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**CAPITAL-EMBODIED TECHNOLOGICAL PROGRESS AND OBSOLESCENCE: HOW DO THEY AFFECT INVESTMENT BEHAVIOUR?**

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## ABSTRACT/RÉSUMÉ

**Capital-embodied technological progress and obsolescence: How do they affect investment behaviour?**

This paper analyses how technological progress embodied in capital goods raises productivity and income, while at the same time it can modify the allocation of consumption, investment and the capital stock. With capital-embodied technological progress, new capital goods become more productive, thus more valuable, but the production capacity of the existing capital goods declines comparatively and they become less valuable. In a dynamic and stochastic general equilibrium framework, a shock to the process of capital-embodied technological progress is shown not to raise investment as much as could be expected, allowing the owners of capital goods mainly to raise consumption instead. As a result, overall capacity taking account of the improvement in the quality of capital goods rises only modestly. The muted investment response might seem very conservative, because the owners of capital could take greater advantage of the sudden acceleration in the improvement of the quality of capital goods which allows them to raise their production capacity more than usually. However, this conservative behaviour is consistent with an anticipated faster decline in the value of capital goods which become quickly obsolete, raising the cost of capital for the owners. Finally, this paper analyses the implications of the shock to capital-embodied technological progress coinciding with other shocks, namely, a positive one to the investment accelerator mechanism and a negative one to the risk premium. With deceleration in the quality improvement of capital goods, investors would require higher rates of return while affecting negatively the valuation of the capital stock.

*JEL Classification:* D92; E22; O31; O47

*Keywords:* Capital stock; capital goods; technological progress; obsolescence; asset valuation; investment.

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## ABSTRACT/RÉSUMÉ

**Comment le progrès technologique et l'obsolescence incorporés dans les biens d'équipement jouent-ils sur les comportements d'investissement ?**

Dans le présent document, on analyse comment le progrès technologique incorporé dans les biens d'équipement permet d'accroître la productivité et le revenu, tout en modifiant dans le même temps l'allocation entre consommation, investissement et stock de capital. Grâce à l'incorporation des avancées technologiques, les biens d'équipement nouveaux gagnent en capacité productive et par conséquent, en valeur, tandis que la capacité de production du stock existant va comparativement en diminuant et perd en valeur. À l'aide d'un modèle d'équilibre général dynamique et stochastique, on observe qu'un choc sur le processus d'incorporation du progrès technologique dans les biens d'équipement n'a pas pour effet d'accroître l'investissement comme on pourrait s'y attendre, mais permet surtout aux détenteurs de capital productif d'augmenter leur consommation. Par conséquent, la capacité productive globale, qui tient compte de l'amélioration qualitative des biens d'équipement, ne progresse que modestement. Cette réaction en demi-teinte de l'investissement peut sembler très prudente, dans la mesure où les détenteurs de capital pourraient profiter plus largement de l'accélération soudaine de la qualité de biens d'équipement et augmenter ainsi leur capacité de production plus qu'habituellement. Cependant, cette prudence est cohérente avec la diminution plus rapide anticipée pour la valeur de biens d'équipement qui deviennent obsolètes à brève échéance et augmentent le coût du capital pour les détenteurs. Enfin, on analyse les implications de ce choc sur le processus d'incorporation du progrès technologique, qui coïncide avec d'autres chocs, à savoir un choc positif sur l'accélérateur d'investissement et un choc négatif sur la prime de risque. Face à une décélération de l'amélioration qualitative des biens d'équipement, les investisseurs exigeraient de meilleurs rendements, tandis que la valorisation du stock de capital serait affectée négativement.

*Classification JEL :* D92 ; E22 ; O31 ; O47

*Mots-clés :* stock de capital ; biens d'équipement ; progrès technologique ; obsolescence ; valorisation des actifs ; investissement.

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## **CAPITAL-EMBODIED TECHNOLOGICAL PROGRESS AND OBSOLESCENCE: HOW DO THEY AFFECT INVESTMENT BEHAVIOUR?**

**By YOSUKE JIN<sup>1</sup>**

### **Introduction**

1. A recent OECD study shows that business investment declined at the peak of the crisis and that its recovery has been sluggish among the OECD countries (OECD, 2015). The study argues that sluggish business investment needs to be considered in the context of important structural changes, such as the rising share of ICT and intangible/knowledge-based investment which depreciates faster. The present paper highlights the role of capital-embodied technological progress. First, acceleration in capital-embodied technological progress (as was the case until the mid-2000s), is followed by a large loss in the value of old equipment, which raises the cost of capital that matters for capital owners. Second, the deceleration in capital-embodied technological progress since the mid-2000s translates into comparatively lower volume in investment (i.e. once it is quality-adjusted according to the NIPA methodology), all else equal. Furthermore, weak investment via the accelerator mechanism and a rise in risk premium can be associated with deceleration in capital-embodied technological progress.

2. Capital-embodied technological progress makes new capital goods more productive, thus more valuable, than older ones. According to the vintage capital model (Solow, 1960), different vintages of capital embody different states of technology, and capital-embodied technological progress raises productivity in the aggregate. Greenwood et al. (1997), assuming constant technological progress embodied in capital goods, derived a balanced growth path where output, consumption and investment all grow at a trend rate which combines both neutral and capital-embodied technological progress, while the quality-adjusted capital stock grows at a faster rate with the real interest rate remaining constant.

3. The key variable to identify capital-embodied technological progress is the constant-quality deflator of capital goods, first developed by Gordon (1990). It is used for quality-adjustments of investment and the capital stock, measuring capital goods of different vintages in terms of standard efficiency units, which reflect the difference in the productivity of different vintages. Capital-embodied technological progress can be then identified from a faster accumulation of capital which is due to the improvement in the quality of capital goods (i.e. more standard efficiency units), once the behavioural response of agents is separately identified (Greenwood et al., 1997; Greenwood and Krussel, 2007).

4. Once capital is controlled for quality and age, its price falls when capital-embodied technological progress occurs (Geske et al., 2007). This fall in the price applies to the whole class of capital goods, and the constant-quality deflator of capital goods is constructed on this basis. This decline in the price of

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capital goods is associated with an anticipated faster decline in the value of capital goods in the future due to the introduction of new capital goods which embody more advanced technologies (Jorgenson, 1999).

5. Capital-embodied technological progress induces “economic obsolescence” of existing capital goods, which is the loss in the value of existing capital because it is no longer technologically suited to economic conditions or because technically superior alternatives become available (Hulten and Wykoff, 1981; Diewert and Wykoff, 2006). Obsolescence is a value phenomenon, not one that affects the physical services provided by capital goods. It reduces the capitalisation value of the existing production capacity (Greenwood and Jovanovic, 1999; Laitner and Stlayanov, 2003). It generates capital losses to the owner of capital, thus raising the user cost of capital (Boucekkine et al., 2005).

6. This paper considers capital-embodied technological progress, along a balanced growth path identical to the one derived by Greenwood et al. (1997). Capital-embodied technological progress is identified by the declining constant-quality deflator of capital goods. Investment and the capital stock are quality-adjusted, thus capital goods of different vintages are measured in terms of standard efficiency units through the constant-quality deflator. The corresponding equilibrium rental rate per standard efficiency unit, derived using exactly the same formula as the conventional one (Whelan, 2002), is found to be constant, although the quality-adjusted capital stock rises at a faster pace. The equilibrium value of the marginal unit of quality-adjusted capital goods is constant, consistent with the constant rental rate per efficiency unit. The purchase price of new capital goods is found to be constant, all else equal, since the rise in the price due to their quality content and the decline in the price due to capital-embodied technological progress exactly offset each other.

7. The effects of a shock to the process of capital-embodied technological progress are then estimated within a framework of a dynamic stochastic general equilibrium (DSGE) model, focusing particularly on how capital owners would change their investment behaviour. A general equilibrium model is suitable for this analysis, in order to consider not only the production side (rise in productivity) but also the wealth side (the decline in the value of the existing capital). The model framework draws on Smets and Wouters (2007), while incorporating the identification of capital-embodied technological progress following Justiniano et al. (2011). In this paper, additionally, the properties of capital-embodied technological progress related to the capital goods, rental rate and the value of the capital stock, all quality adjusted, are built in the model.

8. In this model, a positive shock to the process of capital-embodied technological progress, that is, a more-than-usual improvement in the quality of new capital goods, leads to a rise in productivity which is reflected as a larger flow in volume of capital goods measured in terms of standard efficiency units. In this circumstance, on the one hand, capital owners can reduce their investment amount, since it is compensated by the improvement in the quality of capital goods. On the other hand, they can take advantage of the sudden acceleration in the improvement of the quality of capital goods, which allows them to raise their production capacity more than usually. At the same time, they have to take into account the eventual losses associated with their investment, since capital-embodied technological progress simultaneously induces a decline in the value of capital by certain, but unforeseeable, extent (economic obsolescence).

9. The analysis shows that the shock to capital-embodied technological progress does not raise investment as much as could be expected; this is in line with other recent findings, which found a limited contribution to cyclical output fluctuations (Schmitt-Grohe and Uribe, 2008; Justiniano et al., 2011). This paper considers in detail why the investment response is limited. The analysis in this paper finds that, on impact, investment rises only in quality-adjusted terms and the investment amount is virtually unchanged. This contrasts with Greenwood et al. (2000) as well as Benhabib and Hobijn (2003), which find a boom-like rise in investment following such a shock. This difference likely arises because the shock is associated with the decline in the value of the capital stock. The analysis shows that, on impact, the value of the

capital stock indeed declines somewhat, though not to the extent predicted by Greenwood and Jovanovic (1999), which in turn weighs down the investment amount. The analysis also shows that the owners of capital even reduce the investment amount gradually, which is at least initially more than compensated by the improvement in the quality of capital goods, thus overall the production capacity rises only slightly. The overall limited response in quality-adjusted investment seems very conservative because the owners of capital could take greater advantage of the sudden rise in investment opportunities. This conservative behaviour, however, may be consistent with an anticipated faster decline in the value of capital goods which become quickly obsolete. While reducing the actual amount of investment and total hours worked, the owners of capital raise consumption in a relatively durable way, which is pushed up by higher total rental payments.

10. Finally, the analysis in this paper also shows the implications of the shock to the process of capital-embodied technological progress coinciding with other shocks. A shock to capital-embodied technological progress may simultaneously generate a shock in the efficiency with which household savings are channelled into new productive capital goods, which is possibly related to the functioning of financial markets. Following such a shock there is a boom-like rise in near-term investment. The shock to capital-embodied technological progress may also simultaneously generate a shock which reduces the risk premium. If the risk premium rises as investors require excess returns, they lower the price of risky assets. Indeed, in a circumstance where the quality improvement decelerates, households are worse off in order to keep up the production capacity. This leads them to require higher rates of return on capital goods consistently with higher discount rates, resulting in a reduction in the value of the capital stock.

11. The remainder of this paper is structured as follows: Section 2 briefly reviews the theory of capital-embodied technological progress, specifying some properties to be considered in the empirical analysis that follows. Section 3 specifies key data which identify capital-embodied technological progress. Section 4 specifies the dynamic stochastic general equilibrium model which is estimated to investigate the effects of a shock to the process of capital-embodied technological progress. Section 5 discusses the baseline results and extends the empirical analysis. Section 6 concludes.

