Centro de Economia e Finanças da UPorto

CEF.UP Working Paper
2011-02

Lumpy Investment in Sticky Information General Equilibrium

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June 05, 2011

Abstract

This paper introduces lumpy micro-level investment into a sticky information general equilibrium model. Lumpy investment arises because of inattentiveness in capital investment decisions instead of the more popular assumption of non-convex adjustment costs. Sticky information is the only source of rigidity in the model and it is pervasive to all markets and decisions. The model yields aggregate dynamics that are substantially different from those of an otherwise identical model with frictionless investment, and much closer to the empirical evidence. These results therefore strengthen the case for the relevance of lumpy micro-level investment for the business cycle.

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

JEL classification: E10, E22, E30, E32

* This paper is a revised version of a chapter of my Ph.D. dissertation at the Universidade do Porto. I am extremely grateful to Ricardo Reis for his invaluable guidance, to Alper Çenesiz for helpful comments, and to Manuel M. F. Martins for extensive and critical comments on an early draft of this paper which have considerably improved its content and readability. I would also like to thank professor Ruediger Bachmann for providing the data on quarterly investment rates, Assia Ezzeroug and Maik Wolters for discussions on the implementation of sticky information models in Dynare, and the Fundação para a Ciência e a Tecnologia for financial support (Ph.D. scholarship). Any errors are my own.

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1 Introduction

Figure 1 plots output and investment over the U.S. 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 are nevertheless 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 over 15 years is concentrated in a period of two or three (contiguous) years.

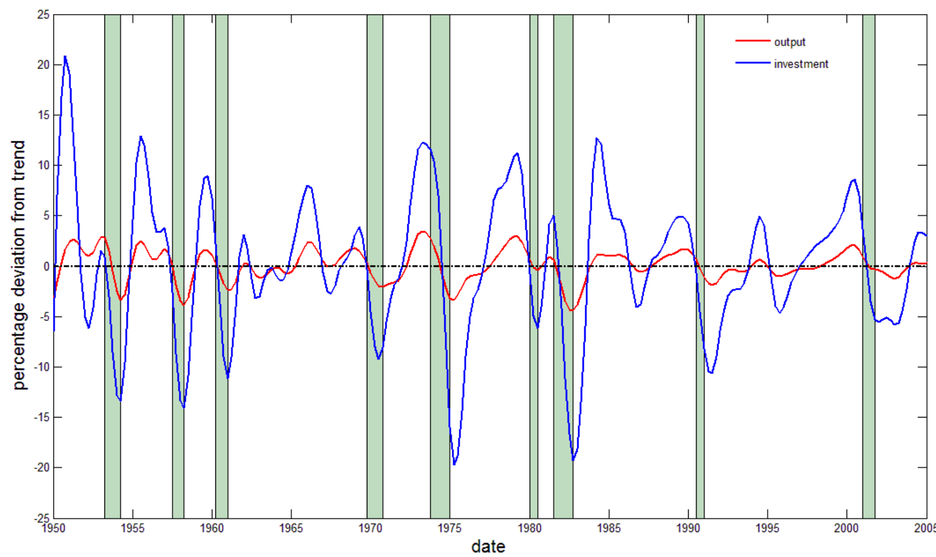

Figure 1: Output and investment over the U.S. business cycle

Note. The figure displays detrended quarterly real GDP and real private domestic investment in the U.S. over the period 1950-2005. The trends have been computed using the band-pass Baxter-King 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, obviously, in determining economic long-term growth), capital accumulation has somewhat been ignored in canonical versions of the New Keynesian model (*e.g.* Galí, 2008). By now, however, standard DSGE models do feature endogenous capital accumulation (*e.g.* Levin et al., 2005 and Smets and Wouters, 2007). Developing a sound

[1] Barro's findings come from analyzing the role of investment during five U.S. recessions (namely, those ending in 1961Q1, 1970Q4, 1975Q1, 1982Q4 and 1991Q4).

microfounded model able to explain aggregate investment dynamics has nevertheless kept economists busy for years. To reproduce smooth aggregate investment dynamics, these DSGE models introduce convex investment adjustment costs. In doing so, however, the lumpy nature of plant-level investment is simply brushed away, and so these models' microfoundations for investment behavior seem rather weak. More recent theoretical research (*e.g.* Caballero, 1999) has proposed an alternative source for the smooth aggregate investment dynamics, suggesting that it may result from aggregation of asynchronous and lumpy micro-level capital adjustments, which can be generated by fixed costs of capital adjustment.

An important debate running through the recent general equilibrium literature is whether micro-level lumpy capital adjustments have important implications for aggregate investment and, more generally, for the business cycle. The origin of the debate over the (ir)relevance of lumpy investment for aggregate dynamics dates back to Thomas (2002). Previously, partial equilibrium state-dependent lumpy adjustment 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 plays no important role for the aggregate dynamics of the model economy. In fact, her lumpy investment model generates business cycle dynamics that are alike to those generated by an otherwise identical model characterized by frictionless investment. According to Thomas (2002, pag. 508), the irrelevance result arises because "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, contrasted the Thomas result and found that lumpy investment matters for aggregate dynamics. They re-calibrated Thomas' (2002) model and found that the recalibrated model has properties that differ from those of the standard RBC model. This result led them to conclude that the irrelevance result does not come only from general equilibrium effects, but also depends on how the model is calibrated. Currently, there are studies supporting either the relevance or the irrelevance result.[2]

Against this background, this paper evaluates the relevance of lumpy investment in a sticky information DSGE framework. In a companion paper to this one, Verona (2011), we show that time-dependent lumpy capital adjustment behavior arises naturally when firms face costs of gathering, absorbing, and processing information. We also find that such partial equilibrium model is successful in fitting quantitative facts on plant-level investment rates. In this paper we embed that theoretical framework into the Mankiw and Reis (2006, 2007) sticky information general equilibrium (SIGE) model. Specifically, we augment the SIGE model with a set of firms that make capital investment decisions with inattentiveness. In the capital-augmented version of the SIGE model, as in the original SIGE model, the only source of rigidity is inattentiveness,

[2] Papers supporting the relevance result include Bayer (2006), Sveen and Weinke (2007), Iacoviello and Pavan (2007), Bachmann et al. (2010) and Fiori (2010). Khan and Thomas (2003, 2008) and House (2008) in turn provide additional evidence in favor of the irrelevance result. A similar irrelevance result has been obtained in Veracierto (2002), who analyzes the role of plant-level irreversibilities in investment for aggregate fluctuations.

which is a pervasive feature of all markets and decisions – consumption, wages, prices and capital investment decisions are all based, to some degree, on outdated information.

This paper provides two main contributions.

First, embedding into the SIGE model lumpy investment that is consistently microfounded on inattentiveness in capital investment decisions, reconciles general equilibrium modelling with the recent developments in the microeconomic theories of investment. This model allows us to provide further contributions to the debate over the (ir)relevance of lumpy investment for the business cycle.

Second, enhancing the SIGE model with capital and investment overcomes one of its weaknesses pointed out in Reis (2009b). Such 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. Moreover, we provide a fully fledged microfounded DSGE model that relies only on one rigidity – inattentiveness – to mimic the inertia present in the 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. In doing so, such a model also allows us to address how far inattentiveness alone affects macroeconomic dynamics.

The paper is organized as follows. Section 2 presents the capital-augmented sticky information general equilibrium (SIGEK) model, section 3 presents the key log-linearized equations, and section 4 analyzes the business cycle implications of the model. Finally, section 5 concludes. Technical details are relegated to appendix A.

2 The capital-augmented sticky information general equilibrium model

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

Within the firms sector, there are two types of firms, intermediate- and final-good firms, and there is a continuum of each indexed by i and f, respectively, in the unit interval. Monopolistic competitive intermediate-good firms have two departments: an attentive hiring department that chooses how much of each variety of labor to hire, and an inattentive pricing department that sets the price of the firm's output. Perfectly competitive final-good firms also have two departments: an attentive purchasing department that chooses how much of each variety of intermediate goods to buy, and an inattentive producing department that produces the final good by combining its optimally chosen firm-specific capital with a Dixit-Stiglitz aggregator of varieties of intermediate goods.

Each household is made up of a consumer and a worker, 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 labor services to intermediate-good firms. Both consumers and workers are inattentive and make optimal decisions only sporadically.

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

Figure 2 sketches the structure of the model. Compared to the original SIGE model, the SIGEK model features a new set of agents, the final-good firms.[3] To lay down the model formally, we start by describing the market clearing conditions and policy processes and then set out the agents' problems.

