation	0.846	0.172	0.970	0.724
standard deviation	0.011	0.102	0.0014	0.0007

[a] Annual private fixed nonresidential investment-to-capital ratio. [b] See Verona (2013, Table 3). [c] Quarterly private fixed investment-to-capital ratio. [d] For the baseline parameters, see Table 3.

4.3 Relation to capital adjustments with non-convex adjustment costs

There are some general equilibrium studies which analyse the relevance of lumpy investment for the business cycle. All of them use models with non-convex adjustment costs, while the model presented in this paper is the first to consider information costs as a source of investment lumpiness. Even though both models are successful in replicating the observed lumpy behaviour at the micro-level, there is an important difference between adjustment with non-convex adjustment costs and adjustment with information costs, which in turn lead to distinct dynamics and predictions.

Whenever there are costs for collecting information and planning, but no direct costs for adjusting capital, the optimal adjustment is time-dependent, as opposed to state-dependent. In the inattentiveness model, the stock of capital at any point between planning dates is chosen regardless of the state of the world on that date, and the date of the next adjustment does not depend on the state on that date. Information costs therefore lead to time-dependent adjustments. Information collection is costless in models with non-convex adjustment costs, so that the firm constantly observes the state of the economy and, accordingly, decides whether to adjust or to stay inactive. Non-convex adjustment costs lead to state-dependent adjustments.

[15] A similar result has been obtained by Khan and Thomas (2008). Their state-dependent lumpy investment general equilibrium model matches the data on aggregate investment rates much better than its partial equilibrium counterpart.

Distinguishing between time and state-dependent adjustments has crucial implications for many economic questions. For instance, in state-contingent adjustment models, a monetary policy shock may cause many firms to adjust their capital stocks immediately, which therefore dampens (or offsets) the real impact of the shock. Instead, monetary policy has long-lasting real effects if firms make investment decisions in a time-dependent fashion since today's news does not affect the fraction of firms that respond immediately to the shock.

With state-contingent adjustment models, Thomas (2002) and Khan and Thomas (2008) argue that general equilibrium effects – *i.e.* consumption smoothing motive – are responsible for the irrelevance result. By contrast, Gourio and Kashyap (2007) and Bachmann et al. (2013) point out that the irrelevance result does not only come from general equilibrium forces, but also depends on the model's calibration, especially with regard to the parameters of the capital adjustment cost function. That is, both general equilibrium forces and the calibration of adjustment costs play a relevant role and can bias the results in one direction or the other.

In this paper, it is likely that by changing some parameter values, the model will match business cycle moments more closely, but further improvements would not change the conclusion that the frictionless and the lumpy model yield different aggregate dynamics. Therefore, the model's calibration is not driving the qualitative results obtained here. At the same time, general equilibrium effects actually bring the model more in line with observed aggregate fluctuations, as spikes in aggregate investment obtained in the partial equilibrium model are levelled out by general equilibrium. Hence, since time-dependent adjustments represent the main difference compared with the adjustment implied by non-convex adjustment costs, one may conclude that time-dependent adjustments are actually the source of the relevance result obtained here. Since many firms are inattentive and adjust their capital stocks infrequently, it is to be expected that the model with lumpy investment would yield different dynamics than the same model with frictionless investment.

5 Conclusion

This paper has analysed the (ir)relevance of micro-level lumpy investment for the business cycle.

I have embedded lumpy investment consistently micro-founded on inattentiveness into the Mankiw and Reis (2006, 2007) SIGE model. Specifically, I have augmented the SIGE model with a set of firms that make capital investment decisions inattentively. The resulting model features inattentiveness as the only source of stickiness. I have found that the model with lumpy investment yields business cycle dynamics (both impulse response functions and second moments) that are significantly different from those of its frictionless investment counterpart. This result strengthens the case in favour of the relevance of microeconomic investment lumpiness for the business cycle.