## Theory

12. In this section, the theory of capital-embodied technological progress is briefly reviewed and some properties to be built in the subsequent general equilibrium analysis are specified. This section mainly focuses on how the capital stock is quality-adjusted when taking account of capital-embodied technological progress and how the rental rate and the value of the marginal unit of capital goods are attached to the quality-adjusted capital stock. This section draws largely on Whelan (2002).

## Production

13. Following the vintage capital model by Solow (1960), the production function is given as follows:

$$(1) \quad Y(t) = A(t)K^p(t)^{\alpha(t)}L(t)^{1-\alpha(t)}.$$

The production function consists of two factors of production, capital,  $K^p$ , and labour,  $L$ , as well as total factor productivity associated with neutral technological progress,  $A$ .

14. The capital stock of a given time  $t$ ,  $K^p(t)$ , consists of capital goods of different vintages:

$$(2) \quad K^p(t) = \int_{-\infty}^t I(v)e^{\gamma v}e^{-\delta(t-v)}dv,$$

where  $I(v)$  stands for a cohort of capital goods with its vintage identified by  $v$ . The state of technology which is embodied in new capital goods improves at the rate  $\gamma$ , which is identified by  $e^{\gamma v}$ . The state of

technology embodied in capital goods which differs across vintages is reflected in “standard efficiency units”, the measurement of the volume of capital goods. Therefore, with capital-embodied technological progress, the flow of new capital goods is measured to be larger in volume, in terms of standard efficiency units, than that of old ones, given the same amount of investment. The volume of new capital goods grows continuously faster by  $\gamma$  per cent, if capital-embodied technological progress occurs continuously at the constant rate  $\gamma$ . The physical decay of capital goods should be taken into account once they are measured in terms of standard efficiency units (OECD, 2009), and here it is assumed that they decay at the constant rate  $\delta$ .<sup>2</sup>

15. The production associated with capital goods of a specific vintage,  $v$ , can be specified as:

$$(3) Y_v(t) = A(t)(I(v)e^{\gamma v}e^{-\delta(t-v)})^{\alpha(t)}L_v(t)^{1-\alpha(t)}.$$

It is assumed that the quantity of labour allocated to capital goods of different vintages is perfectly adjusted to the difference in their productivity, identified by their number of standard efficiency units. Then,  $L_v(t)$  is the quantity of labour that works with capital goods of vintage  $v$  at the time  $t$ . The output associated with capital goods of a given vintage falls over time, as they age and their share in the total capital stock (measured in standard efficiency units) falls, with  $L_v$  also falling over time exactly at the same pace.

### **Rental rate and price**

16. Given Equation (3), the producer maximises the profits generated by capital goods of a specific vintage:

$$(4) \pi_v(t) = A(t)(I(v)e^{\gamma v}e^{-\delta(t-v)})^{\alpha(t)}L_v(t)^{1-\alpha(t)} - w(t)L_v(t) - r_v(t)I(v)e^{-\delta(t-v)}.$$

The producer chooses how much labour should work with vintage, depending on its number of standard efficiency units, which is then paid at the wage rate  $w(t)$ . The rental rate of capital goods,  $I(v)$ , is  $r_v(t)$ ,

2. In practice, the capital stock is calculated by the perpetual inventory method (PIM), taking account of the efficiency of capital goods of different vintages (OECD, 2009). The stock of one particular class of capital goods (e.g. computer devices) is calculated first by measuring this class of capital goods of different vintages in terms of standard efficiency units, then by applying the cohort specific retirement-physical decay pattern, which is shown as:

$$K_t^j = \sum_{s=0}^T \tilde{h}_s^j \frac{I_{t-s}^j}{P_{t-s}^j},$$

where  $K_t^j$  is the stock of one particular class of capital goods,  $j$ , at time  $t$ ;  $I_{t-s}^j$  is the investment made at time  $t-s$ , with  $s$  being the age, in this particular class of capital goods;  $P_{t-s}^j$  is the constant-quality deflator for this class of capital goods  $j$ , for the cohort  $t-s$  (this is the price index of capital goods as measured by the Bureau of Economic Analysis);  $\frac{I_{t-s}^j}{P_{t-s}^j}$  is then the volume of capital goods of this particular class measured in terms of standard efficiency units;  $\tilde{h}_s^j$  is the cohort specific (i.e.  $t-s$ ) retirement-physical decay pattern. The productive capital stock then aggregates the stock of all classes of capital goods, using the user cost of capital as a weight:

$$K_t^P = \sum r_t^j K_t^j,$$

using the user cost of capital of each class of capital goods,  $r_t^j$ , as a weight for this class of capital goods in the total capital stock. For those classes of capital goods which depreciate quickly, thus with a higher user cost of capital, a higher weight is attached.

which is equal to the marginal productivity of  $I(v)$ , thus  $r_v(t) = \frac{\partial Y_v(t)}{\partial (I(v)e^{-\delta(t-v)})}$  under the no-arbitrage conditions in the rental market.  $r_v(t)$  in the third term on the right-hand side of Equation (4) is attached to  $I(v)$  in non-quality adjusted terms so far (which will be modified below), because it is helpful to show first how the difference in productivity across vintages (explained by  $e^{\gamma v}$ ) is reflected in different rental rates across vintages.

17. The price of a new unit of capital goods equals the discounted stream of rental payments over the future, thus:

$$(5) \quad p_v(v) = \int_v^\infty r_v(s) e^{-(r+\delta)(s-v)} ds.$$

Differentiating Equation (5) with respect to  $v$  yields  $\dot{p}_v(v) = (r + \delta)p_v(v) + \int_v^\infty e^{-(r+\delta)(s-v)} \frac{dr_v(s)}{dv} ds - r_v(v)$ . The rental rate of capital goods differs across different vintages and the term  $\frac{dr_v(s)}{dv}$  equals  $\gamma r_v(s)$ . From this property and Equation (5), the rental rate of capital goods can be rewritten as:

$$(6) \quad r_v(v) = p_v(v) \left( r + \delta + \gamma - \frac{\dot{p}_v(v)}{p_v(v)} \right)$$

with

$$r_v(t) = r_t(t) e^{-\gamma(t-v)}$$

which, if  $\gamma = 0$ , is identical to the conventional formula on the rental rate (Jorgenson, 1963; Hall and Jorgenson, 1967). This rental rate of a given vintage is higher by the factor of  $\gamma$  initially, but declines over time faster at the rate  $\gamma$ . This decline in the rental rate is associated with the fact that the value of capital goods declines as they age not only because of physical decay but also because of the introduction of new and improved capital goods making them comparatively less productive (“economic obsolescence”, Diewert and Wykoff, 2006).

18. The price of a unit of vintage  $v$  capital goods, which is the discounted stream of profits it generates over time, can be written as:

$$(7) \quad p_v(t) = \int_t^\infty r_v(s) e^{-(r+\delta)(s-t)} ds = e^{-(\gamma+\delta)(t-v)},$$

according to which the price of capital goods of the latest vintage is constant over time at unity (since  $v = t$ ).

From Equation (7), the price of a unit of vintage  $v$  investment good can be identified as:

$$(7)' \quad \ln(p_v(t)) = -(\gamma + \delta)(t - v),$$

by controlling quality changes, such that  $\theta \ln(X_v) = \gamma v$ :

$$(7)'' \quad \ln(p_v(t)) = -\gamma t + \theta \ln(X_v) - \delta(t - v).$$

The price of a unit of vintage  $v$  declines by  $\gamma$ , at time  $t$  when capital-embodied technological progress occurs, after controlling for quality changes,  $\theta \ln(X_v)$ , which in practical terms captures the effects of product characteristics such as computer memories. This decline in the price attributed to time,  $-\gamma t$ , is associated with an anticipated faster decline in value of capital goods in the future (Jorgenson, 1999).

19. When the capital stock is quality-adjusted, the corresponding rental rate, thus the marginal productivity of the quality-adjusted capital stock, should also be considered. Adjusting Equation (6) in

terms of standard efficiency units, that is, divided by  $e^{\gamma v}$ , yields  $\tilde{r}(t) = r_t(t)e^{-\gamma t}$ . The decline in the price of a unit specific to time  $t$  is  $p(t) = e^{-\gamma t}$ . Using this property and from Equation (6), the quality-adjusted rental rate applying for all vintages is:

$$(8) \quad \tilde{r}(t) = p_t(t) \left( r + \delta - \frac{p_t'(t)}{p_t(t)} \right)$$

which is identical to the conventional rental rate. As  $p_t(t)$  is constant over time (Equation (7)), the marginal productivity of the quality-adjusted capital stock also remains constant, although the quality-adjusted capital stock as a whole continues to increase at a higher rate by the factor of  $\gamma$ .

### **Wealth stock**

19. The wealth stock, the value aspect of a capital stock, also consists of capital goods purchased at different times,  $I(v)$ , with their vintage identified by  $v$ . In taking into account not only physical decay but also economic obsolescence (the loss in value due to the decline in economic efficiency), the wealth stock can be written as:

$$(9) \quad K^w(t) = \int_{-\infty}^t I(v) e^{-(\gamma+\delta)(t-v)} dv.$$

20. The wealth stock in quality-adjusted terms (once capital goods of different vintages are measured in terms of standard efficiency units), is shown to be identical to the productive capital stock, with the depreciation rate identical to the rate of physical decay:

$$(10) \quad \tilde{K}^w(t) = \int_{-\infty}^t I(v) e^{\gamma v} e^{-\delta(t-v)} dv = e^{\gamma t} K^w(t),$$

which shows that the quality-adjusted wealth stock grows  $\gamma$  per cent faster than the non-quality adjusted one. The value of the wealth stock can be obtained from multiplying this quality-adjusted wealth stock by the quality-adjusted price index (controlled by the age and quality changes, see Equation (7)'),  $p(t) = e^{-\gamma t}$ . Once the price index incorporates an anticipated decline in value of capital goods in the future, then no separate accounting for obsolescence is required (Jorgenson, 1999). Then, the value of capital goods across different vintages depends on how many standard efficiency units they can be converted into, which continues to decline over time due to the introduction of capital goods of new vintages which are more productive (thus more standard efficiency units) and valuable.

21. The decline in the value of the capital stock leads to capital losses to capital owners, which is attributed to the loss in economic efficiency (Diewert, 2006). Whether such capital losses matter or not depends on the definition of net income. From producers' perspective, the losses do not matter since their net income is defined taking account of how the productive capacity of the capital stock is maintained; thus for producers only the physical decay matters (or the cost of capital takes account only of  $\delta$ ). From capital owners' perspective, capital losses matter since their net income is defined taking account of how their wealth is maintained (or the cost of capital takes account not only of  $\delta$  but also of  $-\frac{p'(t)}{p(t)}$ ). And it is the latter notion which corresponds to the total return which financial markets require (Schreyer, 2005). Therefore, in order to keep their wealth intact, capital owners require higher profits per unit of capital goods, which are netted out by larger capital losses than would otherwise be the case. Such considerations, all else equal, lead capital owners to restrain the total amount of investment when a shock to capital-embodied technological progress occurs.