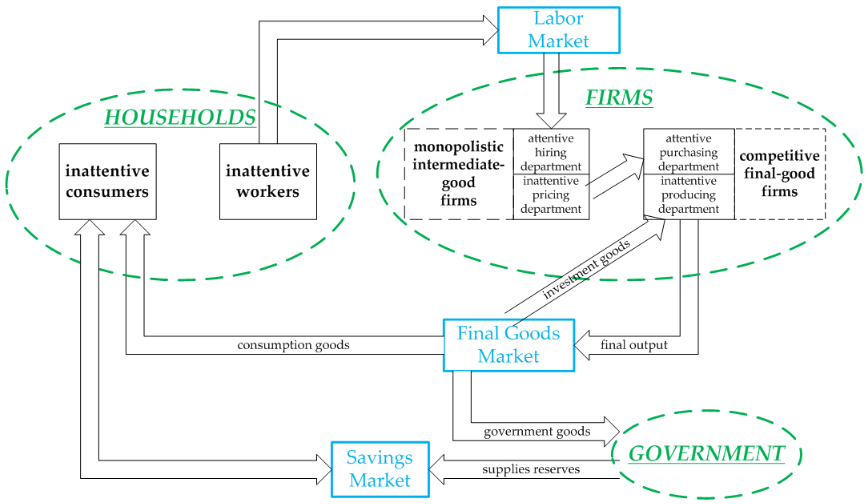

Figure 2: Structure of the model

2.1 Market clearing conditions and economic policy

The total output produced by final-good firms, Y_t^{FIN}, is divided into consumption, investment and government goods. Market clearing in the final goods market thus 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 $I_t = \int_0^1 INV_{t,f} df$ represent, respectively, total consumers consumption and total final-good firms investment. Government consumption G_t is financed by lump-sum taxes to households that keep the budget balanced at

[3] We separate final good production from intermediate goods production because of three main reasons. First, the separation allows us to have an agent to be inattentive about the new decision, capital. Second, it is common in the literature to separate the final good production from the intermediate goods, so as to have the Dixit-Stiglitz aggregation occurring in production rather than in consumption. As it is well known, it is irrelevant which way is chosen. Third, if the capital accumulation decision is linked to the pricing decision of firms, then a possible problem is that when one gets some estimates of the sticky information parameter, it will be hard to understand what is driving them.

all dates. The fraction G_t is stochastic and shocks to it can be interpreted as aggregate demand shocks. The government also 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 relation, whereas policy is set according to a Taylor rule that only reacts to inflation.

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

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

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-good firm f of variety i at time t.

There is a labor market for each variety of labor k. The intermediate-good firms i demand labor, which is supplied by the household k that has the monopoly over its labor services. Market clearing requires:

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

where $L_{t,k}$ is the total labor supply of variety k at time t, and $N_{t,i}(k)$ is the labor demand by intermediate-good firm i of variety k at time t. Total output and labor 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-good firms

2.2.1 Attentive purchasing departments

The purchasing department of the $f-$the 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 a random and time-varying elasticity of substitution $\hat{v}_t$. Each department solves the following problem, given current prices and a total desired amount of inputs $Y_{t,f}$:

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

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

Optimal behavior implies that the demand for each variety i by firm f is:

$$Y_{t,f}^{INT}(i) = Y_{t,f} \left[\frac{P_{t,i}}{P_t}\right]^{-\hat{v}_t} \quad ,$$

where $P_t = \left[\int_0^1 P_{t,i}{}^{1-\hat{v}_t} di\right]^{\frac{1}{1-\hat{v}_t}}$ is the static price index. Integrating over the continuum of departments f and using the market clearing condition (3) gives the total demand for the intermediate-good of variety i:

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

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

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 shock to the final goods production. The timing in (6) implies that capital becomes productive with a one-period delay.

The firm can purchase or sell capital instantaneously and frictionlessly, without any adjustment costs, at a constant price normalized 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 us consider the problem faced by the producing department that last updated its information τ periods ago. Following the SIGE tradition, we assume that, in each period, a fraction η of firms, randomly drawn from the population, updates their information, so there are $\eta(1-\eta)^{\tau}$ firms in this situation. Each of these firms chooses the stock of capital $K_{t,\tau}$ to maximize expected real profits:

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

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

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

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

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

2.3.1 Attentive hiring departments

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

$$\min_{\{N_{t,i}(k)\}_{k\in[0,1]}} \qquad \int_0^1 W_{t,k} N_{t,i}(k)\, dk$$

$$subject\ to \qquad N_{t,i} = \left[\int_0^1 N_{t,i}(k)^{\frac{\hat{\gamma}_t - 1}{\hat{\gamma}_t}}\, dk\right]^{\frac{\hat{\gamma}_t}{\hat{\gamma}_t - 1}} \qquad .$$

The solution to this problem is:

$$N_{t,i}(k) = N_{t,i}\left(\frac{W_{t,k}}{W_t}\right)^{-\hat{\gamma}_t} \qquad ,$$

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

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

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

2.3.2 Inattentive pricing departments

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

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

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

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

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

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

If the firm observed all the variables on the right-hand side, this condition would state that the nominal price charged, $P_{t,\tau}$, is equal to a markup, $\hat{\upsilon}_t / (\hat{\upsilon}_t - 1)$, over nominal marginal costs, which corresponds to the cost of an extra unit of labor, 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 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 consumers j at date t, $L_{t,k}$ is the labor supplied by worker k at date t, ψ is the Frisch elasticity of labor supply and χ captures relative preferences for consumption versus leisure.

At each date t, the household faces a budget constraint given by:

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

where A_{t+1} denotes the real resources of households at the beginning of period $t+1$ and T_t are lump-sum transfers. These transfers comprise the profits received from intermediate-good firms, lump-sum taxes paid to the government, and payments for an insurance contract that households sign at the beginning of each time 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, so at each period there are $\delta(1-\delta)^\tau$ of consumers in this situation. They choose a plan for current and future consumption, $\{C_{t+\tau,\tau}\}_{\tau=0}^{\infty}$, which is a sequence $\{C_{t,0}\,;\, C_{t+1,1}\,;\, C_{t+2,2}\,;\, \cdots\}$ 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:[4]

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

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 agent. It states that the marginal utility of consuming today equals the expected discounted marginal utility of consuming tomorrow times the return on savings. The second equation states that marginal utility of consumption for inattentive consumers equals the one they would expect in case there was full information.

In the labor market, a randomly drawn fraction of workers ω updates their plans each period, so at each period there are $\omega(1-\omega)^\tau$ of workers in this situation. They choose a plan for current and future wages, $\{W_{t+\tau,\tau}\}_{\tau=0}^{\infty}$, which is a sequence $\{W_{t,0}\,;\, W_{t+1,1}\,;\, W_{t+2,2}\,;\, \cdots\}$ where $W_{t,\tau}$ is the time-t wage set by a worker who last updated the information τ periods ago. 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

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

[4] The dynamic problem solved by consumers and workers is more complicated than those solved by firms. We refer the reader to appendix A for details.

The first equation is the intertemporal labor supply Euler equation for an attentive worker. If $\hat{\gamma}_t$ was constant, the equation states that the marginal disutility of supplying labor today $(L_{t,0}^{1/\psi})$ divided by the real wage $(W_{t,0}/P_t)$ is equal to the discounted marginal disutility tomorrow $(L_{t+1,0}^{1/\psi})$ divided by the corresponding real wage $(W_{t+1,0}/P_{t+1})$ times the real interest rate. With a time-varying $\hat{\gamma}_t$, the Euler equation takes into account the change in the markup charged by the monopolistic worker. The second condition notes that workers who are not perfectly informed set wages so that their expected disutility from working mirrors the disutility from working expected by the attentive workers.

3 The sticky information equilibrium

The detailed presentation of the model log-linearization is presented in appendix A. In this section we discuss the key reduced-form relations. We log-linearize the equilibrium conditions around the non-stochastic steady state. Small caps denote the log-deviations of the respective large-cap variable from this steady state, with the exceptions of the following variables: 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. Small letters with no subscript denote parameters and steady-state values.

The aggregate capital stock is:

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

The level of capital stock (k_t) is positively related to the expected value of the firm's production (y_{t+1}^{FIN}) and negatively related to the current level of capital stock because of decreasing return to scale in production $(\alpha < 1)$. A lower real interest rate (r_t) implies a lower opportunity cost of holding capital and therefore an 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 adjustment takes place gradually over time.

Aggregate investment (inv_t) is:

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

The Phillips curve is:

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

The price level (p_t) depends on past expectations of its current value, real marginal costs and the desired markup. Marginal costs are larger the higher are the real wages paid to workers $(w_t - p_t)$, the more is produced (y_t) because of decreasing returns to scale ($\beta < 1$), and the lower is aggregate productivity (a_t). The desired markup falls with the elasticity of substitution across the varieties of goods (v_t). Unexpected shocks to any of these variables only raise prices by λ because only this share of price-setting firms is attentive and, thus, aware of the news.

The IS curve is:

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

where $c_t^n = \lim_{\tau \to \infty} E_t c_{t+\tau}$ is a measure of consumers' wealth and $R_t = \sum_{\tau=0}^{\infty} \left(i_{t+\tau} - \Delta p_{t+1+\tau}\right)$ is the long real interest rate. Higher expected future wealth increases current spending, whereas higher expected interest rates encourage savings and lower spending. The higher is δ, the larger is the share of informed consumers who respond to shocks as they occur, therefore the more responsive consumption is to changes in these variables.

The wage curve is:

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

Wages (w_t) increase one-to-one with the price level, as workers care about real income; they increase with real wages in the economy, since higher real wages push up the demand for a particular labor variety through substitution; they increase with labor supplied (l_t), because of the increasing marginal disutility of working; they increase with wealth, since leisure is a normal good; they decrease with interest rates, since lower interest rates decrease the return on savings and the incentive to work; and they fall as the elasticity of substitution across labor varieties increases (γ_t) since workers' desired markup falls. As ω increases, a larger fraction of workers is informed so wages become more responsive to changes in these determinants, whereas otherwise wages only respond gradually over time.

The aggregate resource constraint is

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

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

The policy rules are

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

and

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

Intermediate output is given by

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

and labor is given by

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

Equations (14)-(23) characterize the equilibrium for y_t^{FIN} (final output), c_t (consumption), w_t (wage), p_t (price), 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 (labor) given exogenous shocks to ε_t (monetary policy), Δa_t (aggregate intermediate-good productivity growth), g_t (aggregate demand), v_t (intermediate-good markup), γ_t (labor markup) and z_t (aggregate final-good 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 $s \neq s'$.