The model has also allowed for addressing how far inattentiveness alone affects business cycle dynamics. I have found that the model with pervasive inattentiveness is better at matching business cycle moments than a classical model or an otherwise identical model with frictionless investment. These findings confirm the claim of Mankiw and Reis (2006) that pervasive information stickiness is necessary to explain business cycle dynamics in sticky information models.

Introducing lumpy investment, with a microeconomic foundation based on inattentiveness, in a sticky information general equilibrium model therefore seems to be a fruitful approach for further business cycle and monetary policy analysis. However, before using the SIGEK model for normative policy analysis and for policy advice, it would be worthwhile estimating the model since it has been calibrated using different sources and the calibration has not been fully optimized. The main focuses of interest would be the measures of information stickiness, in particular the one regarding the capital investment decision since few (if any) estimates are available in the literature. After estimating the model, it would be interesting to investigate how different these measures are from those obtained by Reis (2009a,b), and to disentangle the role played by each informational friction in shaping business cycle dynamics. The estimated model would also allow an in-depth comparison to be undertaken with workhorse sticky prices DSGE models and with the DSGE model with rational inattention developed by Mackowiak and Wiederholt (2011), as well as with empirical VAR evidence. I leave these tasks for future research.

Table 3: Structural parameters

	value	source[a]	description
Preference and production			
β	0.67	RR	return to scale (intermediate-goods firms)
ψ	5.15	RR	Frisch elasticity of labour supply
v	10.09	RR	elasticity of substitution across goods varieties
γ	9.09	RR	elasticity of substitution across labour varieties
α	0.33	FV	share of capital in final-goods firm's production function
Nonpolicy shocks			
$\rho_{\Delta a}$	0.03	RR	serial correlation of the intermediate-goods productivity shock
$\sigma_{\Delta a}$	0.66	RR	standard deviation of the intermediate-goods productivity shock
ρ_g	0.99	RR	serial correlation of the aggregate demand shock
σ_g	0.83	RR	standard deviation of the aggregate demand shock
ρ_v	0.28	RR	serial correlation of the goods mark-up shock
σ_v	1.06	RR	standard deviation of the goods mark-up shock
ρ_γ	0.86	RR	serial correlation of the labour mark-up shock
σ_γ	1.23	RR	standard deviation of the labour mark-up shock
ρ_z	0.75	FV	serial correlation of the final-goods productivity shock
σ_z	0.5	FV	standard deviation of the final-goods productivity shock

Table 3: Structural parameters (continue)

	value	source[a]	description
Monetary Policy			
ρ_ε	0.29	RR	serial correlation of the monetary policy shock
σ_ε	0.44	RR	standard deviation of the monetary policy shock
ϕ_π	1.17	RR	interest rate response to inflation
Inattentiveness			
δ	0.08	RR	fraction of consumers updating information every quarter
ω	0.74	RR	fraction of workers updating information every quarter
λ	0.52	RR	fraction of intermediate-goods firms updating information every quarter
η	0.1	FV	fraction of final-goods firms updating information every quarter
Others			
α_c	0.85	FV	steady-state share of consumption in GDP
α_i	0.15	FV	steady-state share of investment in GDP
ρ	0.035	FV	steady-state real depreciation rate (quarterly)
r	0.01	FV	steady-state real interest rate (quarterly)

Note. [a] RR: Reis (2009b, Table 2). FV: my calibration.