## Data

### *Constant-quality investment deflator*

22. As discussed, the price index of investment goods is key to identify technological progress embodied in investment goods.<sup>3</sup> The price index of a unit of vintage  $v$  investment good is:

$$(7)' \ln(p_v(t)) = -(\gamma + \delta)(t - v),$$

by controlling quality changes, such that  $\theta \ln(X_v) = \gamma v$ :

$$(7)'' \ln(p_v(t)) = -\gamma t + \theta \ln(X_v) - \delta(t - v).$$

Thus, after controlling for quality changes,  $\theta \ln(X_v)$ , in isolation,  $-\gamma t$  serves to identify capital-embodied technological progress.  $-\gamma t$  is the price change in all vintages which is specific to a given time. This is the essence in the price index for quality-adjusted equipment which was constructed first by Gordon (1990). This constant-quality deflator of capital goods is used to convert capital goods of different vintages into standard efficiency units.

23. The analysis here uses the price index of fixed private non-residential investment, which is the constant-quality investment goods deflator, calculated by the US Bureau of Economic Analysis. Then this price index is expressed as a ratio to the price index of personal consumption expenditure (PCE). The relative price derived here is basically the reciprocal of the number of quality units as measured by the US Bureau of Economic Analysis (Benhabib and Hobijn, 2003) and has been widely used in the literature.

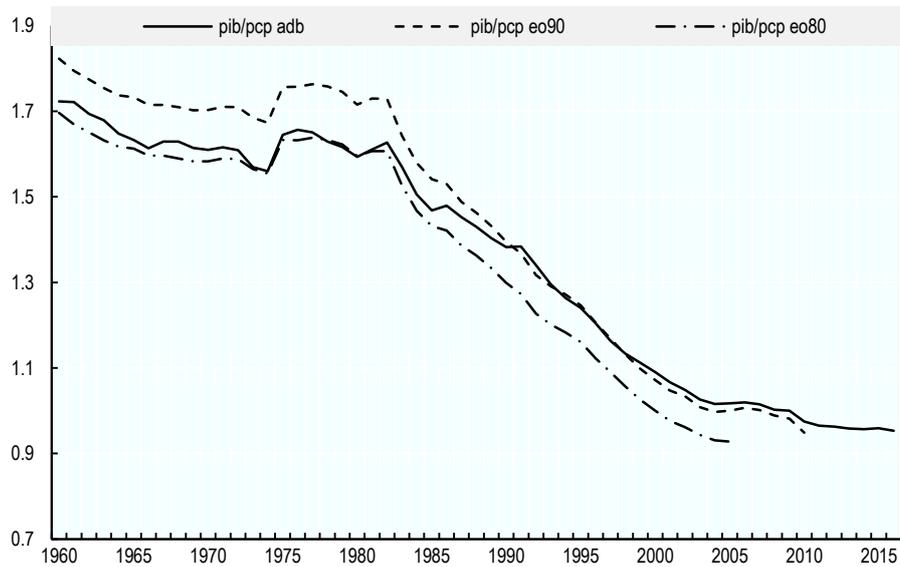
24. Figure 1 shows the evolution of the relative price of fixed private non-residential investment to personal consumption expenditure (PCE) over the past 50 years or so. The evolution is depicted differently according to the vintage of data, but in all cases, the relative price of capital goods declined rapidly over the period, in particular from the early 1980s to the mid-2000s. The difference between data vintages reflects such things as the change in the base year and a shift to the new SNA standard, but it also results from retrospective changes in the price index to take account of new technologies.

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3. The price index is typically measured through the Hedonic regression (e.g. Oliner, 1993; Doms et al., 2004), which can be illustrated as follows:

$$\ln p_{s,v,t} = a + \beta \cdot D_s + \mu \cdot D_v + \gamma \cdot D_t + \epsilon.$$

The price of a particular class of investment goods is explained by the age,  $s$ , by the vintage,  $v$ , and by the time of purchase,  $t$ . In this equation, the coefficient  $\beta$  captures the effects of depreciation, while the coefficient  $\mu$  captures the effects of product characteristics such as computer memories. The coefficient  $\gamma$  yields an estimate of the average price change of the class of assets under consideration, while controlling for the age and for the characteristics.  $\gamma$  declines when technological progress embodied in capital goods occurs (Equation (7)'').

**Figure 1. Evolution of the relative price of capital goods**

Note: “pib/pcp adb” shows the price index of non-residential business investment as a ratio to the price index of personal consumption expenditure, directly taken from the US Bureau of Economic Analysis in early 2017. “pib/pcp eo90” shows the ratio measured when the OECD Economic Outlook 90 was published in 2011 and “pib/pcp eo 80” shows the ratio measured when the OECD Economic Outlook 80 was published in 2006.

Source: OECD Analytical Database.

### *Consumption as numéraire*

25. In terms of growth accounting, there are two strands of measuring the improvement in the quality of capital goods: the Solow model and the Jorgenson model, following the terminology by Greenwood et al. (1997). Both of the models assume capital accumulation is quality-adjusted:

$$(2) \quad K^p(t) = \int_{-\infty}^t I(v)e^{\gamma v} e^{-\delta(t-v)} dv.$$

26. The models differ when it comes to the assumption for the resource constraint. According to the Jorgenson model, the resource constraint should also be quality-adjusted:

$$(11) \quad Y = C + I(v)e^{\gamma v} + G = A(K^p)^\alpha L^{1-\alpha}.$$

If  $I$  and  $e^{\gamma v}$  do not enter separately into the model, an optimal allocation for  $C$ ,  $K$ , and  $I$  is independent of the evolution of  $e^{\gamma v}$ , in other words, agents would choose the same path of  $I(v)e^{\gamma v}$  regardless of the evolution of  $e^{\gamma v}$ . In the Jorgenson model, changes in  $e^{\gamma v}$  will be exactly offset in general equilibrium by changes in  $I$  and hence, the implied changes in  $e^{\gamma v}$  are offset one to one by changes in non-quality adjusted  $I$  (Greenwood et al, 1997; Greenwood and Krussel, 2007).

27. According to the Solow model, the resource constraint should not be given in quality-adjusted terms:

$$(12) \quad Y = C + I + G = A(K^p)^\alpha L^{1-\alpha},$$

which identifies the contribution of the improvement in the quality of investment goods and the behavioural response of non-quality adjusted  $I$  separately. The following analysis adopts the assumption in the Solow model and measure  $I$  in non-quality adjusted terms in the resource constraint.

28. To be precise, all variables in the resource constraint are measured in terms of consumption units, deflating  $Y$ ,  $C$  and  $I$  by the PCE index. Simultaneously, capital-embodied technological progress is identified by the relative price of capital goods, which is reflected in the equation of capital accumulation. This is also consistent with the fact that the purchase price of new capital goods is constant despite capital-embodied technological progress, all else being equal: it does not decline with the constant-quality deflator (which is used for the purpose of accounting for the improvement in the quality of capital goods).

## Model

### *A standard DSGE model*

29. In the following empirical analysis, a dynamic stochastic general equilibrium (DSGE) model is estimated, which is essentially based on Smets and Wouters (2007). The DSGE model contains many frictions which affect households' and firms' decisions, enabling it to fit the macroeconomic data well (Christiano et al., 2005; Smets and Wouters, 2007).<sup>4</sup> Such frictions include habit formation in consumption, investment adjustment costs, fixed costs in production, and sticky nominal price and wage settings.<sup>5</sup>

30. The following model description focuses on households – the owner of capital; the full model description can be found in the Appendix to Smets and Wouters (2007). Households own the capital stock and rent capital services at a given rate and provide labour in order to maximise their objective function, subject to an intertemporal budget constraint and a standard motion of capital accumulation.

31. Household  $j$  chooses consumption  $C_t^j$ , hours worked  $L_t^j$ , and investment  $I_t^j$ , so as to maximise the following objective function:

- 
4. The model consists of: final goods producers, intermediate goods producers, households, the labour union sector, and the government. Final good producers buy intermediate goods of different prices on the market, package them into final output, and sell it to consumers and the government in a perfectly competitive market. Intermediate good producers use capital services and labour, and maximise their profits under a given production technology with fixed costs and pricing rules. Households are the owner of capital and rent capital services at a given rate and they provide labour in order to maximise their objective function subject to the budget constraint. They decide on the capital stock and investment in order to maximise their objective function, subject to the intertemporal budget constraint and a standard motion of capital accumulation. Households supply labour to an intermediate labour union which differentiates labour services and sets wages according to the wage-setting rules. The government follows a Taylor-rule type nominal interest rule with respect to deviations of inflation and output from their respective target levels.
  5. The Calvo model in both wage- and price-setting is augmented by the assumption that prices that are not optimised instantaneously are partially indexed to past inflation rates. Prices are therefore set in function of current and expected marginal costs, but are also determined by past inflation rates. Similarly, wages depend on past and expected future wages and inflation.

$$(13) \quad E_t \sum_{s=0}^{\infty} \beta^s \left[ \frac{1}{1-\sigma_c} (C_{t+s}^j - hC_{t+s-1}^j)^{1-\sigma_c} \right] \exp \left( \frac{\sigma_c-1}{1+\sigma_l} (L_{t+s}^j)^{1+\sigma_l} \right),$$

where  $\beta$  is the discount factor applied by households,  $\sigma_c$  is (the inverse of) the elasticity of intertemporal substitution,  $\sigma_l$  is (the inverse) of the elasticity of labour supply. The model includes external habit formation,  $h$ , which takes into account the externality in consumption, that is, individuals' consumption depends on past aggregate consumption levels.

32. The maximisation of the objective function is subject to the budget constraint:

$$(14) \quad C_{t+s}^j + I_{t+s}^j + \frac{B_{t+s}^j}{\varepsilon_t^b R_{t+s} P_{t+s}} - T_{t+s} \leq \frac{B_{t+s-1}^j}{P_{t+s}} + \frac{W_{t+s} L_{t+s}^j}{P_{t+s}} + \frac{R_{t+s}^k K_{t+s-1}^j}{P_{t+s}},$$

where  $W$  is the aggregate nominal wage rate and  $R^k$  is the rental rate of capital.  $R$  is the nominal interest rate controlled by the central bank.  $B$  is the one-period bond and  $\varepsilon^b$  is the shock on the discount factor, associated with the risk premium households require to hold assets. It represents a wedge between the interest rate controlled by the central bank and the rate at which households accumulate their assets. A positive shock to this wedge increases the required return on assets and reduces current consumption. Simultaneously, it also increases the cost of capital and reduces the value of capital and investment (see below). The disturbance is assumed to follow a first-order autoregressive process with an IID-normal error term:

$$\ln \varepsilon_t^b = \rho_b \ln \varepsilon_{t-1}^b + \eta_t^b, \eta_t^b \sim N(0, \sigma_b)$$

33. The maximisation of the objective function is also subject to the capital accumulation equation:

$$(15) \quad K_t^j = (1 - \delta) K_{t-1}^j + \varepsilon_t^i \left[ 1 - S \left( \frac{I_t^j}{I_{t-1}^j} \right) \right] I_t^j,$$

where  $\delta$  is the depreciation rate,  $S(\cdot)$  is the adjustment cost function with  $S(\cdot) = 0$ ,  $S'(\cdot) = 0$ , and  $S''(\cdot) > 0$  around equilibrium, as the adjustment costs arise from a change in investment rather than in the level of investment. Bloom (2009) shows that quadratic adjustment costs could be a reasonable approximation at the aggregate level. This adjustment cost function is associated with an accelerator mechanism built in the model. A high elasticity of adjustment costs reduces the sensitivity of investment to the value of the capital stock.