4 Is lumpy investment relevant for the business cycle?

Having presented the SIGEK model's key relations, we now study the impact of lumpy micro-level investment on the aggregate business cycle. Through this section, we analyze and contrast the behavior of four models:

1. the SIGEK model with pervasive inattentiveness;
2. the SIGEK model with frictionless investment, which is obtained setting $\eta = 1$;
3. a classical model, *i.e.* the SIGEK model when $\eta = \lambda = \omega = \delta = 1$ so that all agents are attentive;
4. the Mankiw and Reis SIGE model.

Recall that the Thomas' (2002) irrelevance conclusion arises from the fact that her lumpy investment model generates business cycle dynamics that are alike to those generated by an otherwise identical model characterized by frictionless investment. Accordingly, comparing the results from model 1 with those from model 2 allows for gauging whether lumpy investment consistently microfounded on inattentiveness is relevant for 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 obtained with model 1 to those obtained with 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.[5]

[5] All simulations have been conducted with Dynare. The results for the SIGE model have been obtained by simulating the Reis (2009a) model using the calibration in table 4. To make results comparable with those of other models, the simulation of the SIGE model has been conducted setting $\alpha_y = 0$ in the monetary policy rule, that is, dropping the interest rate response to the output gap, so that the nominal interest rate only responds to inflation.

We calibrate the model assuming that a period is a quarter. The share of consumption in total output α_c is assumed to be 0.85, so that 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 $18\,\%/year$. The share of capital in the final-good firm's production function α is set to 0.33. The inattentiveness parameter η is assumed to be 0.1, which implies that final-good firms are inattentive on average for 10 quarters.[6] The serial correlation and the standard deviation of the final-good 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). Those values have been obtained from the estimation of the SIGE model using Bayesian methods on post-86 U.S. data. Table 4 shows the baseline parameter values for the SIGEK model.

In what follows we first analyze the impulse responses to the various structural shocks and then we investigate the ability of the models to match some second order moments of U.S. aggregate data.

4.1 Impulse response functions

Figures 8 to 13 plot the impulse response functions to one-standard-deviation impulses to the six shocks. In all figures presented, variables are reported as 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 the SIGEK model with pervasive inattentiveness and with frictionless investment, respectively, while red-cross lines represent the responses of the SIGE model. For the sake of clarity, we do not report the impulse responses of the classical model, which are way too large and essentially have no persistence. We first describe the dynamics of the SIGEK model with pervasive inattentiveness, and then we compare it with the dynamics of the SIGEK model with frictionless investment and of the SIGE model.

Figure 8 plots the effects of a positive (expansionary) monetary policy shock. The model with pervasive inattentiveness predicts that output, consumption, investment, capital, hours worked, real wage and inflation all increase in the short run in response to a monetary expansion. The responses however do not show any hump-shaped pattern and, with few exceptions, they also 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 9 displays the responses to a positive intermediate-good productivity shock. By construction, the impact of this technology shock on output, consumption, investment and the real wage can be permanent. A positive productivity shock in fact permanently raises these variables but lowers hours worked and the output gap on impact, consistently with the findings in Galí (1999). Figure 10 displays the responses to a positive final-good productivity shock. Although the effect of this shock is transitory, the dynamics is qualitatively similar to that of the intermediate-good productivity shock.

[6] The value for η lies within the empirically plausible range for the lumpiness parameter indicated by Sveen and Weinke (2007). After analyzing the micro evidence reported by Doms and Dunne (1998), Sveen and Weinke suggest that the lumpiness parameter should take values between 0.06 and 0.12.

Turning to the aggregate demand (government spending) shock, figure 11 shows that a positive innovation to aggregate demand raises inflation, output, and hours worked. While increasing investment significantly, this shock has a negative wealth effect that induces consumption to fall.

Figure 12 displays the effects of a positive shock to the price markup. The shock makes the economy more competitive (the desired price markup decreases) and so inflation falls while output, consumption and investment increase on impact. However, all variables respond quickly because the price markup shock is also quite short-lived ($\rho_{\nu} = 0.28$). Figure 13 shows the effects of a positive wage markup shock (which corresponds to a fall in the desired markup). The real wage falls and there is an expansion in output, hours worked, consumption and investment. The fall in wages induces a fall in prices, so inflation falls and the central bank reduces the nominal interest rate over time to gradually push inflation back to its steady state value. Noticeably, the responses of most variables are both hump-shaped and delayed.

Even though the shape of the impulse response functions of the SIGEK model with frictionless investment is qualitatively similar to that of the model with pervasive inattentiveness, there are visible differences between them. As one would expect, the main quantitative difference is that the responses of some variables, especially those of capital and investment, are much larger because attentive final-good firms make their capital investment decisions every period, so they react instantly to shocks. Interestingly, a positive intermediate-good productivity shock in this economy raises hours worked instead of lowering them. The intuition is that, with frictionless capital adjustment, final-good firms invest much more because they expect to produce more. However, in order to expand their production, they have to both accumulate more capital and purchase more intermediate goods (recall that these goods are one input in the final-good production function). This pushes up the production of intermediate goods (see equation 22), which more than compensates the increase in productivity and leads intermediate-good firms to hire more labor (see equation 23).

Figures 8-9 and 11-13 also report the impulse response functions implied by the SIGE model. Overall, the dynamics does not change significantly when the SIGE model is augmented by a microfounded 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.

Overall, and in contrast with Thomas' findings, the impulse response analysis seems to indicate that lumpy investment is relevant for the business cycle, since there are substantial quantitative differences between the models' responses with lumpy and with frictionless investment.

4.2 Second moments: models versus U.S. aggregate data

We now examine whether the SIGEK model yields empirically reasonable aggregate dynamics by comparing the model's predictions with some key second order moments characterizing the post-86 U.S. economy. In particular, we focus on the volatility and autocorrelations of output, investment, consumption, hours, real wage and inflation, as well as on the cross-correlation of output with the other variables.[7]

Output and investment

Table 1 and figure 3 display output and investment moments in the U.S. data as well as the corresponding models' predictions. 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. It also does not perform well when it comes to fitting the lead-lag relation with output. The SIGEK model with frictionless investment ($\eta = 1$) does not perform much better than the classical model. In particular, the absence of sticky information in capital decisions makes investment too volatile (in both absolute and relative terms) with no persistence whatsoever. Even though the contemporaneous correlation with output is close to that observed in the data, all cross-correlations at lags other than zero are almost null. Pervasive inattentiveness, in turn, improves the ability of the model to fit the facts on output and investment. Output is less volatile and more persistent than in the classical model as well as in the frictionless investment model.[8] 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 high lags) and the overall shape of the cross-correlation curve.

By now, the results indicate that the SIGEK model is capable of delivering a plausible aggregate role for lumpy investment – the model's implied second moments of output and investment are significantly different from and closer to the data than those implied by an otherwise identical model with frictionless investment. We now analyze whether the quantitative differences in the models' output and investment moments extend to other key macroeconomic variables.

Consumption, hours, real wage and inflation

Table 2 reports the variabilities and autocorrelation coefficients of consumption, hours, real wage and inflation, and figure 4 plots the cross-correlations of these variables with output at different leads and lags.[9]

The results still exhibit interesting differences, both qualitatively and quantitatively, between the lumpy and the frictionless investment model. In particular, the inclusion of lumpy investment adjustment does affect and, most importantly, improve the model's performance along these dimensions. The crucial conclusion is

[7] All data have been taken from the FRED database available through the Federal Reserve Bank of St. Louis. The cyclical components of each series have been obtained applying the Baxter-King bandpass filter and they are similar to those obtained with the Hodrick-Prescott filter.

[8] The SIGE model yields similar moments for output.

[9] The SIGE model yields similar predictions.

Table 1: Aggregate output and investment, models vs data in the post-86 U.S.

Series		Standard deviation absolute	Standard deviation relative to output	coefficients of autocorrelation (order) 1	2	3	4
output	data	0.90	1.00	0.93	0.76	0.52	0.29
	classical	3.16	1.00	0.60	0.51	0.48	0.46
	SIGEK ($\eta = 1$)	4.34	1.00	0.35	0.30	0.29	0.29
	SIGEK	2.67	1.00	0.90	0.83	0.79	0.75
investment	data	4.33	4.84	0.93	0.75	0.51	0.27
	classical	24.61	7.78	0.14	0.01	-0.01	-0.01
	SIGEK ($\eta = 1$)	23.39	5.39	0.05	0.00	0.00	0.01
	SIGEK	6.41	2.40	0.71	0.56	0.46	0.40

Note. The moments for U.S. data have been obtained applying the Baxter-King bandpass filter to the logarithm of the original series, with a band of 6 to 32 quarters.