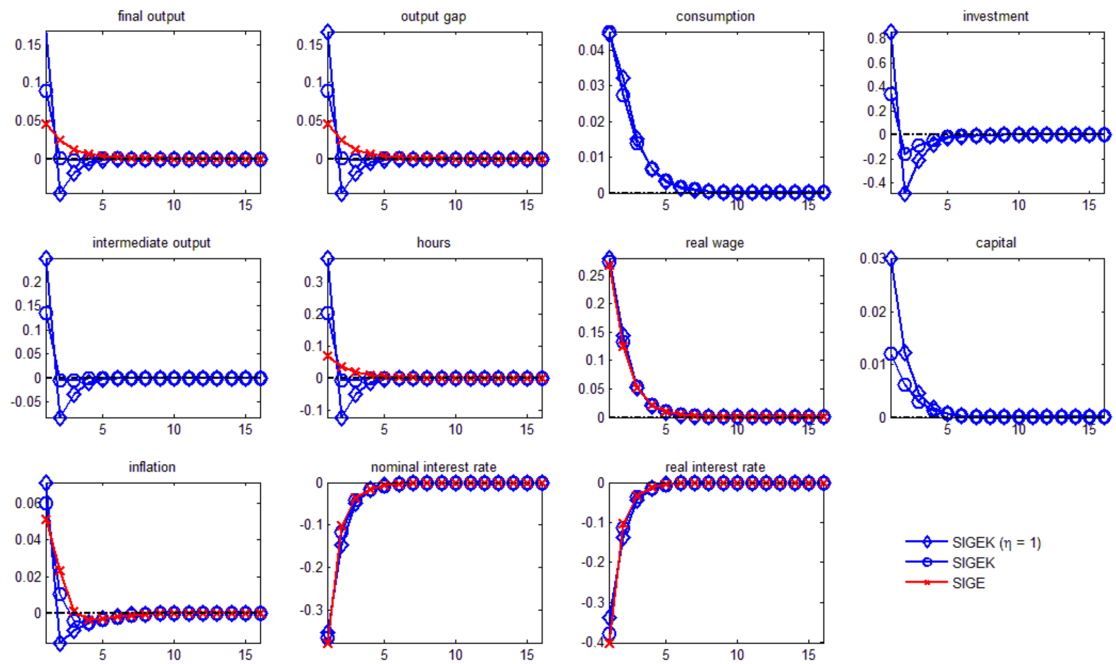

Figure 5: Impulse response functions to a monetary policy shock

Note. Values expressed as percentage deviation from their steady-state values. SIGEK model with pervasive inattentiveness: blue-circle line. SIGEK model with frictionless investment ($\eta = 1$): blue-diamond line. SIGE model: red-cross line. Steady state: black dashed-dotted line. Baseline parameters: see Table 3.