34. In Smets and Wouters (2007),  $\varepsilon^i$  was assumed to be the shock to capital-embodied technological progress without explicitly taking account of changes in the relative price of capital goods. In the framework developed here, which explicitly identifies such technological progress (see below), it is assumed that  $\varepsilon^i$  is related to the effectiveness with which the flow of household savings is channelled into new productive capital, which is called “investment efficiency shock”. One possible channel is the functioning of the financial sector, although this is not explicitly modelled here. Imperfect information between the capital producing borrowers and the financial intermediaries could give rise to a stochastic external finance premium (Bernanke et al., 1998). This assumption follows Justiniano et al. (2011) in demonstrating that  $\varepsilon^i$  is correlated with a decline in the spread between the returns on AAA corporate bonds and high-yield bonds. The shock follows a first-order autoregressive process with an IID-normal error term:

$$\ln \varepsilon_t^i = \rho_i \ln \varepsilon_{t-1}^i + \eta_t^i, \eta_t^i \sim N(0, \sigma_i).$$

35. In equilibrium, households will make the same choices for consumption, hours worked, and investment. The first-order conditions can be written as follows for consumption (Equation 16), labour supply (Equation 17), bonds holdings (Equation 18), investment (Equation 19) and capital (Equation 20).

$$(16) \quad \Xi_t = \exp\left(\frac{\sigma_c - 1}{1 + \sigma_l} L_t\right)^{1 + \sigma_l} (C_t - \lambda C_{t-1})^{-\sigma_c}$$

$$(17) \quad \left[\frac{1}{1 - \sigma_c} (C_t - \lambda C_{t-1})^{1 - \sigma_c}\right] \exp\left(\frac{\sigma_c - 1}{1 + \sigma_l} L_t\right) = -\Xi_t \frac{W_t^h}{P_t}$$

If the elasticity of intertemporal substitution is lower than 1 ( $\sigma_c > 1$ ), then consumption and hours worked are complements in utility, and consumption depends positively on current hours worked and negatively on expected growth in hours worked (Basu and Kimball, 2002).

$$(18) \quad \Xi_t = \beta \varepsilon_t^b R_t E_t \left[ \frac{\Xi_{t+1}}{\pi_{t+1}} \right]$$

where  $\Xi_t$  is the Lagrange multiplier associated with the budget constraint. This formulation can be thought to be the stochastic discount factor which determines the price of risk assets (Cochran, 2001). The stochastic discount factor discounts the future value in a manner that depends on future outcomes. This outcome dependence is included in order to make adjustment for risk (Hansen and Renault, 2009).

$$(19) \quad 1 = Q_t \varepsilon_t^i \left(1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right) \frac{I_t}{I_{t-1}}\right) + \beta E_t \left[ \frac{\Xi_{t+1}}{\Xi_t} Q_{t+1} \varepsilon_{t+1}^i S'\left(\frac{I_{t+1}}{I_t}\right) \left(\frac{I_{t+1}}{I_t}\right)^2 \right]$$

$$(20) \quad Q_t = \beta E_t \left[ \frac{\Xi_{t+1}}{\Xi_t} \left(\frac{R_{t+1}^k}{P_{t+1}}\right) + Q_{t+1} (1 - \delta) \right]$$

where  $Q_t = \frac{\Xi_t^k}{\Xi_t}$  is Tobin's Q, with  $\Xi_t^k$  being the Lagrange multiplier associated with the capital accumulation constraint. In the estimation of the (deviation from the) log-linearized model, the first-order condition for bond holdings (Equation 18) can be associated with that of the value of the capital stock (Equation 20). Then, the current value of the capital stock depends positively on its expected future value and the expected real rental rate on capital, and negatively on the *ex ante* real interest rate and the risk premium disturbance.

36. The aggregate production function is given by:

$$(21) \quad Y_t = \varepsilon_t^a K_t^\alpha [\gamma_z L_t]^{1 - \alpha} - \gamma_z \Phi$$

where  $K$  is the effective capital services used in production (the capital stock accumulated by the end of the previous period),  $L$  is aggregate labour input, and  $\Phi$  stands for the fixed costs of production.  $\gamma_z$  represents the labour-augmenting deterministic growth rate in the economy.  $\varepsilon^a$  is a separate shock to total factor productivity, and follows the process:

$$\ln \varepsilon_t^a = \rho_a \ln \varepsilon_{t-1}^a + \eta_t^a, \eta_t^a \sim N(0, \sigma_a).$$

### **Properties of capital-embodied technological progress**

37. As mentioned earlier, the model should explicitly identify capital-embodied technological progress from the data, drawing on Justiniano et al. (2011). The analysis in this paper will additionally

incorporate the properties of capital-embodied technological progress discussed in previous sections. As discussed in the previous section, capital-embodied technological progress is identified by changes in the relative price of investment goods. Given the same amount of investment, capital-embodied technological change generates a larger flow of investment when measured in terms of standard efficiency units than in the case where such progress does not exist. This process can be written as:

$$(22) \quad \tilde{I}_t = Y_t I_t, \text{ with } Y_t^{-1} = P_{It}/P_t,$$

and from Equation (7) the decline in the price of a unit of capital goods specific to time  $t$  is:

$$(23) \quad P_{It} = e^{-\gamma t}$$

where  $\tilde{I}$  is quality-adjusted investment (i.e. measured in terms of standard efficiency units),  $I$  is the investment amount measured in consumption units,  $P_I$  is the price index of investment goods (the constant-quality investment deflator) while  $P$  is the consumption price index.  $Y$  stands for the state of capital-embodied technological progress which generates the flow of capital goods in terms of standard efficiency units. Then the technology  $Y$  is assumed to grow at a trend rate,  $\gamma$ , which is subject to exogenous shocks  $\varepsilon^q$ .

$$\ln \varepsilon_t^q = \rho_q \ln \varepsilon_{t-1}^q + \eta_t^q, \eta_t^q \sim N(0, \sigma_q).$$

38. In Justiniano et al.'s framework, investment goods producers maximise their profits as they convert consumption goods into investment goods, the efficiency of which is explained by  $Y$ , while the price of investment goods they produce falls with capital-embodied technological progress. However, as shown in the previous section, the price of investment goods they use (which is in fact the constant-quality deflator of investment goods) is not the purchase price of new investment goods which in fact remains constant over time, all else equal (Equation (7)). The framework developed here does not assume investment goods producers. Instead, households, the owner of capital, take the improvement in the quality of capital goods as exogenous and acquire them at the market price, which is constant. They can of course internalise quality improvements, that is, higher production capacity associated with the rise in the quality-adjusted capital stock.

39. **ASSUMPTION 1.** Capital-embodied technological progress occurs at the constant rate  $\gamma$  around equilibrium, which is identified by the decline in the relative price of capital goods at the same rate  $\gamma$ ; the purchase price of new capital goods is however supposed to be constant with capital-embodied technological progress constantly taking place.

40. With this assumption, the capital accumulation equation can be re-written as:

$$(15)' \quad \tilde{K}_t(j) = (1 - \delta)_{t-1}(j) + \varepsilon_t^i \left[ 1 - S\left(\frac{I_t^j}{I_{t-1}^j}\right) \right] \tilde{I}_t(j).$$

The adjustment costs,  $S(\cdot)$ , are measured in terms of the investment amount, that is, in consumption units. This is because households acquire investment goods at the market price, and it is the change in the number of physical units, not the volume measured in terms of standard efficiency units, that matters for the calculation of the adjustment costs. In other words, given the same number of physical units, whether each unit is more productive or not does not matter in terms of the adjustment costs. Then, with capital-embodied technological progress, the capital stock continues to increase at a faster rate by  $\gamma$  than in the case where such progress does not exist.

41. Considering the value of the capital stock (Equation 20), the constant process of capital-embodied technological progress does not change the value of the marginal unit of quality-adjusted capital goods. This is because the rental rate per standard efficiency unit, which is applied to the whole class of vintages, remains constant (Equation 8). In differentiating the rental rate across different vintages (Equation 6), the rental rate of investment goods of the latest vintage is always higher by  $\gamma$ , but the whole class of capital goods, once installed, continues to lose the value at rate  $\gamma$ . These two effects offset each other exactly, which is recursive in terms of the relationship between  $Q_t$  and  $Q_{t+1}$ .

42. ASSUMPTION 2. The quality-adjusted capital stock continues to increase at a faster rate by the factor of  $\gamma$  as capital-embodied technological progress takes place constantly at the rate  $\gamma$ ; however the rental rate per standard efficiency unit remains constant around equilibrium.

43. ASSUMPTION 3. Consistent with the constant rental rate per standard efficiency unit, the value of the marginal unit of quality-adjusted capital goods is constant around equilibrium.

44. With Assumption 2, the aggregate production function can be re-written as:

$$(21)' \quad Y_t = \varepsilon_t^{\alpha} \tilde{K}_t^{\alpha} [\gamma_Z L_t]^{1-\alpha} - \gamma_* \Phi$$

where  $\tilde{K}$  is the effective capital services used in production, which is now quality-adjusted (measured in terms of standard efficiency units). The model then incorporates a balanced steady-state growth path driven by growth in neutral as well as capital-embodied technological progress. Output, consumption, non-quality adjusted investment are then assumed to grow at this composite trend rate,  $\gamma_*$ , while the quality-adjusted capital stock grows at an even faster rate by the factor of  $\gamma$ . The assumption on the trend growth rates correspond exactly to Greenwood et al. (1997) and Greenwood and Krussel (2007). Following Justiniano et al. (2011), the composite trend growth rate can be written as:  $\gamma_* = \gamma_Z \times \gamma^{\frac{\alpha}{1-\alpha}}$ , with  $\gamma_Z$  being the deterministic growth rate of labour-augmenting (neutral) technological progress and  $\alpha$  being the share of capital in production which is constant. As  $Y$  is de-trended by the composite trend rate,  $\gamma_*$ , the fixed costs of production also need to be de-trended by the same rate in order to ensure the existence of a balanced growth path.

45. ASSUMPTION 4. At the steady state, output, consumption and the investment amount all grow at the composite trend growth rate  $\gamma_* = \gamma_Z \times \gamma^{\frac{\alpha}{1-\alpha}}$ , taking account of both neutral and capital-embodied technological progress.

46. In contrast, the aggregate resource constraint is written as:

$$(24) \quad P_t C_t + P_t I_t + P_t G_t = P_t Y_t$$

or

$$(24)' \quad C_t + I_t + G_t = Y_t,$$

as mentioned in the previous section. All are measured in terms of consumption units in the resource constraint, thus investment is not quality-adjusted, while investment and the capital stock are quality-adjusted only in the capital accumulation equation, which makes it possible to identify the behavioural response of agents.

47. Then, the full model is re-written in stationary terms. In particular, the variables with the deterministic trend, including output, consumption, investment and wages are de-trended by the composite

trend growth rate  $\gamma_* = \gamma_z \times \gamma^{\frac{\alpha}{(1-\alpha)}}$ , ; in the capital accumulation equation, investment and the capital stock should also be de-trended additionally by  $\gamma_* \times \gamma = \gamma_z \times \gamma^{\frac{(1+\alpha)}{(1-\alpha)}}$ , while the steady-state rental rate,  $R^k$ , will remain the same (Equation 8).