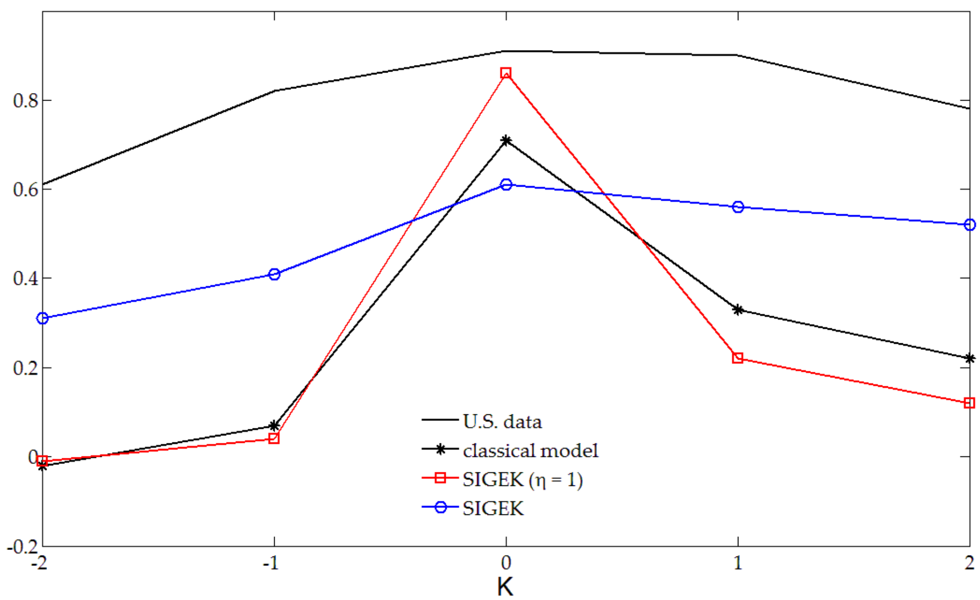

Figure 3: Cross-correlation of investment with output at lag K, $K = \{-2, -1, 0, 1, 2\}$

Note. The figure reports the cross-correlation of the cyclical component of investment with the $K-$quarter lag of the cyclical component of output. The moments for U.S. data have been obtained applying the Baxter-King bandpass filter to the logarithm of the original series, with a band of 6 to 32 quarters. U.S. data: black line. SIGEK model: blue-circle line. SIGEK model ($\eta = 1$): red-square line. Classical model: black-asterisk line.

Table 2: Aggregate variables, models vs data in the post-86 U.S.

Series		Standard deviation: absolute	Standard deviation: relative to output	coefficients of autocorrelation (order): 1	2	3	4
consumption	data	0.79	0.88	0.95	0.81	0.61	0.41
	classical	3.09	0.98	0.56	0.45	0.41	0.38
	SIGEK ($\eta = 1$)	1.96	0.45	0.94	0.89	0.83	0.79
	SIGEK	2.00	0.75	0.95	0.89	0.85	0.80
hours	data	1.39	1.55	0.96	0.86	0.70	0.52
	classical	6.42	2.03	0.43	0.32	0.29	0.27
	SIGEK ($\eta = 1$)	9.48	2.18	0.22	0.16	0.16	0.15
	SIGEK	5.33	2.00	0.83	0.73	0.65	0.60
real wage	data	1.00	1.11	0.91	0.69	0.44	0.25
	classical	2.22	0.70	0.44	0.31	0.27	0.26
	SIGEK ($\eta = 1$)	1.45	0.33	0.86	0.72	0.63	0.57
	SIGEK	1.56	0.59	0.88	0.77	0.69	0.63
inflation	data	0.23	0.26	0.65	0.58	0.58	0.57
	classical	2.03	0.64	0.23	0.08	0.04	0.03
	SIGEK ($\eta = 1$)	0.94	0.22	0.37	0.39	0.39	0.36
	SIGEK	0.70	0.26	0.88	0.81	0.74	0.67

Note. The moments for U.S. data have been obtained applying the Baxter-King bandpass filter to the logarithm of the original series, with a band of 6 to 32 quarters.

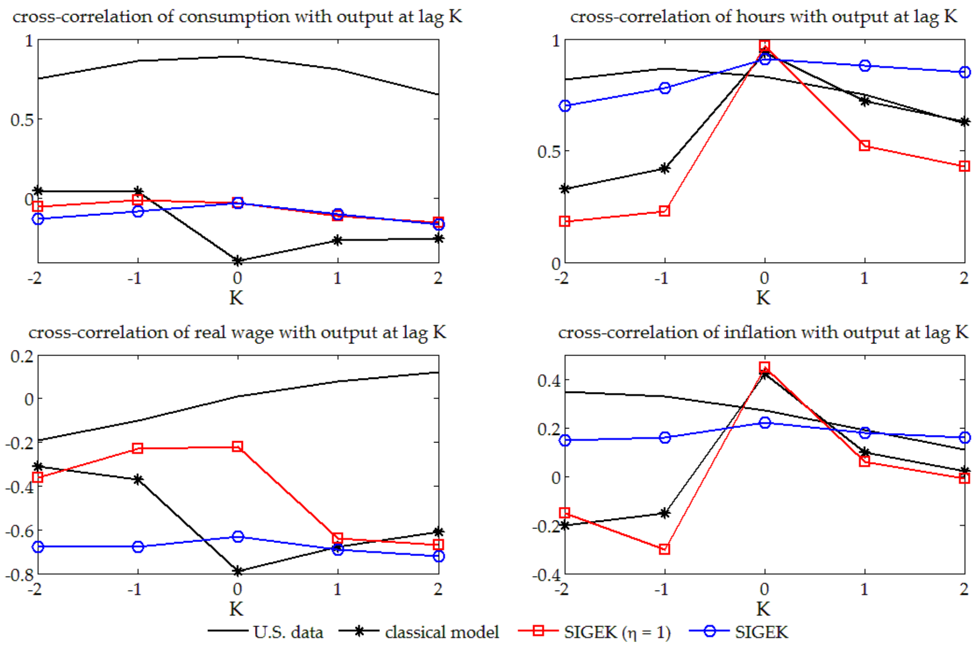

Figure 4: Cross-correlation of other variables with output at lag K, $K = \{-2, -1, 0, 1, 2\}$

Note. The figure reports the cross-correlation of the cyclical component of the respective variable with the $K-$quarter lag of the cyclical component of output. The moments for U.S. data have been obtained applying the Baxter-King bandpass filter to the logarithm of the original series, with a band of 6 to 32 quarters. U.S. data: black line. SIGEK model: blue-circle line. SIGEK model ($\eta = 1$): red-square line. Classical model: black-asterisk line.

that the model that overall best captures the moments of consumption, hours, real wage and inflation is the SIGEK model with pervasive inattentiveness.

We can thus conclude that the business cycle is clearly affected by lumpy investment at the micro-level. Moreover, pervasive sticky information improves the ability of the SIGEK model to overall mimic the dynamics of key macroeconomic data (although some moments, especially the cross-correlations of consumption and real wage with output, seem hard to mimic).

How sensitive are the second order moments of investment to changes in the degree of inattentiveness η?

The previous results have been obtained by setting the degree of information stickiness η to 0.10 for final-good firms, in line with the suggestion of Sveen and Weinke (2007). To check for robustness, figures 5-7 contrast the SIGEK model's investment moments with their empirical counterparts, for different values of the parameter η.

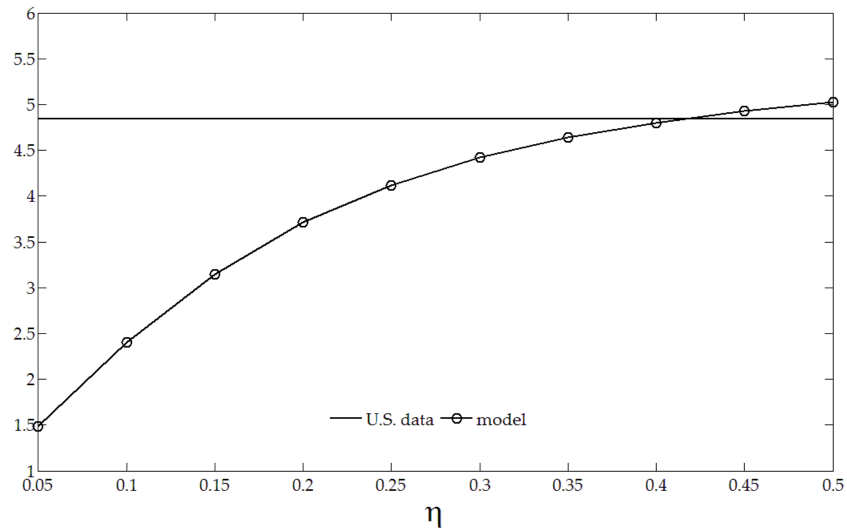

Figure 5: Standard deviation of investment (sensitivity analysis for different values of η)
Note. U.S. data: black line. SIGEK model: black-circle line. Other parameters than η: see table 4.

Recall that the stickier information is, the smaller is the fraction of updating firms (smaller η) and the smaller is the impact of shocks on capital and investment. Thus, as the degree of information stickiness increases (η decreases), investment should become less volatile and more persistent. Figures 5 and 6 confirm this conjecture. The standard deviation decreases and the autocorrelation function shifts upward as η decreases.

The figures further show that the SIGEK model has difficulties in simultaneously mimicking the volatility and the persistence of investment. On the one hand, the model is able to match the high volatility of investment observed in the data only when firms are often attentive, updating their information on average once every eight months ($\eta \simeq 0.4$). One the other hand, a high degree of information stickiness ($\eta < 0.1$) is required to match the high persistence of investment.

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

Finally, figure 7 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. Lower values of η (higher degrees of inattentiveness in investment) seem to improve the ability of the model to fit the overall lead-lag relation of investment with output.

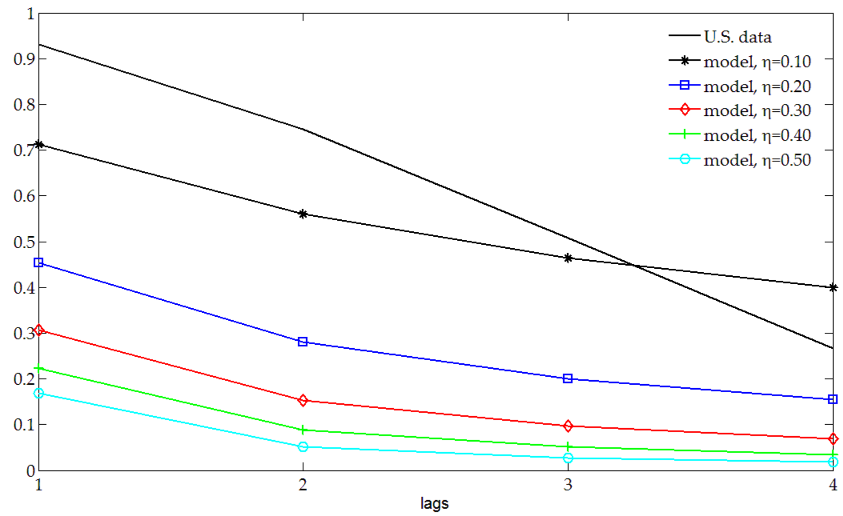

Figure 6: Autocorrelation of investment at lags 1 to 4 (sensitivity analysis for different values of η)

Note. U.S. 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 4.