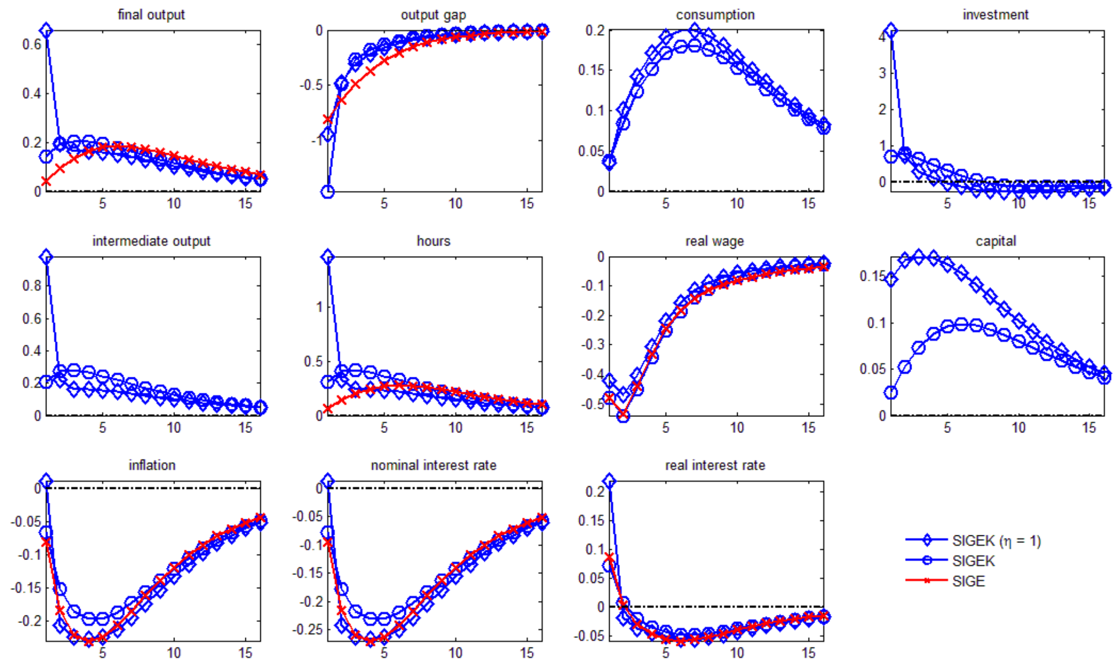

Figure 6: Impulse response functions to a wage mark-up shock

Note. Values expressed as percentage deviation from their steady-state values. SIGEK model with pervasive inattentiveness: blue-circle line. SIGEK model with frictionless investment ($\eta = 1$): blue-diamond line. SIGE model: red-cross line. Steady state: black dashed-dotted line. Baseline parameters: see Table 3.

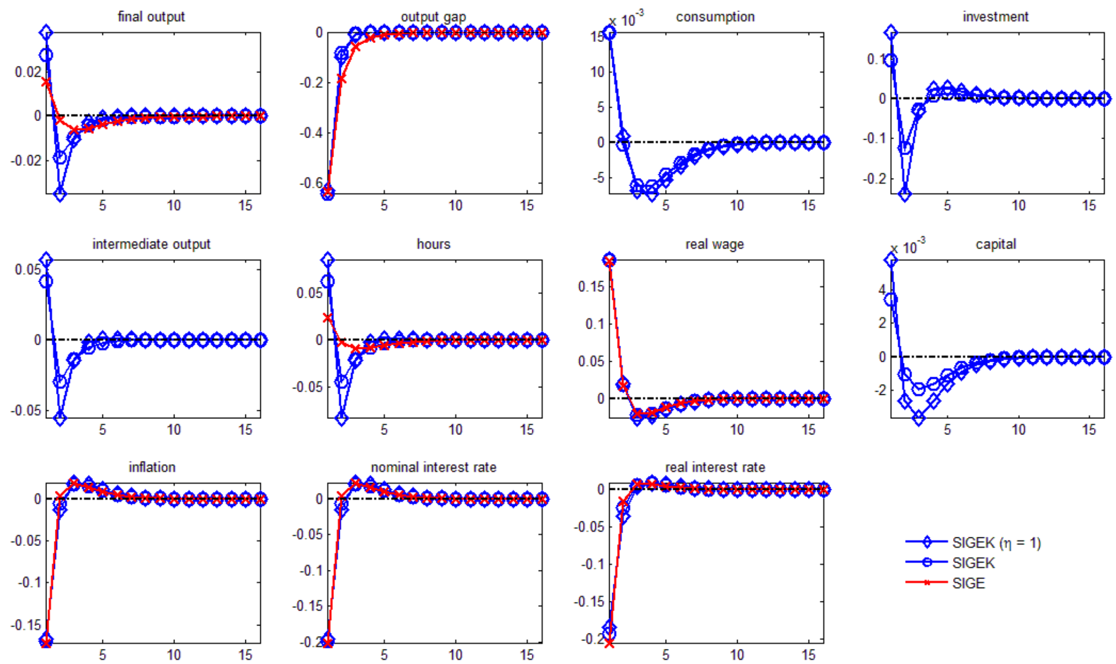

Figure 7: Impulse response functions to an intermediate-goods mark-up shock

Note. Values expressed as percentage deviation from their steady-state values. SIGEK model with pervasive inattentiveness: blue-circle line. SIGEK model with frictionless investment ($\eta = 1$): blue-diamond line. SIGE model: red-cross line. Steady state: black dashed-dotted line. Baseline parameters: see Table 3.