48. Finally, the model is log-linearized around the steady state. The full specification of the estimated model can be found in Smets and Wouters (2007, pp. 588-591). In this paper, the model consists of 14 equations determining 14 endogenous variables, including just one more equation to those in Smets and Wouters (2007), namely, the process of the improvement in the quality of investment goods (Equations 22).<sup>6</sup> The stochastic behaviour of the system of linear rational expectations equations is driven by eight exogenous disturbances, including also just one more disturbance on the process of capital-embodied technological progress. The model is then estimated using eight key observable variables, again adding just one more variable in the measurement equation, namely, the relative price of investment goods, along with real GDP, real consumption, real investment and real wage, hours worked, inflation, the Federal Funds Rate. In the following empirical analysis, the quarterly data from 1986:Q1 to 2015:Q4 are used, since 1986:Q1 seems to correspond to the starting point where the relative price of investment goods began declining steeply and steadily (Figure 1).

49. The corresponding measurement equation is:

$$X_t = \begin{bmatrix} \Delta \ln Y_t \\ \Delta \ln C_t \\ \Delta \ln I_t \\ \Delta \ln W_t \\ \ln L_t \\ \Delta \ln P_t \\ R_t \\ \Delta \ln \left( \frac{P_t^I}{P_t} \right)^{-1} \end{bmatrix} = \begin{bmatrix} \bar{y}_* \\ \bar{\gamma}_* \\ \bar{\gamma}_* \\ \bar{\gamma}_* \\ \bar{l} \\ \bar{\pi} \\ \bar{r} \\ \bar{\gamma} \end{bmatrix} + \begin{bmatrix} y_t - y_{t-1} \\ c_t - c_{t-1} \\ i_t - i_{t-1} \\ w_t - w_{t-1} \\ l_t \\ \pi_t \\ r_t \\ v_t - v_{t-1} \end{bmatrix}$$

where a variable in logarithm is denoted by a lower case letter. GDP, consumption, investment, wages, total hours worked and the relative price of investment goods are expressed in 100 times log. GDP, consumption and investment and wages are deflated with the Personal Consumption Expenditures (PCE) deflator. The aggregate real variables are expressed per capita. Inflation is the first difference of the log of the Consumer Price Index. The interest rate is the Federal Funds Rate. The interest rate and inflation rate are expressed on a quarterly basis.<sup>7</sup>  $\bar{y}_* = 100 \times (\gamma_* - 1)$  is the quarterly composite trend growth rate (combining the trend growth rates of both neutral and capital-embodied technological progress) of real GDP, consumption, investment and real wages;  $\bar{l} = 100 \times (l - 1)$  is the steady-state hours worked, which is normalised to be equal to zero;  $\bar{\pi} = 100 \times (\pi - 1)$  is the quarterly steady-state inflation rate;  $\bar{r} = 100 \times (r - 1)$  is the steady-state nominal interest rate; and  $\bar{\gamma} = 100 \times (\gamma - 1)$  is the quarterly trend growth rate of capital-embodied technological progress.

6. Instead, the model excluded the capacity utilisation of the capital stock as i) it did not essentially change the results this paper focuses on and ii) it made the model specification cumbersome.

7. All data are taken from the OECD Analytical Database, which integrates official data provided by national authorities, such as the US Bureau of Economic Analysis.

## Empirical results

50. At the steady state, output, consumption and the investment amount all grow at the composite trend growth rate,  $\gamma_*$ , while investment, once quality-adjusted, and the quality-adjusted capital stock grow at an even faster pace by the factor of  $\gamma$ . In the following estimation of the DSGE model, an exogenous shock to the process around equilibrium is considered. A positive shock to the process results in a rise in productivity, but simultaneously it reduces the value of the existing capital goods by certain, but unforeseeable, extent. These considerations affect the capital owner's investment behaviour.

### Parameter estimation

51. The structural parameters are estimated by maximising the log posterior function, which combines the prior information on the parameters with the likelihood of the data; then, the Metropolis-Hastings algorithm is used to evaluate the posterior distribution.<sup>8 9</sup> The priors on the parameters followed Smets and Wouters (2007), except for  $\gamma$ , the trend growth rate of capital-embodied technological progress, and the shock process to its evolution.<sup>10</sup>

**Table 1. Prior and posterior distribution of structural parameters and shock processes**

		Baseline: I:1986 - IV:2015					
		Prior distribution			Posterior distribution		
		Distr.	Mean	St. Dev.	Median	90% Confidence interval	
$\sigma_c$	(Elasticity of intertemporal substitution) <sup>-1</sup>	Normal	1.5	0.375	1.55	1.26	1.80
$\sigma_l$	(Elasticity of labour supply) <sup>-1</sup>	Normal	2	0.75	1.80	1.40	2.30
$h$	External habit formation	Beta	0.7	0.1	0.54	0.48	0.61
$S(\cdot)$	Investment adjustment function	Normal	4	1.5	4.49	3.39	5.52
$\Phi$	Fixed costs of production	Normal	1.25	0.125	1.61	1.55	1.67
$\alpha$	Share of capital	Normal	0.3	0.05	0.22	0.19	0.24
$\gamma_a$	Steady-state neutral technology growth	Normal	0.4	0.1	0.28	0.23	0.32
$\gamma$	Steady-state growth in embodied progress	Normal	0.4	0.1	0.38	0.35	0.42
$\rho_a$	Autoregression tfp shock	Beta	0.5	0.2	0.98	0.97	0.99
$\rho_b$	Autoregression risk premium shock	Beta	0.5	0.2	0.93	0.89	0.96
$\rho_i$	Autoregression investment shock	Beta	0.5	0.2	0.69	0.61	0.78
$\rho_q$	Autoregression embodied progress shock	Beta	0.5	0.2	0.98	0.97	0.99
$\varepsilon^a$	Exogenous shock to tfp	Inv. Gamma	0.1	2	0.39	0.34	0.43
$\varepsilon^b$	Exogenous shock to risk premium	Inv. Gamma	0.1	2	0.04	0.03	0.05
$\varepsilon^i$	Exogenous shock to investment	Inv. Gamma	0.1	2	0.42	0.35	0.49
$\varepsilon^q$	Exogenous shock to embodied progress	Inv. Gamma	0.1	2	0.57	0.51	0.63

Source: Author's calculation.

8. The model is estimated by Dynare, a package of pre-coded Matlab routines to estimate Dynamic Stochastic General Equilibrium (DSGE) models (Adjemian et al., 2011, <http://www.dynare.org>).

9. Five parameters, including the rate of depreciation, were fixed following Smets and Wouters (2007).

10. The standard errors of the innovations are assumed to follow an inverse-gamma distribution with a mean of 0.10 and standard deviation 2, and the persistence of shocks – the AR(1) processes – is beta distributed with mean 0.5 and standard deviation 0.2.

52. Table 1 reports the estimated structural parameters. The elasticity of intertemporal substitution, the parameters of habit formation and the elasticity of labour supply are estimated to be 0.65 (=1/1.55), 0.54 and 0.56 (=1/1.80), respectively, which are broadly comparable with Smets and Wouters (Table 2), and are well within the range found in the literature (for example, the elasticity of intertemporal substitution is found to be around 0.5 on average). The adjustment cost function is estimated to be 4.5 and the parameter of the fixed adjustment costs is estimated to be 1.6, which are both comparable with other studies.

53. Table 1 also reports the persistence of shocks. The productivity shock is found to be as persistent as in Smets and Wouters, with an AR(1) coefficient of 0.98. Compared with their results, the persistence of the risk premium shock is estimated to be markedly high with an AR coefficient of 0.93 (against 0.22), while the persistence of the shock to investment is estimated to be almost identical to the one estimated by Smets and Wouters with an AR coefficient of 0.69 (against 0.71). The persistence of the shock to capital-embodied technological progress is also estimated to be rather strong (0.98).

54. In the estimation, the trend growth rate is found to be around 0.39% per quarter, combining the trend growth rate of neutral technology of 0.28% and the contribution of technological progress embodied in capital goods of 0.11 points (its trend growth is 0.38%, which is multiplied by  $\alpha/(1 - \alpha)$ , with the share of capital  $\alpha$  being 0.22). On top of this trend growth, both quality-adjusted investment and the quality-adjusted capital stock grow faster by 0.38 points, thus in total they grow around 0.77% at the steady state.

**Table 2. Comparison of prior and posterior distribution**

	Baseline	SW (2007)	JPT (2011)
Estimation period:	1986-2015	1966-2004	1954-2009
$\sigma_c$ (Elasticity of intertemporal substitution) <sup>-1</sup>	1.55	1.38	<b>1.00</b>
$\sigma_l$ (Elasticity of labour supply) <sup>-1</sup>	1.80	1.83	4.49
$h$ External habit formation	0.54	0.71	0.86
$S(\cdot)$ Investment adjustment function	4.49	5.74	3.14
$\Phi$ Fixed costs of production	1.61	1.60	N.A.
$\alpha$ Share of capital	0.22	0.19	0.17
$\rho_a$ Autoregression tfp shock	0.98	0.95	0.29
$\rho_b$ Autoregression risk premium shock	0.93	0.22	0.61
$\rho_i$ Autoregression investment shock	0.69	0.71	0.81
$\rho_q$ Autoregression embodied progress shock	0.98	N.A.	0.16
$\varepsilon^a$ Exogenous shock to tfp	0.39	0.45	0.94
$\varepsilon^b$ Exogenous shock to risk premium	0.04	0.23	0.03
$\varepsilon^i$ Exogenous shock to investment	0.42	0.45	5.79
$\varepsilon^q$ Exogenous shock to embodied progress	0.57	N.A.	0.63

Note: The numbers in bold are not estimated but fixed.