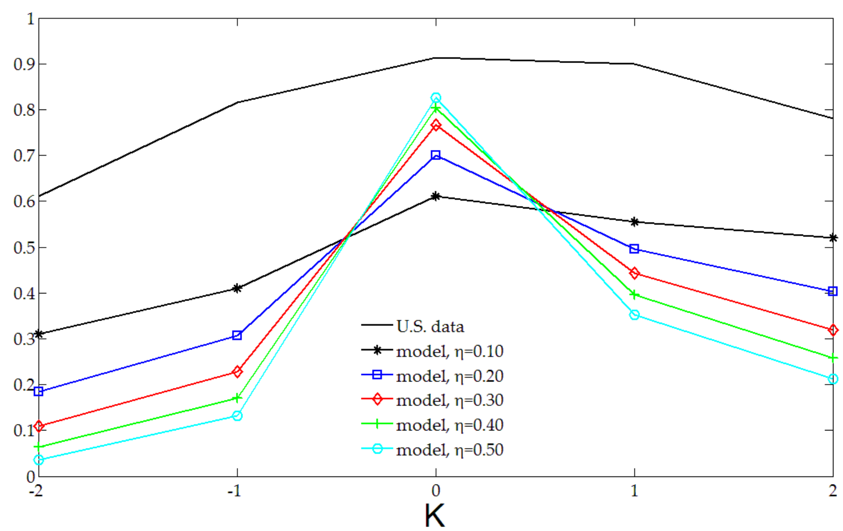

Figure 7: Cross-correlation of investment with output at lag K, $K = \{-2, -1, 0, 1, 2\}$ (sensitivity analysis for different values of η)

Note. U.S. 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 4.

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

In table 3 we report two moments of the aggregate investment rate. Columns 2 and 3 are taken from Verona (2011, table 2) and show the moments in the data (annual values) and the respective moments implied by his partial equilibrium model with lumpy investment. Columns 4 and 5 report the moments in the data (quarterly values) and the respective moments implied by the SIGEK model with pervasive inattentiveness.

Table 3 shows that there is an unambiguous improvement in the model fit moving from the partial equilibrium lumpy investment model to its general equilibrium counterpart with pervasive inattentiveness. In fact, while in a partial equilibrium framework the aggregate investment rate is less persistent and much more volatile than in the data, its persistence increases sharply (although still remaining lower than in the data) and its excessive volatility is virtually eliminated when lumpy investment is included in general equilibrium.[10]

Table 3: Aggregate investment rate, models vs U.S. data

	annual data 1984-2005[a,b]	partial equilibrium model [b]	quarterly data post-86[c]	SIGEK model [d]
serial correlation (corr $\left[\left(\frac{i}{k}\right)_t, \left(\frac{i}{k}\right)_{t-1}\right]$)	0.846	0.172	0.970	0.724
standard deviation	0.011	0.102	0.137	0.07

[a] Data are annual private fixed nonresidential investment-to-capital ratio. [b] See Verona (2011, table 2). [c] Data are quarterly private fixed investment-to-capital ratio. [d] Baseline parameters: see table 4.

5 Conclusion

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

In Verona (2011) we showed that lumpy capital adjustment behavior arises naturally when firms face costs of gathering, absorbing, and processing information. In this paper we have embedded that theoretical framework into the Mankiw and Reis (2006, 2007) SIGE model. Specifically, we have augmented the SIGE model with a set of firms that make capital investment decisions with inattentiveness. In the SIGEK model, as in the original SIGE model, inattentiveness is a pervasive feature of all markets and decisions, and it is the only feature that leads to a deviation from a classical model.

We 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 coun-

[10] Khan and Thomas (2008) obtain a similar result using a state-dependent lumpy investment model. They find that their general equilibrium model matches the data on aggregate investment rates much better than its partial equilibrium counterpart.

terpart. In delivering this result the model has strengthened the case in favor of the relevance of lumpy micro-level investment for the business cycle.

The SIGEK model has also allowed for addressing how far inattentiveness alone affects macroeconomic dynamics. We have found that the model with pervasive inattentiveness is better at matching business cycle moments than is either a classical model or an otherwise identical SIGEK model with frictionless investment. These findings are promising and confirm the Mankiw and Reis (2006) claim that pervasive inattentiveness 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 seems to be a fruitful approach for further business cycle and monetary policy analysis. In particular, we intend to estimate the model using both Bayesian and maximum likelihood methods so as to analyze a) how well the SIGEK model fits the business cycle and b) which are the optimal monetary policy rules in such estimated model.

Appendix A - Technical appendix

Inattentive consumers

Consumers, who revise their plans every period with a probability δ, have a value function $V(A_t)$ conditional on date t being a planning date. Consumers choose a plan for current ($\tau = 0$) and future ($\tau \geq 1$) consumption all the way into infinity $\{C_{t+\tau,\tau}\}_{\tau=0}^{\infty}$ considering that with a vanishingly small probability they may never update again:

$$\begin{aligned} V(A_t) &= \max_{\{C_{t+\tau,\tau}\}_{\tau=0}^{\infty}} \left\{ \sum_{\tau=0}^{\infty} \xi^{\tau} (1-\delta)^{\tau} \ln C_{t+\tau,\tau} + \xi\delta \sum_{\tau=0}^{\infty} \xi^{\tau} (1-\delta)^{\tau} E_t \left[V(A_{t+1+\tau}) \right] \right\} \\ \textit{subject to} \quad & A_{t+1+\tau} = \Pi_{t+1+\tau} \left(A_{t+\tau} - C_{t+\tau,\tau} + \frac{W_{t+\tau,\tau} L_{t+\tau,\tau} + T_{t+\tau}}{P_{t+\tau}} \right) \quad for\ \tau = 0, 1, 2, ... \end{aligned}$$

The first term in the Bellman equation equals the expected discounted utility if the consumer never updates her information again. The second term includes the sum of the continuation values over all of the possible future dates at which the agent may plan again, each occurring with a probability $\delta(1-\delta)^{\tau}$. Since preferences are additively separable in consumption and leisure, and since consumers do not control labor supply, then the term in leisure drops out of the problem.

The optimality conditions are:

$$\begin{gathered} \xi^{\tau} (1-\delta)^{\tau} \tfrac{1}{C_{t+\tau,\tau}} \\ = \\ \xi\delta \textstyle\sum_{k=\tau}^{\infty} \xi^{k} (1-\delta)^{k} E_t \left[V'(A_{t+1+k}) \bar{\Pi}_{t+\tau,t+1+k} \right] \quad for\ \tau = 0, 1, 2, ... \end{gathered} \tag{A.1}$$

where

$$\bar{\Pi}_{t+\tau,t+1+k} = \prod_{z=t+\tau}^{t+k} \Pi_{z+1}$$

is the compound return between $t+\tau$ and $t+1+k$.

The envelope theorem condition is:

$$V'(A_t) = \xi\delta \sum_{k=0}^{\infty} \xi^{k} (1-\delta)^{k} E_t \left[V'(A_{t+1+k}) \bar{\Pi}_{t,t+1+k} \right] \quad . \tag{A.2}$$

Combining (A.1) for $\tau = 0$ with (A.2) yields $1/C_{t,0} = V'(A_t)$, that is, the marginal utility of an extra unit of consumption equals the marginal value of an extra unit of wealth. Writing (A.2) recursively and using the last result gives

$$\frac{1}{C_{t,0}} = V'(A_t) = \xi E_t \left[\Pi_{t+1} V'(A_{t+1}) \right] = \xi E_t \left[\Pi_{t+1} \frac{1}{C_{t+1,0}} \right] .$$

Then considering (A.1) for $\tau \geq 1$ and (A.2) for date $t+\tau$ yields

$$\frac{1}{C_{t+\tau,\tau}} = V'(A_{t+\tau}) = E_t \left[\frac{1}{C_{t+\tau,0}} \right] \Leftrightarrow \frac{1}{C_{t,\tau}} = E_{t-\tau} \left[\frac{1}{C_{t,0}} \right] .$$

Inattentive workers

Workers, who revise their plans every period with a probability ω, have a value function $\hat{V}(A_t)$ conditional on date t being a planning date. Workers choose a plan for current ($\tau = 0$) and future ($\tau \geq 1$) wage all the way into infinity $\{W_{t+\tau,\tau}\}_{\tau=0}^{\infty}$, considering that with a vanishingly small probability they may never update again:

$$\begin{aligned} \hat{V}(A_t) = & \max_{\{W_{t+\tau,\tau}\}_{\tau=0}^{\infty}} \left\{ - \sum_{\tau=0}^{\infty} \xi^{\tau} (1-\omega)^{\tau} E_t \left[\frac{L_{t+\tau,\tau}^{1+1/\psi} + 1}{1+1/\psi} \right] \right. \\ & \left. + \xi\omega \sum_{\tau=0}^{\infty} \xi^{\tau} (1-\omega)^{\tau} E_t \left[\hat{V}(A_{t+1+\tau}) \right] \right\} \\ \textit{subject to} \quad & A_{t+1+\tau} = \Pi_{t+1+\tau} \left(A_{t+\tau} - C_{t+\tau,\tau} + \frac{W_{t+\tau,\tau} L_{t+\tau,\tau} + T_{t+\tau}}{P_{t+\tau}} \right) \quad \textit{for } \tau = 0,1,2,... \\ & L_{t+\tau,\tau} = \left(\frac{W_{t+\tau,\tau}}{W_{t+\tau}} \right)^{-\hat{\gamma}_{t+\tau}} N_{t+\tau} \quad \textit{for } \tau = 0,1,2,... \end{aligned}$$

The first term in the Bellman equation equals the expected discounted utility if the worker never updates her information again. The second term includes the sum of the continuation values over all of the possible future dates at which the agent may plan again, each occurring with a probability $\omega(1-\omega)^{\tau}$.