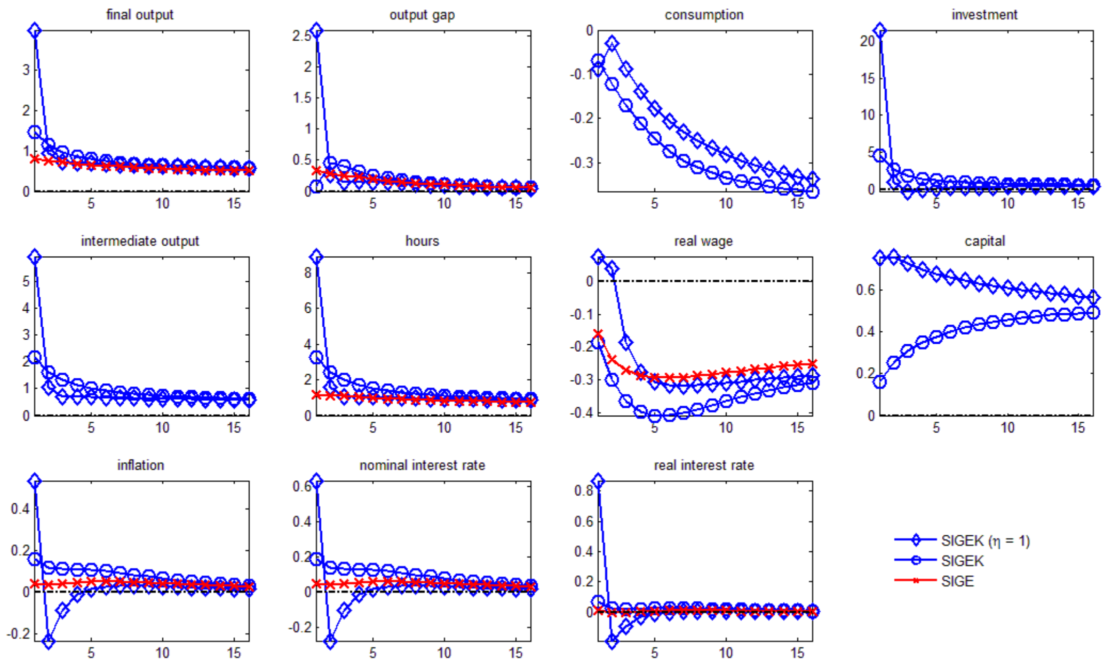

Figure 8: Impulse response functions to a demand shock

Note. Values expressed as percentage deviation from their steady-state values. SIGEK model with pervasive inattentiveness: blue-circle line. SIGEK model with frictionless investment ($\eta = 1$): blue-diamond line. SIGE model: red-cross line. Steady state: black dashed-dotted line. Baseline parameters: see Table 3.