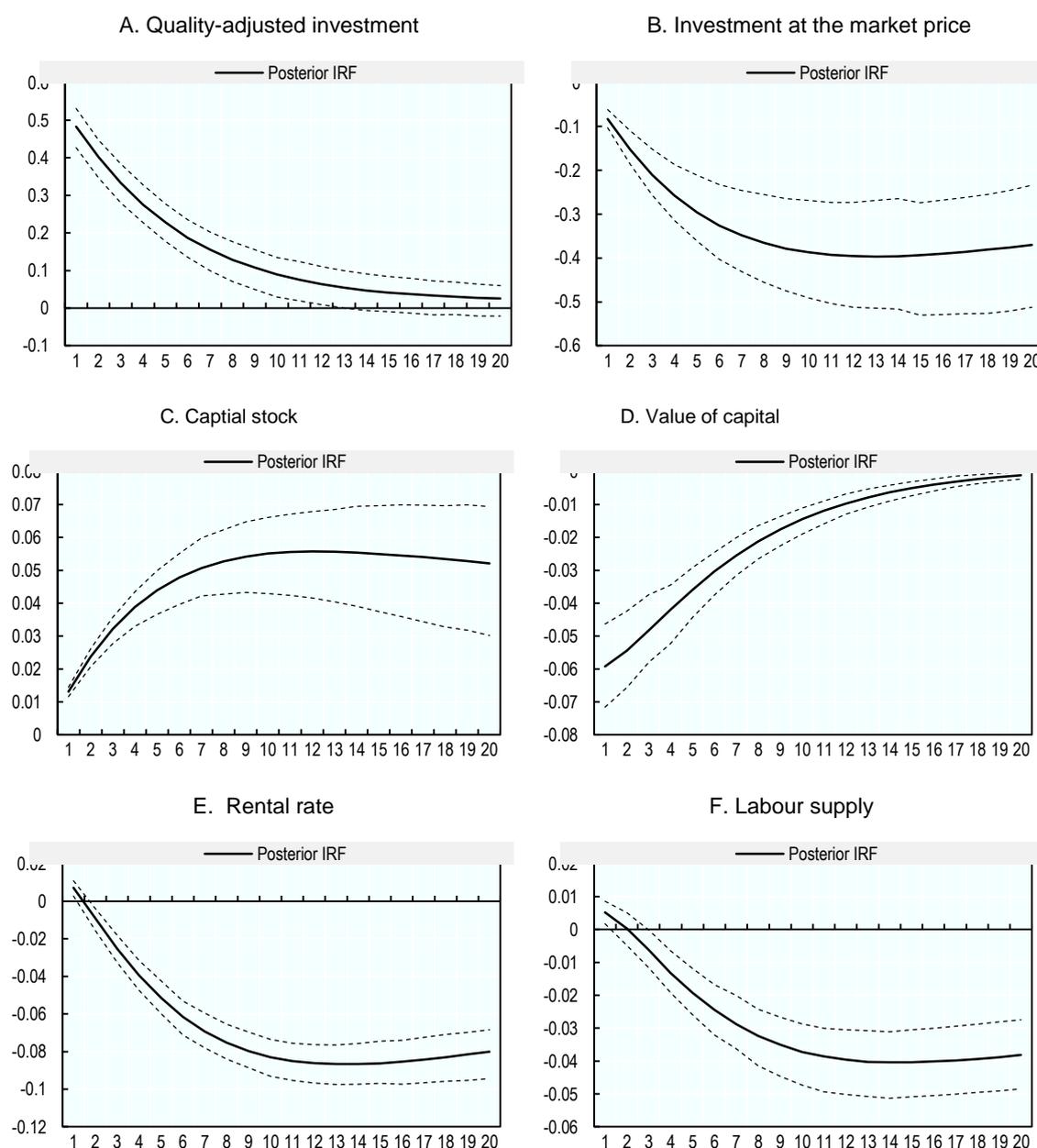
Source: Author's calculation; Smets and Wouters (2007); Justiniano et al. (2011).

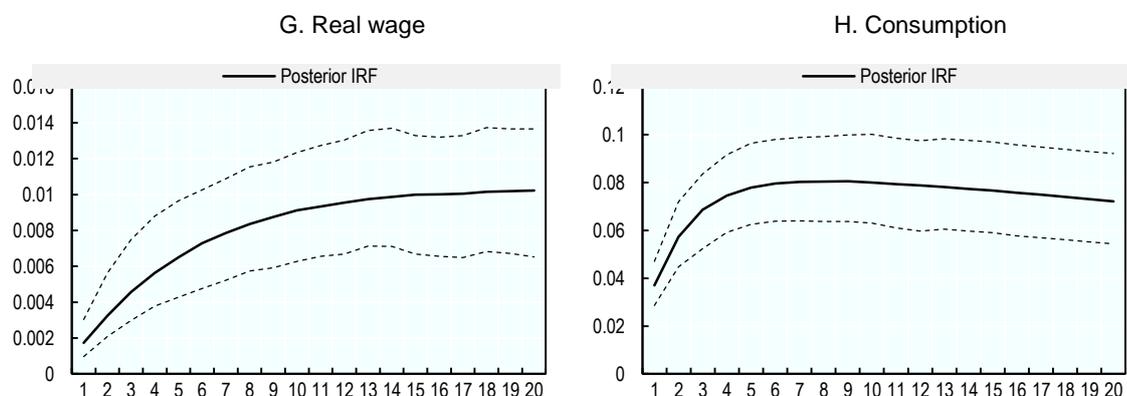
### **Impulse response functions**

55. In this section, the impulse response functions against a shock to the process of capital-embodied technological progress are reported (the shock is standardised to be 0.57 points). With this shock, quality-adjusted investment rises on impact by 0.48 percentage points at a quarterly rate (on top of the steady-state growth of around 0.77%), which is gradually attenuated over the medium term (Figure 2, Panel A). This response is measured in quality-adjusted terms, thus the actual amount of investment at the market price and the improvement in the quality of capital goods should be distinguished. The actual amount of investment declines on impact but only slightly and not to the extent that it completely offsets the impact

of a positive shock to the improvement in the quality of capital goods (Figure 2, Panel B). The decline in the amount of investment becomes gradually strong, but without exceeding the trend growth rate (of around 0.39% per quarter). By around the 20<sup>th</sup> quarter after the shock, both the improvement in the quality of capital goods and the decline in the amount of investment almost exactly offset each other and the impulse response of quality-adjusted investment reaches towards zero. As a result, overall, the quality-adjusted capital stock does not rise much following the one-off shock (Figure 2, Panel C).

**Figure 2. Impulse response functions with a shock to capital-embodied technological progress**



**Figure 2. Impulse response functions with a shock to capital-embodied technological progress (Cont.)**

Note: The straight line is the impulse response functions against a shock to capital-embodied technological progress. The dashed lines show the 90% confidence intervals.

Source: Author's calculation.

56. Since a one-off shock to capital-embodied technological progress improves the quality of new capital goods more than usual, the extent to which the value of the existing capital stock is reduced is also larger than usual (see Equation 7 on the differentiated pricing across different vintages). On impact, the value of the capital stock overall declines, albeit only slightly, against a one-off shock to the process of technological progress (Figure 2, Panel D). This is consistent with an anticipated decline in the value of capital goods in the future associated with capital-embodied technological progress (thus faster decline than  $p(t) = e^{-\gamma t}$  at the steady state, see Section 2.3). The rental rate in quality-adjusted terms is found to decline, albeit slightly, over the medium term (Figure 2, Panel E). In order to understand this mechanism, it may be easier to consider the rental rate of different vintages in non-quality adjusted terms (i.e. differentiating the rental rates across vintages, see Equation 6). The one-off shock induces a more-than-usual loss in the discounted stream of rental payments from old capital goods, which outweighs a more-than-usual rise in the discounted stream of rental payments from new capital goods. These considerations are likely to make a difference with the results in Greenwood et al. (2000) as well as Benhabib and Hobbijn (2003) which find a boom-like rise in investment following such a shock.

57. This slight and gradual decline in the rental rate is likely to be also associated with the decline in the total hours worked over the same period (Figure 2, Panel F), in spite of a slight rise in the wage rate (Figure 2, Panel G). The decline in labour supply is in turn likely associated with the fact that households now have to work less in order to maintain the same level of consumption as total rental payments rise due to the rise in the quality-adjusted investment.

58. Households raise their consumption relatively persistently (Figure 2, Panel H), in contrast with relatively persistent decline in the amount they invest over the medium term. Households take advantage of the environment where less investment is required to maintain the same level of consumption. Note that given the rise in the quality-adjusted capital stock, total rental payments will be higher over the medium term, in spite of the slight decline in the rental rate per unit, than in the case without the shock. There seems to be a slight decline in total labour earnings as the slight increase in the real wage rate is more than offset by the decline in total hours worked, which however can be compensated by the rise in total rental payments.

*Applications: different structural parameters*

59. The behaviour of households can be analysed further by changing the value of structural parameters. The value of the following structural parameters is fixed to be somewhat extreme: the elasticity of intertemporal substitution, external habit formation, investment adjustment costs, and the model is estimated accordingly (Table 3). The value of the structural parameters related to price and wage rigidities can also be fixed so that they are close to zero (Table 3). With the re-estimated structural parameters, the impulse response functions against the shock to capital-embodied technological progress are reported (Figure 3).

**Table 3. Sensitivity analysis with different parameter values**

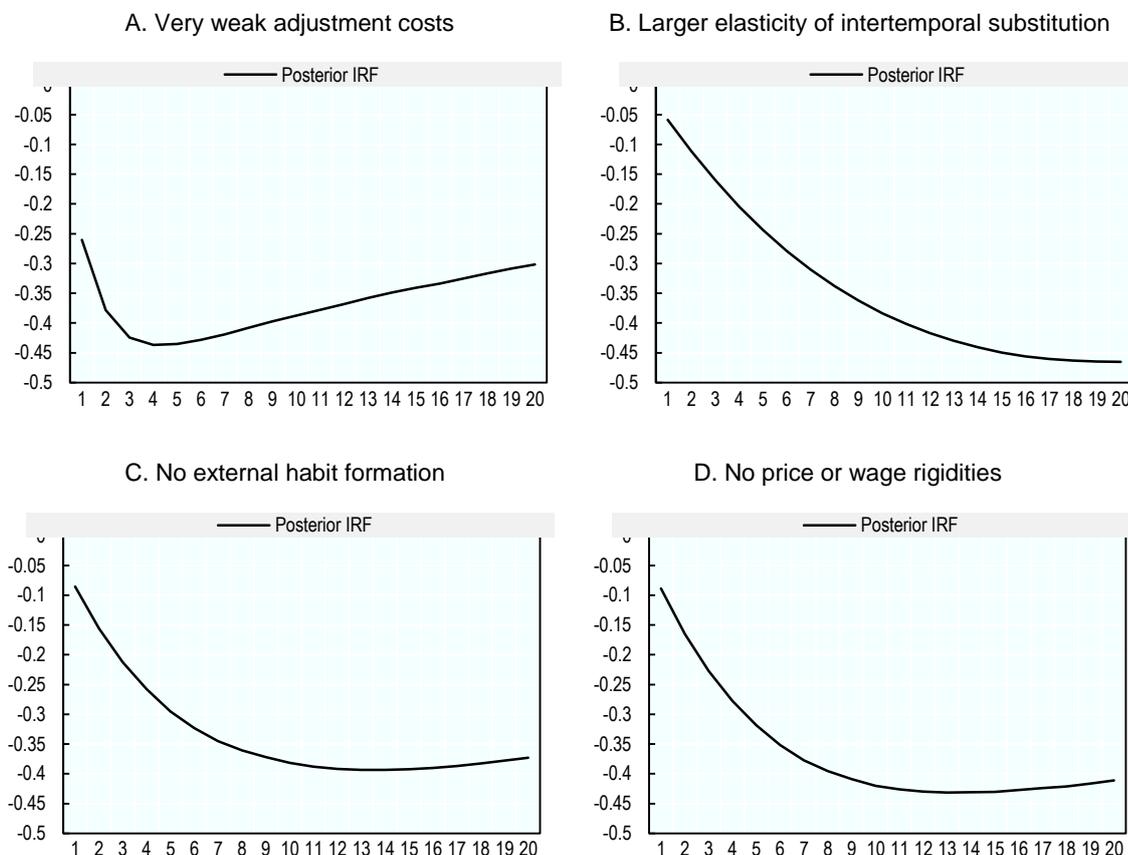
	Baseline	$S(\cdot) = 0.1$	$\sigma = 0.5$	$\lambda = 0.1$	minimum price and wage rigidities	
	Posterior distribution					
	Median					
$\sigma_c$	(Elasticity of intertemporal substitution) <sup>-1</sup>	1.55	1.40	<b>0.5</b>	2.78	1.19
$\sigma_l$	(Elasticity of labour supply) <sup>-1</sup>	1.80	2.91	3.51	1.49	0.62
$h$	External habit formation	0.54	0.30	0.76	<b>0.1</b>	0.52
$S(\cdot)$	Investment adjustment function	4.49	<b>0.1</b>	8.38	5.18	4.97
$\Phi$	Fixed costs of production	1.61	1.47	1.50	1.46	1.68
$\alpha$	Share of capital	0.22	0.29	0.17	0.23	0.24
$\rho_a$	Autoregression tfp shock	0.98	0.98	0.98	0.98	0.98
$\rho_b$	Autoregression risk premium shock	0.93	0.97	0.94	0.95	0.94
$\rho_i$	Autoregression investment shock	0.69	0.83	0.85	0.76	0.74
$\rho_q$	Autoregression embodied progress shock	0.98	0.97	0.98	0.98	0.98
$\varepsilon^a$	Exogenous shock to tfp	0.39	0.39	0.41	0.40	0.37
$\varepsilon^b$	Exogenous shock to risk premium	0.04	0.05	0.05	0.04	0.03
$\varepsilon^i$	Exogenous shock to investment	0.42	2.90	0.24	0.40	0.38
$\varepsilon^q$	Exogenous shock to embodied progress	0.57	0.57	0.57	0.56	0.57

Note: The numbers in bold are not estimated but fixed.