The optimality conditions are:

$$\begin{gathered} \xi^{\tau} (1-\omega)^{\tau} E_t \left(\hat{\gamma}_{t+\tau} L_{t+\tau,\tau}^{1+1/\psi} \right) / W_{t+\tau,\tau} \\ = \\ \xi\omega \textstyle\sum_{k=\tau}^{\infty} \xi^{k} (1-\omega)^{k} E_t \left[\hat{V}'(A_{t+1+k}) \bar{\Pi}_{t+\tau,t+1+k} (\hat{\gamma}_{t+\tau} - 1) L_{t+\tau,\tau} / P_{t+\tau} \right] \\ \textit{for } \tau = 0,1,2,... \end{gathered} \tag{A.3}$$

The envelope theorem condition is:

$$\hat{V}'(A_t) = \xi\omega \sum_{k=0}^{\infty} \xi^k (1-\omega)^k E_t \left[\hat{V}'(A_{t+1+k}) \bar{\Pi}_{t,t+1+k} \right] \quad . \tag{A.4}$$

Combining (A.3) for $\tau = 0$ with (A.4) gives

$$W_{t,0} = \frac{\hat{\gamma}_t}{\hat{\gamma}_t - 1} \frac{P_t L_{t,0}^{1/\psi}}{\hat{V}'(A_t)} \quad \Rightarrow W_{t+\tau,0} = \frac{\hat{\gamma}_{t+\tau}}{\hat{\gamma}_{t+\tau} - 1} \frac{P_{t+\tau} L_{t+\tau,0}^{1/\psi}}{\hat{V}'(A_{t+\tau})}$$

Writing (A.4) recursively yields

$$\hat{V}'(A_t) = \xi E_t \left[\hat{V}'(A_{t+1}) \Pi_{t+1} \right] \quad .$$

Combining these results implies

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

Condition (A.3) for $\tau \geq 1$ and (A.4) for date $t + \tau$ then imply

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

The log-linear sticky-information equilibrium

Log-linearizing the aggregate resource constraint (equation 1) and policy rules (equation 2) yields:

$$y_t^{FIN} = \alpha_c c_t + \alpha_i inv_t + g_t \quad , \tag{A.5}$$

$$r_t = i_t - E_t (\Delta p_{t+1}) \tag{A.6}$$

and

$$i_t = \phi_\pi \Delta p_t - \varepsilon_t \quad . \tag{A.7}$$

From the attentive agents' problems (equations 5 and 9, respectively):

$$y_{t,\tau}^{INT} = y_t - v (p_{t,\tau} - p_t) \tag{A.8}$$

$$l_{t,\tau} = l_t - \gamma (w_{t,\tau} - w_t) \quad . \tag{A.9}$$

From the inattentive consumer's problem (equation 12):

$$c_{t,\tau} = E_{t-\tau}\left[c_{t+1,0} - r_t\right] \quad . \tag{A.10}$$

From the inattentive worker's problem (equation 13):

$$w_{t,\tau} = E_{t-\tau}\left[p_t + \frac{1}{\psi}l_{t,\tau} - \frac{1}{\gamma-1}\gamma_t - r_t + w_{t+1,0} - p_{t+1} - \frac{1}{\psi}l_{t+1,0} + \frac{1}{\gamma-1}\gamma_{t+1}\right] \quad . \tag{A.11}$$

From the inattentive pricing department's problem (equations 10 and 11, respectively):

$$y_{t,\tau}^{INT} = a_t + \beta l_{t,\tau} \tag{A.12}$$

$$p_{t,\tau} = E_{t-\tau}\left[\omega_t - \left(y_{t,\tau}^{INT} - l_{t,\tau}\right) - \frac{v_t}{v-1}\right] \quad . \tag{A.13}$$

From the inattentive producing department's problem (equations 6, 7 and 8, respectively):

$$y_{t,\tau}^{FIN} = z_t + (1-\alpha)\, y_t + \alpha k_{t-1,\tau} \quad , \tag{A.14}$$

$$k_{t,\tau} = E_{t-\tau}\left[y_{t+1} - \frac{r}{(r+\rho)(1-\alpha)}r_t + \frac{1}{1-\alpha}z_{t+1}\right] \tag{A.15}$$

$$inv_{t,\tau} = \frac{1}{\rho}k_{t,\tau} - \frac{1-\rho}{\rho}k_{t-1,\tau} \quad . \tag{A.16}$$

Aggregating (A.12) gives the aggregate intermediate-good production function

$$y_t^{INT} = a_t + \beta l_t \quad , \tag{A.17}$$

and the market clearing condition implies that $y_t^{INT} = y_t$.

Aggregating (A.14) and (A.16) over τ gives the aggregate final-good production function and aggregate investment:

$$y_t^{FIN} = z_t + (1-\alpha)\, y_t + \alpha k_{t-1} \tag{A.18}$$

$$inv_t = \frac{1}{\rho}k_t - \frac{1-\rho}{\rho}k_{t-1} \quad . \tag{A.19}$$

Finally, the log-linearized definitions of price, wage, consumption and capital indices are:

$$p_t = \lambda \sum_{\tau=0}^{\infty} (1-\lambda)^{\tau}\, p_{t,\tau} \tag{A.20}$$

$$w_t = \omega \sum_{\tau=0}^{\infty} (1-\omega)^{\tau} w_{t,\tau} \tag{A.21}$$

$$c_t = \delta \sum_{\tau=0}^{\infty} (1-\delta)^{\tau} c_{t,\tau} \tag{A.22}$$

$$k_t = \eta \sum_{\tau=0}^{\infty} (1-\eta)^{\tau} k_{t,\tau} \tag{A.23}$$

This set of 19 equations (A.5 - A.23) provides the competitive equilibrium solution for the set of 19 variables (y_t^{FIN}, $y_{t,\tau}^{FIN}$, y_t, $y_{t,\tau}^{INT}$, y_t^{INT}, c_t, $c_{t,\tau}$, l_t, $l_{t,\tau}$, w_t, $w_{t,\tau}$, p_t, $p_{t,\tau}$, inv_t, $inv_{t,\tau}$, k_t, $k_{t,\tau}$, r_t, i_t) as a function of six exogenous shocks (Δa_t, g_t, ε_t, z_t, v_t and γ_t).

The reduced-form sticky-information equilibrium

Leading (A.18) one period and replacing for y_{t+1} in equation (A.15) gives

$$k_{t,\tau} = E_{t-\tau}\left[\frac{y_{t+1}^{FIN} - \alpha k_t}{1-\alpha} - \frac{r}{(r+\rho)(1-\alpha)} r_t\right] \quad .$$

Replacing for $k_{t,\tau}$ in (A.23) gives the expression for aggregate capital stock:

$$k_t = \eta \sum_{\tau=0}^{\infty} (1-\eta)^{\tau} E_{t-\tau}\left[\frac{y_{t+1}^{FIN} - \alpha k_t}{1-\alpha} - \frac{r}{(r+\rho)(1-\alpha)} r_t\right] \quad . \tag{A.24}$$

Combining equations (A.8), (A.12) and (A.13) to replace for $p_{t,\tau}$, $l_{t,\tau}$ and $y_{t,\tau}^{INT}$ in equation (A.20) gives:

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

Using (A.18) to replace for y_t in the previous equation gives the aggregate supply relation:

$$\begin{aligned} p_t \quad = \quad & \lambda \sum_{\tau=0}^{\infty} (1-\lambda)^{\tau} E_{t-\tau}\Bigg[p_t + \frac{\beta(w_t - p_t) + \frac{1-\beta}{1-\alpha}\left(y_t^{FIN} - z_t - \alpha k_{t-1}\right) - a_t}{\beta + v(1-\beta)} \\ & - \frac{\beta}{(v-1)[\beta + v(1-\beta)]} v_t\Bigg] \quad . \end{aligned} \tag{A.25}$$

Iterating forward on equation (A.10) yields

$$c_{t,\tau} = -\sum_{i=0}^{T} E_{t-\tau}(r_{t+1}) + E_{t-\tau}(c_{t+T+1,0}) \quad .$$

Next, take the limit as $T \to \infty$. As time elapses to infinity all agents become aware of past news so $\lim_{i\to\infty} E_t\left(r_{t+i}\right) = \lim_{i\to\infty} E_t\left(r^n_{t+i}\right) = 0$. Moreover, since the probability of remaining inattentive falls exponentially with the length of the horizon, one can approach this limit fast enough to ensure that the sum in the first term converges. As for the second term, $\lim_{i\to\infty} E_t\left(c_{t+i,0}\right) = \lim_{i\to\infty} E_t\left(c^n_{t+i}\right) = c^n_t$. The first equality holds because consumers are fully insured every period and in the limit all are informed. The second equality holds because c^n_t follows a random walk. Using the definition of the long rate R_t, the expression above becomes:

$$c_{t,\tau} = E_{t-\tau}\left(c^n_t - R_t\right) \ .$$

Replacing for $c_{t,\tau}$ in (A.22) gives the IS curve:

$$c_t = \delta \sum_{\tau=0}^{\infty} (1-\delta)^\tau E_{t-\tau}\left(c^n_t - R_t\right) \ . \tag{A.26}$$