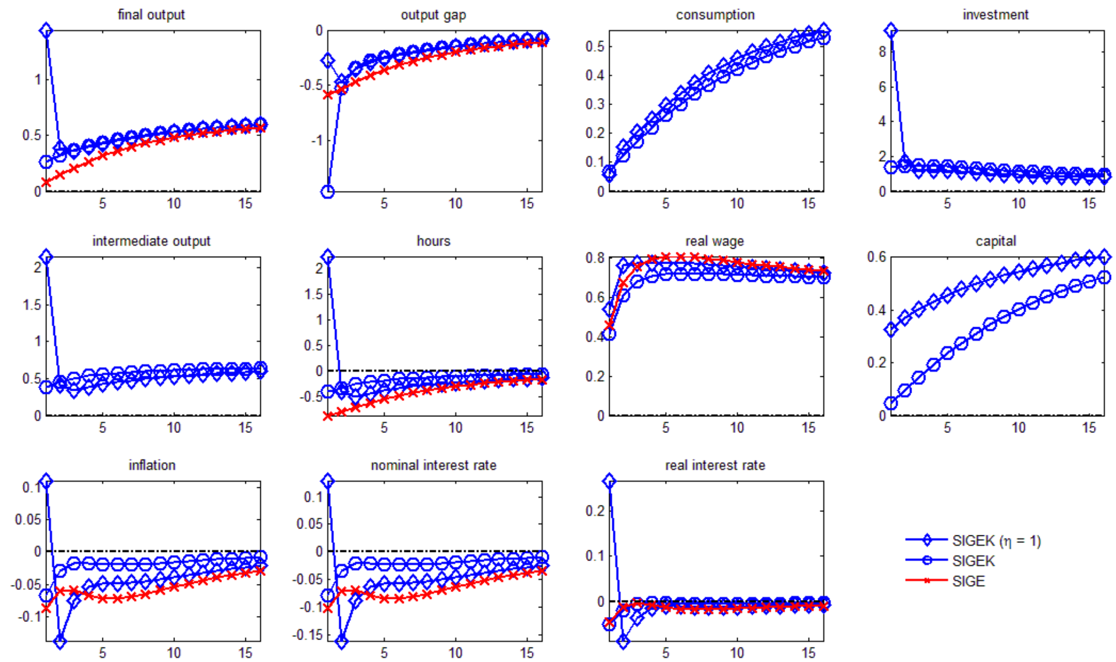

Figure 9: Impulse response functions to an intermediate-goods productivity shock

Note. Values expressed as percentage deviation from their steady-state values. SIGEK model with pervasive inattentiveness: blue-circle line. SIGEK model with frictionless investment ($\eta = 1$): blue-diamond line. SIGE model: red-cross line. Steady state: black dashed-dotted line. Baseline parameters: see Table 3.

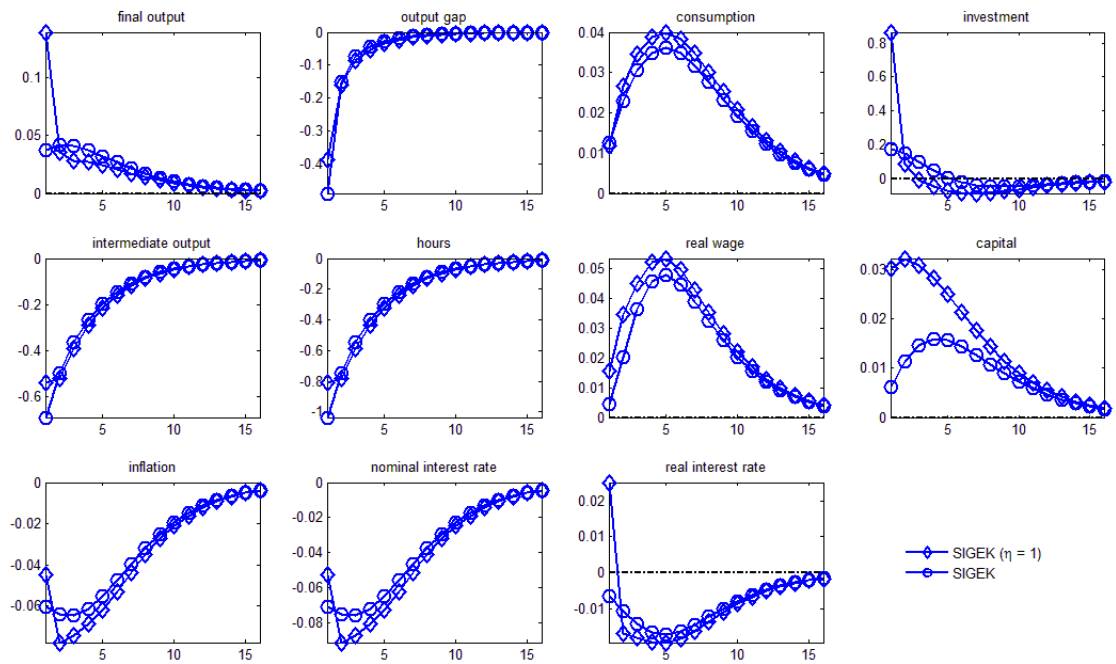

Figure 10: Impulse response functions to a final-goods productivity shock

Note. Values expressed as percentage deviation from their steady-state values. SIGEK model with pervasive inattentiveness: blue-circle line. SIGEK model with frictionless investment ($\eta = 1$): blue-diamond line. Steady state: black dashed-dotted line. Baseline parameters: see Table 3.

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