Source: Author's calculation.

60. If the adjustment costs are extremely low ( $S(\cdot) = 0.1$ ), the decline in the investment amount (investment in non-quality adjusted terms) on impact is stronger than in the baseline result (Figure 3, Panel A), consistent with the fact that investment is now more responsive to changes in the value of capital. If the elasticity of intertemporal substitution is 2 (roughly the inverse of what was estimated in the baseline result), the initial decline in the amount of investment is smaller but the medium-term decline in it is stronger than in the baseline case (Figure 3, Panel B), as households accept large swings in consumption in this case. In contrast, the results were similar to the baseline case when external habit formation is set to be very weak (Figure 3, Panel C). Finally, when assuming an economy where there are virtually no price and wage rigidities, there is no significant difference (Figure 3, Panel D), suggesting that the mechanism related to capital-embodied technological change abstracts from the nominal aspect of the economy.

**Figure 3. IRFs of investment at market prices using different parameter values**



Source: Author's calculation.

**Applications: correlation between shocks**

61. Though no explicit causality is assumed, shocks can be correlated with each other. The model can be re-estimated allowing explicitly the correlation between the shock to capital-embodied technological progress and each of the other shocks (Table 4).

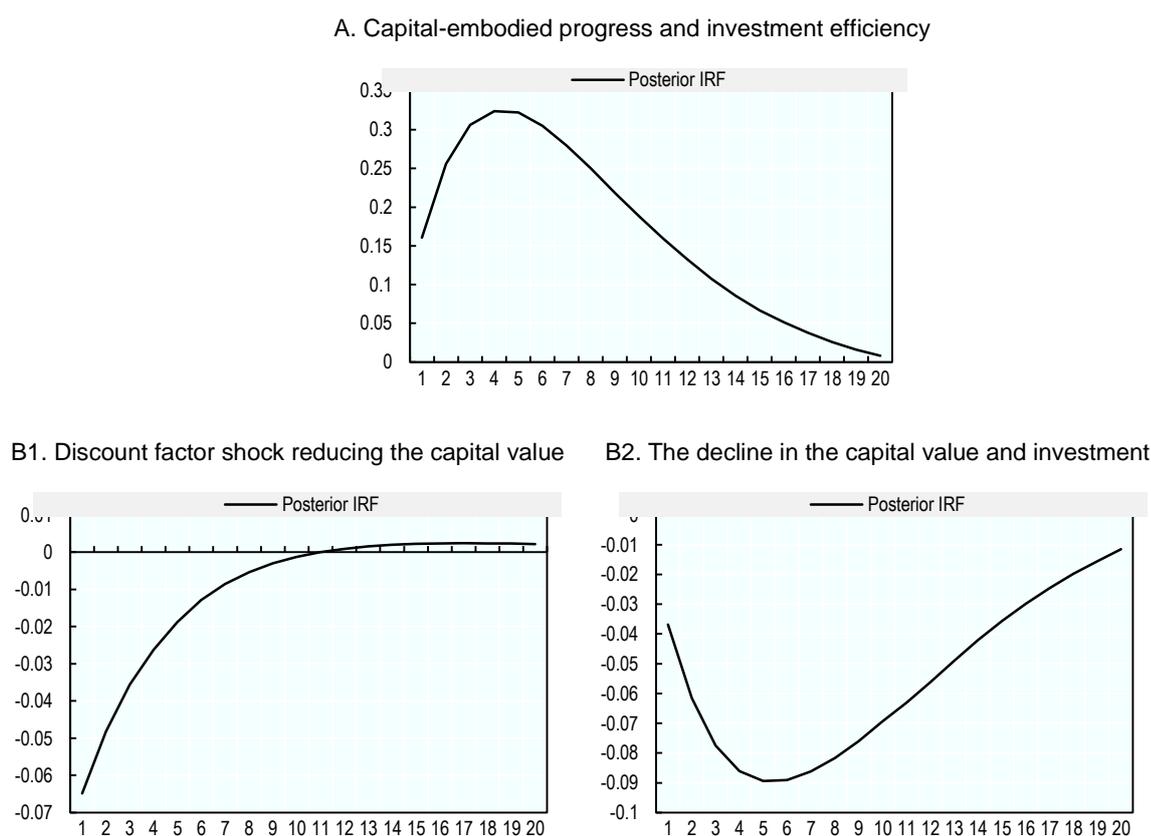
**Table 4. Prior and posterior distribution with correlation between shocks**

Correlation of shocks: 1986:I - 2015:IV							
Prior distribution			Posterior distribution				
Distr.	Mean	St. Dev.	Median	90% Confidence interval			
$\epsilon^q$ ; $\epsilon^a$	Correlation with tfp shock	Normal	0.1	0.5	0.04	-0.08	0.16
$\epsilon^q$ ; $\epsilon^b$	Correlation with risk premium shock	Normal	0.1	0.5	-0.14	-0.25	-0.03
$\epsilon^q$ ; $\epsilon^i$	Correlation with investment shock	Normal	0.1	0.5	0.20	0.08	0.31

Source: Author's calculation.

62. The correlation between the shock to capital-embodied technological progress and the investment efficiency shock is found to be positive and statistically significant (Table 4), thus likely associated with the investment accelerator mechanism. The correlation amplifies the rise in investment growth when a shock to capital embodied-technological progress is positive, while the opposite is true when it is negative. Figure 4 (Panel A) shows the implied effects from the correlation between the shocks. They induce a boom-like rise in investment initially, which slows gradually over the medium term.

**Figure 4. Implied effects on investment at market prices from correlation between shocks**



Source: Author's calculation.

63. In contrast, the shock to capital-embodied technological progress is negatively related to the discount factor shock (Table 4). This associated shock also has some impact on business cycle fluctuations. Figure 4 (Panel B1) illustrates the implied effects of the correlation between the shock to capital-embodied technological progress and the discount factor shock. With a negative shock to capital-embodied technological progress, the value of the capital stock changes by around 0.1% per quarter on impact, which fades out relatively quickly. However, the impact on investment through the decline in the value of capital stock seems to be relatively enduring (Figure 4, Panel B2).

64. The correlation between the shock to capital-embodied technological progress and the discount factor shock seems to be intuitive. According to the results, a positive shock to capital-embodied technological progress reduces the risk premium while a negative one increases it. In a circumstance where households can increase the production capacity due to acceleration in the improvement in the quality of capital, allowing them to raise consumption, they can reduce required rates of return on capital goods ("risky assets"). In contrast, when the quality improvement decelerates, households are worse off in order

to keep up the production capacity. This leads them to require higher rates of return on capital goods consistently with higher discount rates, resulting in a reduction in the value of the capital stock.

### *Separate estimations for sub-sample periods*

65. Finally, the model can be estimated for two sub-samples: the first half of the sample period (1986: I to 2000: IV) and the second half (2001: I to 2015: IV), since the trend growth in capital-embodied technological progress is likely to have declined in the mid-2000s. Indeed, the trend growth in capital-embodied technological progress is estimated to be much higher in the first period (0.55%) than in the second period (0.19%), while that in neutral technology is estimated to be identical over the two sub-sample periods (Table 5).

**Table 5. Sub-sample estimates of prior and posterior distribution**

		Sub-sample: 1986:I - 2000:IV		Sub-sample 2001:I - 2015:IV			
		Posterior distribution		Posterior distribution			
		Median	Confidence interval	Median	Confidence interval		
$\sigma_c$	(Elasticity of intertemporal substitution) <sup>-1</sup>	0.84	0.64	1.04	1.18	0.93	1.47
$\sigma_l$	(Elasticity of labour supply) <sup>-1</sup>	2.38	1.77	3.01	1.74	0.90	2.93
$h$	External habit formation	0.52	0.43	0.60	0.71	0.62	0.79
$S(\cdot)$	Investment adjustment function	3.93	2.62	5.10	5.44	3.91	6.96
$\Phi$	Fixed costs of production	1.59	1.48	1.70	1.56	1.39	1.74
$\alpha$	Share of capital	0.25	0.21	0.29	0.23	0.19	0.27
$\gamma_a$	Steady-state neutral technology growth	0.29	0.24	0.34	0.29	0.22	0.36
$\gamma$	Steady-state growth in embodied progress	0.55	0.50	0.60	0.19	0.14	0.24
$\rho_a$	Autoregression tfp shock	0.84	0.77	0.90	0.96	0.94	0.99
$\rho_b$	Autoregression risk premium shock	0.92	0.87	0.97	0.93	0.90	0.97
$\rho_i$	Autoregression investment shock	0.25	0.11	0.37	0.52	0.37	0.65
$\rho_q$	Autoregression embodied progress shock	0.89	0.82	0.96	0.81	0.70	0.91
$\varepsilon^a$	Exogenous shock to tfp	0.33	0.28	0.38	0.56	0.49	0.65
$\varepsilon^b$	Exogenous shock to risk premium	0.06	0.04	0.08	0.17	0.11	0.24
$\varepsilon^i$	Exogenous shock to investment	0.57	0.46	0.67	0.44	0.35	0.52
$\varepsilon^q$	Exogenous shock to embodied progress	0.48	0.40	0.55	0.68	0.59	0.76
B. Correlation of shocks							
		Sub-sample : 1986:I - 2000:IV		Sub-sample 2001:I - 2015: IV			
		Posterior distribution		Posterior distribution			
		Median	Confidence interval	Median	Confidence interval		
$\varepsilon^q ; \varepsilon^a$	Correlation with tfp shock	-0.10	-0.30	0.08	0.10	-0.04	0.23
$\varepsilon^q ; \varepsilon^b$	Correlation with risk premium shock	-0.13	-0.31	0.06	-0.14	-0.23	-0.04
$\varepsilon^q ; \varepsilon^i$	Correlation with investment shock	0.38	0.24	0.51	0.17	0.05	0.28

Source: Author's calculation.