Performing analogous step, iterating forward on (A.11) and using the fact that $\left(w^n_t - p^n_t - \frac{l^n_t}{\psi}\right) = c^n_t$ results in

$$\psi w_{t,\tau} = E_{t-\tau}\left[\psi p_t + l_{t,\tau} - \frac{\psi\gamma_t}{\gamma-1} - \psi R_t\right] + \psi c^n_t \ .$$

Using (A.9) to replace for $l_{t,\tau}$ and replacing $w_{t,\tau}$ in (A.21) gives the wage curve:

$$\begin{aligned} w_t \ &= \ \omega \sum_{\tau=0}^{\infty} (1-\omega)^\tau E_{t-\tau}\left[p_t + \frac{\gamma}{\gamma+\psi}\left(w_t - p_t\right) + \right. \\ &\left. + \frac{\frac{\left(y^{FIN}_t - z_t - \alpha k_{t-1}\right)}{1-\alpha} - a_t}{\beta\left(\gamma+\psi\right)} + \frac{\psi}{\left(\gamma+\psi\right)}\left(c^n_t - R_t\right) - \frac{\psi}{\left(\gamma+\psi\right)\left(\gamma-1\right)}\gamma_t\right] \ . \end{aligned} \tag{A.27}$$

Equations (A.24)-(A.27), together with aggregate investment (A.19), the aggregate budget constraint (A.5), the Fisher equation (A.6) and the Taylor rule (A.7) characterize the equilibrium for y^{FIN}_t, c_t, w_t, p_t, inv_t, k_t, r_t and i_t given exogenous shocks to Δa_t, ε_t, γ_t, v_t, z_t and g_t.

The classical equilibrium

In the classical economy, $\lambda = \omega = \delta = \eta = 1$ so all agents are attentive. The model collapses into the following system of 9 equations in 9 variables (y^{FIN}_t, y_t , c_t, inv_t, w_t, p_t, k_t, r_t and i_t):

$$c_t = E_t\left[c_{t+1} - r_t\right]$$

$$\beta\left(w_t - p_t\right) + (1-\beta)\, y_t - a_t - \frac{\beta}{(v-1)} v_t = 0$$

$$\psi\left(w_t - p_t\right) = \frac{y_t - a_t}{\beta} + \frac{\psi}{\theta}c_t - \frac{\psi}{(\gamma - 1)}\gamma_t$$

$$y_t^{FIN} = \alpha_c c_t + \alpha_i inv_t + g_t$$

$$k_t = E_t\left[y_{t+1} - \frac{r}{(r+\rho)(1-\alpha)}r_t + \frac{1}{1-\alpha}z_{t+1}\right]$$

$$inv_t = \frac{1}{\rho}k_t - \frac{1-\rho}{\rho}k_{t-1}$$

$$y_t^{FIN} = z_t + (1-\alpha)\,y_t + \alpha k_{t-1}$$

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

$$i_t = \phi_\pi \Delta p_t - \varepsilon_t \ .$$

Defining:

$$\Omega_1 = 1 - \beta + \frac{1}{\psi} \ ; \ \Omega_2 = \frac{r}{(r+\rho)(1-\alpha)} \ ; \ \Omega_3 = \alpha_c + \frac{(1-\alpha)\beta}{\Omega_1}$$

$$\Omega_4 = -\frac{\alpha_i}{\rho}\left(\Omega_2 + \frac{\beta}{\Omega_1}\right) \ ; \ \Omega_5 = \Omega_3 + \frac{\alpha_i \Omega_2}{\rho} - \left(\Omega_2 + \frac{\beta}{\Omega_1}\right)\left[\alpha - \frac{\alpha_i(1-\rho)}{\rho}\right]$$

$$\Omega_6 = \Omega_2\left[\alpha - \frac{\alpha_i(1-\rho)}{\rho}\right] \ ,$$

then c_t is the solution of the following expectational difference equation:

$$\Omega_4 E_t\left(c_{t+1}\right) + \Omega_5 c_t + \Omega_6 c_{t-1} = f\ \left(a_{t-1}, a_t, \gamma_{t-1}, \gamma_t, v_{t-1}, v_t, g_t, z_t, z_{t-1}\right) \ .$$

Using the solution for consumption, one can show that the solutions for all the other real variables (y_t^{FIN}, y_t , inv_t, $w_t - p_t$, k_t and r_t) are determined as a function only of the exogenous real shocks (Δa_t, γ_t, v_t, z_t and g_t), independently of the monetary policy shock ε_t. The classical dichotomy holds in this economy. The monetary policy shock determines the nominal interest rate and inflation through the Taylor rule and the Fisher equation.

Table 4: Structural parameters

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

Table 4: 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-good firms updating information every quarter
η	0.1	FV	fraction of final-good 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: our calibration.

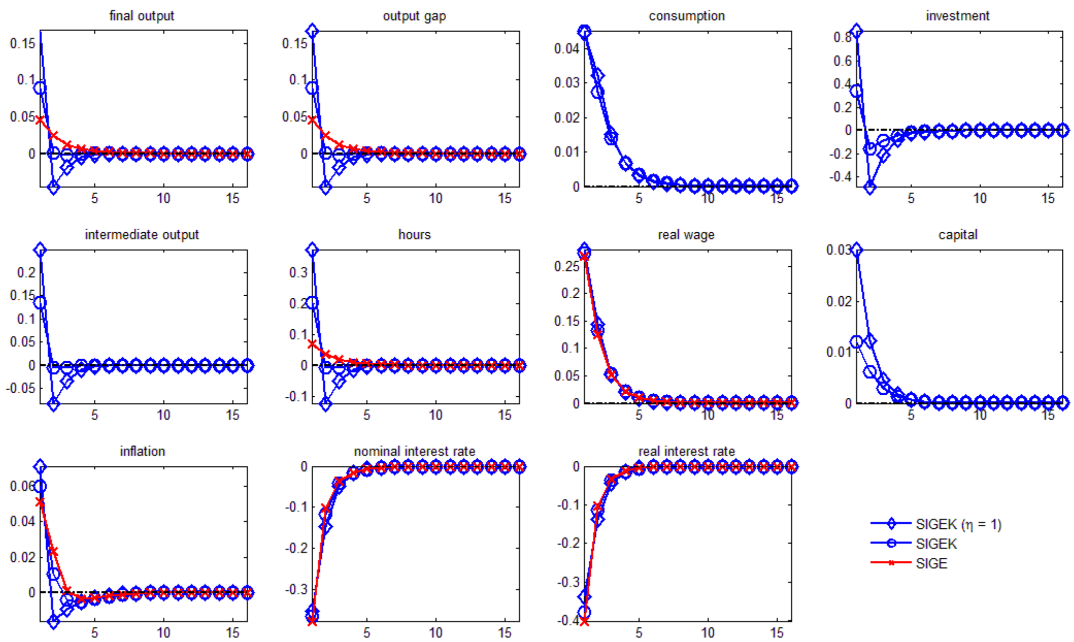

Figure 8: Impulse response functions to a monetary policy shock

Note. Values expressed as percentage deviation from steady state. 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 4.

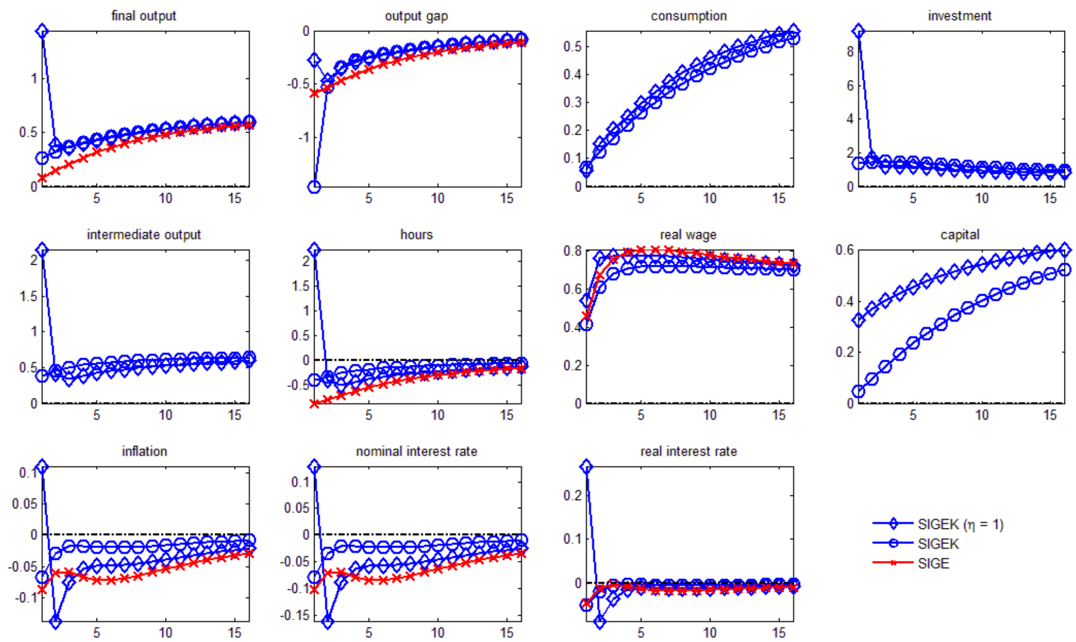

Figure 9: Impulse response functions to an intermediate-good productivity shock

Note. Values expressed as percentage deviation from steady state. 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 4.

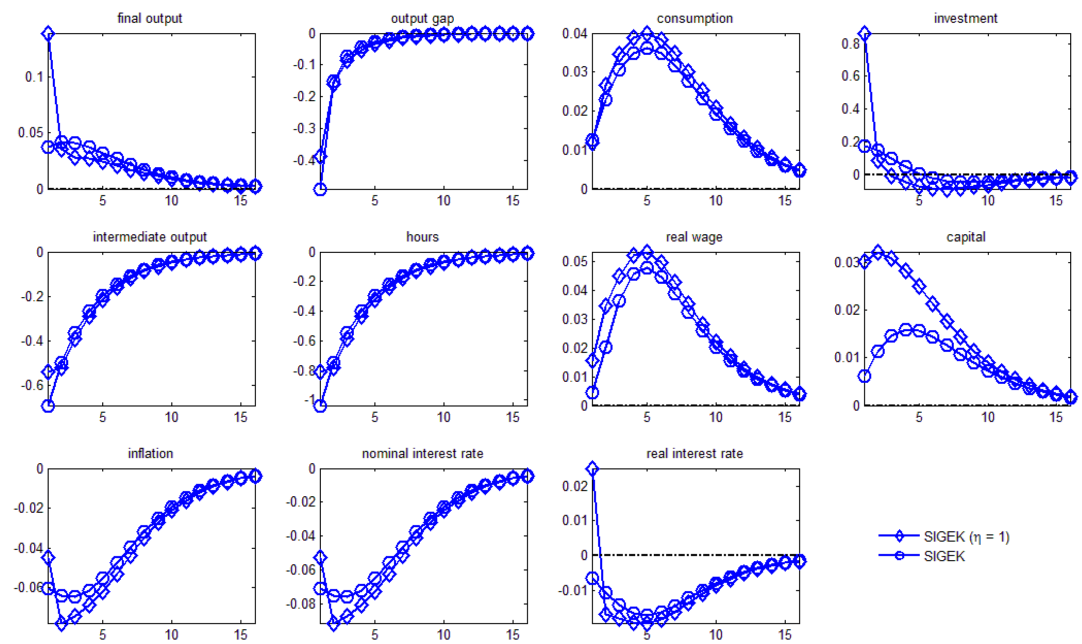

Figure 10: Impulse response functions to a final-good productivity shock

Note. Values expressed as percentage deviation from steady state. 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 4.

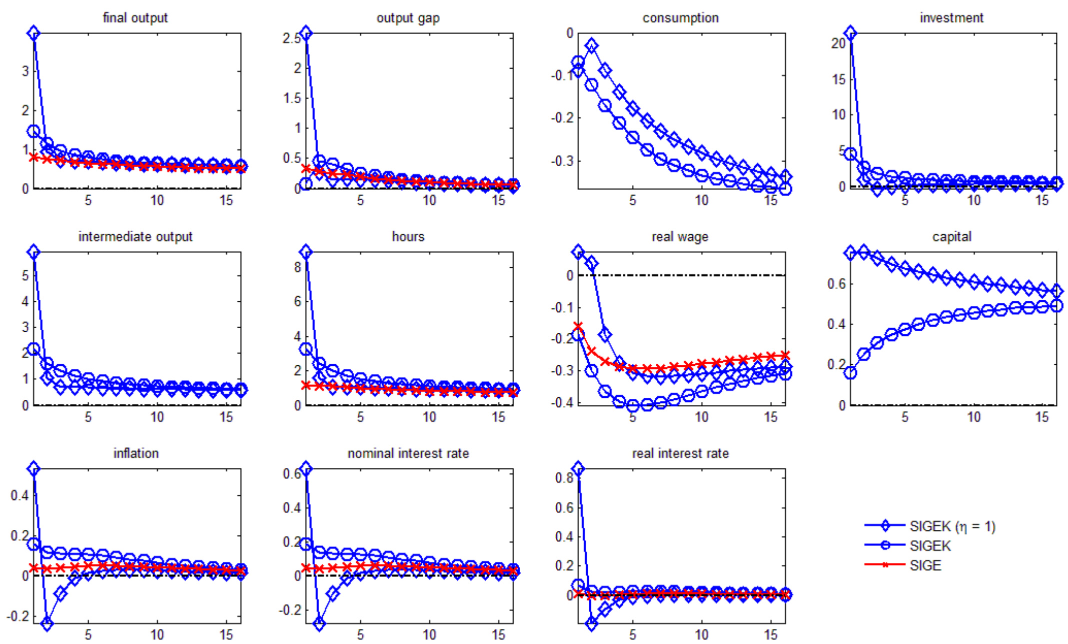

Figure 11: Impulse response functions to a demand shock

Note. Values expressed as percentage deviation from steady state. 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 4.

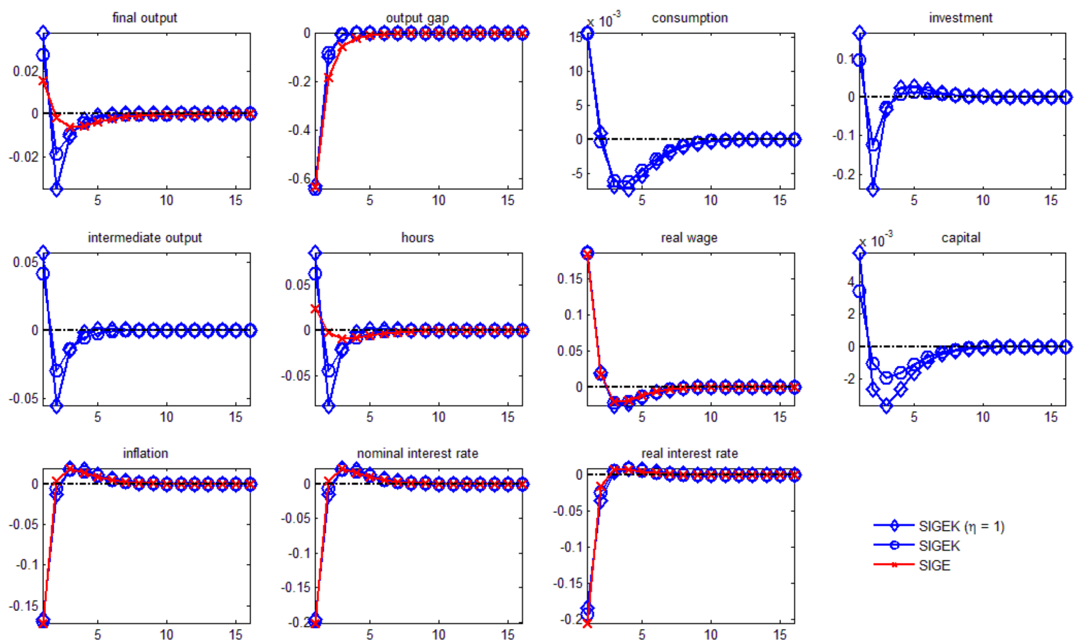

Figure 12: Impulse response functions to an intermediate-good markup shock

Note. Values expressed as percentage deviation from steady state. 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 4.

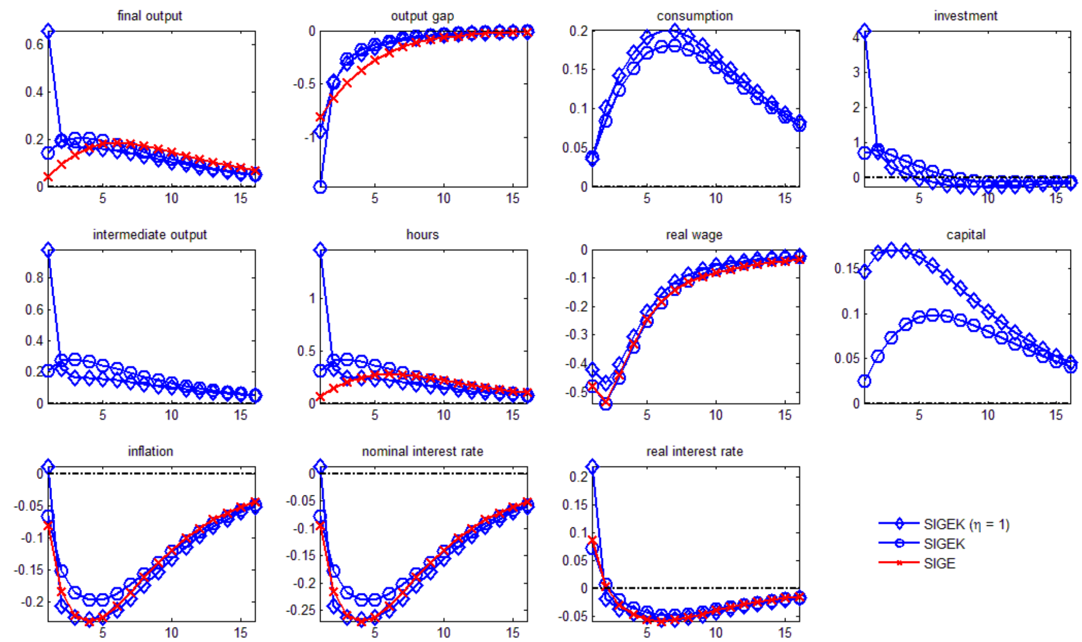

Figure 13: Impulse response functions to a wage markup shock

Note. Values expressed as percentage deviation from steady state. 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 4.

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