66. The structural parameters are estimated to be similar to those reported for the entire sample period, but with some difference in essential parameters such as the elasticity of intertemporal substitution and investment adjustment function. This difference however seems unlikely to change fundamentally the baseline results reported above (Table 1), since they were only marginally affected even when an extreme value was calibrated for these parameters (the sensitivity analysis in Table 3). The elasticity of intertemporal substitution is somewhat lower in the second half of the sample period, as households are likely to have increased risk aversion. The parameter of investment adjustment function is estimated to have risen in the second half of the sample period, which seems to be consistent with the findings in the literature that it is asymmetric between upward and downward adjustments (i.e. it is more costly to adjust capital stock lower; e.g. Hall, 2001).

67. Finally, the negative correlation between the shock to capital-embodied technological progress and that to the risk premium is significant only in the second half of the sample period. If the true model is the baseline model, households have experienced more frequently negative shocks to capital-embodied technological progress during the second half of the sample period, and thus they raised accordingly the risk premium on investing in capital goods (see above). If, on the contrary, the true model is the one separately estimated for the second sub-period, such a mechanism has become only prevailing during the second half of the sample period with some structural change in households' behaviour.

## Conclusion

68. This paper empirically analysed the effects of a shock to the process of capital-embodied technological progress, which otherwise drives output, consumption and investment at a constant rate along a balanced growth path. It analysed the shock to the process of capital-embodied technological progress within a framework of a dynamic stochastic general equilibrium (DSGE) model, largely based on Smets and Wouters (2007), while explicitly identifying the process of capital-embodied technological progress drawing on Justiniano et al. (2011). In the model estimation, this paper also incorporated the properties of capital-embodied technological progress related to the capital goods, rental rate and the value of the capital stock, which are all quality adjusted.

69. This paper found that the overall investment response to the shock is limited. It found that, on impact, investment rises only in quality-adjusted terms, and that the investment amount is virtually unchanged, and that the owners of capital even reduce the investment amount gradually, which is at least initially more than compensated by the improvement in the quality of capital goods. As a result, the overall production capacity rises, albeit only slightly. The overall limited response in quality-adjusted investment seems very conservative because the owners of capital could take greater advantage of the sudden acceleration in the improvement of the quality of capital goods which allows them to raise their production capacity more than usually. However, this conservative behaviour may be consistent with an anticipated faster decline in the value of capital goods which become quickly obsolete. Finally, this paper also showed that the shock to capital-embodied technological progress may simultaneously generate a shock which reduces the risk premium. In a circumstance where the quality improvement decelerates, households are worse off in order to keep up the production capacity. This leads them to require higher rates of return on capital goods consistently with higher discount rates, resulting in a reduction in the value of the capital stock.

70. For further research, it may be worth considering the role of uncertainties on the value of capital goods. In stochastic models, the distribution of future shocks is known and agents make a decision, knowing that future innovations are random but have a zero mean. In a first-order linear approximation considered in this paper, only first order moments (expectations) play a role in determining the behaviour of agents. In order to analyse uncertainties related to the shock process – today's shock in the process of capital-embodied technological progress may be outweighed by yet another shock in the future –, the variance of shocks needs to be considered, which requires a higher order approximation.

71. Finally, it may be worth exploring if the responses to a one-time shock to capital-embodied technological progress could modify agents' behaviour permanently. This paper showed that the owners of capital take advantage of a one-time shock to the improvement in the quality of new capital goods, mainly by raising consumption, while reducing the amount they invest and the total hours worked, which is compensated by higher total rental payments. A durable reduction in the investment amount would result in a durable reduction in the production capacity, unless the shock in the process of the improvement in the quality of capital goods is permanent (i.e. unless it raises the trend growth rate in capital-embodied technological progress).

## BIBLIOGRAPHY

- Adjemian, S., H. Bastani, M. Juillard, F. Mihoubi, G. Perendia, M. Ratto, and S. Villemot (2011), “Dynare: Reference Manual, Version 4”, *Dynare Working Papers*, 1, CEPREMAP. <http://www.dynare.org/wp-repo/dynarewp001.pdf>
- Basu, S., and M. S. Kimball (2002), “Long-Run Labor Supply and the Elasticity of Intertemporal Substitution for Consumption”, [http://www-personal.umich.edu/~mkimball/pdf/cee\\_oct02-3.pdf](http://www-personal.umich.edu/~mkimball/pdf/cee_oct02-3.pdf)
- Benhabib, J., and B. Hopenhayn (2003), “Another View of Investment” in P. Aghion, R. Frydman, J. Stiglitz, and M. Woodford, (eds.), *Knowledge, Information, and Expectations in Modern Macroeconomics*, Princeton: Princeton University Press. [http://assets.press.princeton.edu/chapters/i2\\_7521.pdf](http://assets.press.princeton.edu/chapters/i2_7521.pdf)
- Bernanke, B. S., M. Gertler, and S. Gilchrist (1999), “The Financial Accelerator in a Quantitative Business Cycle Framework” in J. B. Taylor and M. Woodford, (eds.), *Handbook of Macroeconomics, Volume 1C*, Amsterdam: Elsevier Science, North-Holland, 1341-93. <http://cepr.org/sites/default/files/BGG%201999%20Handbook%20chapter.pdf>
- Bloom, N. (2009), “The Impact of Uncertainty Shocks” *Econometrica*, 77(3), 623-685. <http://onlinelibrary.wiley.com/doi/10.3982/ECTA6248/epdf>
- Boucekkine, R., F. del Rio, and O. Licandro (2005), “Obsolescence and Modernization in the Growth Process”, *Journal of Development Economics*, 77(1), 153-171. <http://www.iae.csic.es/investigadoresMaterial/a91711154320archivoPdf3904.pdf>
- Christiano, L.J., Eichenbaum, M., and Evans, C.L. (2005), “Nominal Rigidities and the Dynamic Effect of a Shock to Monetary Policy”, *Journal of Political Economy*, 113(1), 1-45. <http://www.jstor.org/stable/10.1086/426038>
- Cochrane, J. H. (2001), *Asset Pricing*, Princeton, New Jersey: Princeton University Press.
- Diewert, W. E. (2006), “The Aggregation of Capital over Vintages in a Model of Embodied Technical Progress”, *Discussion Paper 05-13*, Department of Economics, University of British Columbia.
- Diewert, W. E., and F. C. Wykoff (2006), “Depreciation, Deterioration and Obsolescence when There is Embodied or Disembodied Technical Change” in E. W. Diewert, B. M. Balk, D. Fixler, K. J. Fox, and A. O. Nakamura (eds.), *Price and Productivity Measurement Volumes 1 and 2*, Trafford Press.
- Doms, M. E., W. E. Dunn, S. D. Oliner, and D. E. Sichel (2004), “How Fast Do Computers Depreciate? Concepts and New Estimates” in J. M. Poterba (ed.), *Tax Policy and the Economy*, National Bureau of Economic Research and MIT Press, 37-79. <http://www.nber.org/papers/w10521>
- Geske, M. J., V. A. Ramey, and M. D. Shapiro (2007), “Why do computers depreciate?”, in E. R. Berndt and C. R. Hulten (eds.), *Hard-to-Measure Goods and Services*, NBER/CRIW Studies in Income and Wealth, Chicago: University of Chicago Press, (67), 121-150. <http://www.nber.org/papers/w10831>
- Gordon, R. (1990), *The Measurement of Durable Goods Prices*, National Bureau of Economic Research Monograph Series, Chicago: University of Chicago Press.
- Greenwood, J., Z. Hercowitz, and P. Krusell (1997), “Long-Run Implications of Investment-Specific Technological Change”, *American Economic Review*, 87(3), 342-362. [http://faculty.wcas.northwestern.edu/~lchrist/papers/aer\\_GHK.pdf](http://faculty.wcas.northwestern.edu/~lchrist/papers/aer_GHK.pdf)

- Greenwood J., Z. Hercowitz, and P. Krusell (2000), “The Role of Investment-specific Technological Change in the Business Cycle”, *European Economic Review*, 44(1), 91-115.  
<http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.13.5255&rep=rep1&type=pdf>
- Greenwood, J., and B. Jovanovic (1999), “The Information-Technology Revolution and the Stock Market”, *American Economic Review*, 89 (2), 116-22.
- Greenwood, J., and P. Krusell (2007), “Growth Accounting with Investment-Specific Technological Progress: A Discussion of Two Approaches”, *Journal of Monetary Economics*, 54(4); 1300-1310.
- Hall, R. E. (2001), “The Stock Market and Capital Accumulation”, *American Economic Review*, 91(5), 1185-202.
- Hall, R. E., and D. W. Jorgenson (1967), “Tax Policy and Investment Behavior”, *American Economic Review*, 57(3), 391-414.
- Hansen, L. P, and E. Renault (2009), “Pricing Kernels and Stochastic Discount Factors” in R. Cont (ed.), *Encyclopedia of Quantitative Finance*, Wiley, 1418-1428.
- Hulten, C. R., and F. C. Wykoff (1981), “The Estimation of Economic Depreciation Using Vintage Asset Prices”, *Journal of Econometrics*, 15(3), 367-396.
- Jorgenson, D. W. (1963), “Capital Theory and Investment Behavior”, *American Economic Review*, 53(2), 247-259.
- Jorgenson, D. W. (1999), “New Methods for Measuring Capital”; Paper presented to the meeting of the Canberra I Group on Capital Measurement, Washington D.C.
- Justiniano, A., G. E. Primiceri, and A. Tambalotti (2011), “Investment Shocks and the Relative Price of Investment”, *Review of Economic Dynamics*, 14(1), 102-121.
- Laitner, J., and D. Stolyarov (2003), “Technological Change and the Stock Market”, *American Economic Review*, 93(4), 1240-67.
- OECD (2009), OECD (2009), *Measuring Capital - OECD Manual 2009: Second edition*, OECD Publishing, Paris. <http://dx.doi.org/10.1787/9789264068476-en>
- OECD (2015), *OECD Economic Outlook*, Paris: OECD.
- Oliner, S. D. (1993), “Constant-Quality Price Change, Depreciation, and Retirement of Mainframe Computers” in Foss, M. F., Manser, M. E. and Young, A. H. (eds.), *Price Measurement and their Uses*, University of Chicago Press. <http://www.nber.org/chapters/c7797.pdf>
- Schmitt-Grohé, S., and M. Uribe (2008), “What’s News in Business Cycles”, Columbia University, Mimeo.
- Schreyer, P. (2005), “Note on Depreciation, Real Holding Gains/Losses and Welfare” presented at the Canberra II Group on measurement of non-financial assets, OECD Statistics Directorate, July 29. [https://econ.sites.olt.ubc.ca/files/2013/06/pdf\\_paper\\_erwin-diewert-note-schreyer.pdf](https://econ.sites.olt.ubc.ca/files/2013/06/pdf_paper_erwin-diewert-note-schreyer.pdf)
- Smets, F., and R. Wouters (2007), “Shocks and Frictions in U.S. Business Cycles: A Bayesian DSGE Approach”, *American Economic Review*, 97(3), 586-606. [http://dept.ku.edu/~empirics/Emp-Coffee/smets-wouters\\_aer07.pdf](http://dept.ku.edu/~empirics/Emp-Coffee/smets-wouters_aer07.pdf)

- Solow, R. M. (1960), "Investment and Technological Progress" in K. J. Arrow, S. Karlin, and P. Suppes (eds.), *Mathematical Methods in the Social Sciences*, Stanford: Stanford University Press, 89-104.
- Whelan, K., (2002), "Computers, Obsolescence, and Productivity", *Review of Economics and Statistics*, Vol. 84(3), 445-61.