D1.3 Scientific paper reporting the final results of the model specification, parameterization and calibration

Deliverable D1.3: D1.3 Scientific paper reporting the final results of the model specification, parameterization and calibration

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Project Information Summary

Table 1: Project Information Summary

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Deliverable Documentation Sheet

Table 2: Deliverable Documentation Sheet

Number	**D1.3**
Title	Scientific paper reporting the final results of the model specification, parameterization and calibration
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Quality Control Assessment Sheet

Table 3: Quality Control Assessment Sheet

Issue	Date	Comment	Author
V0.1	30.09.2017	First draft	Diego Comin, Mario Giarda
V1.1	31.03.2018	Second deliverable	Diego Comin, Mario Giarda
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Executive summary

In this first work package, we develop the baseline model that we will use in various of the work packages of FRAME. This model will be used to analyze the impact of various public innovation policies on the evolution of the economy. Our starting point is Anzoategui et al. (2015) who adopt the medium-term cycles framework developed by Comin and Gertler (2006) and introduce price and wage rigidities as well as a monetary policy rule. Effectively, this is a Neo-Keynesian business cycles framework augmented to have endogenous development and diffusion of new technologies.

A key aspect of the work package consists in modelling a wide array of innovation policies with the aim of exploring their impact on the economy dynamics. To this end, we differentiate between three types of innovation policies. First, standard R&D subsidies. Second, hiring scientists to conduct public R&D. Public R&D is socially desirable because it increases the productivity of private R&D. Third, hiring scientists to facilitate the adoption of new technologies by private companies. We impose a government budget constraint and consider two types of taxes, lump sum and distortionary labor income taxes.

We find that public innovation in the form of any of our policies (direct investment or innovation subsidies) expand the economy in the medium term. This implies that it can serve as a substitute for private investment in innovation. We also show that their effects on the economy depend crucially on some parameters, in particular those related with labor markets. We showed that a great degree of wage rigidities hide the aggregate trade-offs generated by labor tax raises. However, even with these trade-offs acting, innovation policies have a positive impact in the aggregate economy, wealth, consumption, and GDP.

1 Introduction

In this first work package, we develop the baseline model that we will use in various of the work packages of FRAME. This model will be used to analyze the impact of various public innovation policies on the evolution of the economy. Our starting point is Anzoategui et al. (2015) who adopt the medium-term cycles framework developed by Comin and Gertler (2006) and introduce price and wage rigidities as well as a monetary policy rule. Effectively, this is a Neo-Keynesian business cycles framework augmented to have endogenous development and diffusion of new technologies.

Comin and Gertler (2006) differentiate between the stock of developed technologies and the stock of used technologies. This distinction introduces an adoption lag that is endogenous and time-varying. In particular, the response of private investments in adopting new technologies to business cycle conditions may affect significantly the dynamics of productivity in the model.

A key aspect of the work package consists in modelling a wide array of innovation policies with the aim of exploring their impact on the economy dynamics. To this end, we differentiate between three types of innovation policies. First, standard R&D subsidies. Second, hiring scientists to conduct public R&D. Public R&D is socially desirable because it increases the productivity of private R&D. Third, hiring scientists to facilitate the adoption of new technologies by private companies. We impose a government budget constraint and consider two types of taxes, lump sum and distortionary labor income taxes.

Although our policies seem to be abstract, they are consistent with the European Innovation Policies. In fact, the European Parliament considers policies that directly target research and development which are activities to produce basic knowledge. We include this kind of policies in the model as a direct policy affecting the process of R&D creation. The government spends resources on research and development which has an explicit role in the model. Additionally, European authorities emphasize the role of industrial policy, that we consider in the model as adoption of the technologies already generated, which is also affected by a government policy. The European framework of innovation policy also highlights sectoral and education policies, which will be addressed in Work Packages 2 and 3, respectively.[1]

After developing our framework, we proceed to calibrate the model. We calibrate the public adoption parameters with the estimations made by WP6. The results yield some interesting take away. First, the simulations point towards the relevance of wage rigidities to the quantitative implications of the model. Second, they highlight an interesting trade off between public R&D and public diffusion. While the latter has a stronger effect on the short-run, the latter seems to have a stronger effect in the long-run.

This paper is organized as follows: section 3 describes the model; section 4 shows the response of the economy to a technology shock and evaluate the impact of considering endogenous innovation; section 5 shows the response of the economy to our fiscal policies; and section 6 concludes.

[1]Source: `http://www.europarl.europa.eu/RegData/etudes/IDAN/2016/583778/EPRS_IDA(2016)583778_EN.pdf`.

2 European Union's Innovation Policy: a Brief Summary

The European Union is explicit in their scope for policy for innovation. They describe three areas that are essential in the process: (i) Research and Development (R&D), that defines the institutions and activities that create knowledge; (ii) Industrial policy and entrepreneurial policy, that include policies targeting small and medium-sized enterprises; and (iii) education policies, which cover all the actors on the educational system and the policies to foster worker's skills. In this paper, we take care of the first two which can be summarized by an R&D and an adoption process. Although the scope and way of including these kind of policies we describe later is reduced-form, we think they capture well the way public investment affects innovation at a macroeconomic scale. Furthermore, we stress the likely general equilibrium effects of these policies by emphasizing and identifying their trade-offs. This, in order to design the best policy mix possible given the preferences of policymakers and the state of the economy.

As our model is explicit in separating the processes of knowledge creation (we refer to it as "R&D") and the diffusion of that knowledge into the production process (we also refer to it as Adoption), we can explore the effect of targeting the different areas the EU identify as key in the innovation process.[2] Specifically, we include two kinds of policies affecting these two areas that are consistent with the ones applied and that are part of the European Commision policy mix. In the model, we include explicitly public spending in R&D and Adoption, as well as subsidies directed to these activities. Actually, these policies are the main part of the "Supply Side" policies of the mix.

Examples of direct investment in R&D are public spending in basic sciences like funding universities and researchers, while subsidies are all those tax exemptions that reduce the cost of hiring inputs for developing R&D. Direct investment policies are summarized, in our model, by a policy variable that will be exogenous which is public hiring of skilled labor while subsidies are included such that they reduce the cost of private hiring of researchers. Actually, the goal of the European Parliament is to augment investment in R&D from 2 to 3 percent of the GDP. Our task in this work is to analyze the best way to develop and generate this policy as we assume there are feedbacks between public and private innovation activities.

Similar, but broader, is the financing of Diffusion, which is targeted mainly into private firms that are able to develop and create new products and processes. Examples of this are the efforts made under the scope of the "Juncker Plan" by the European Fund of Strategic Investment and the European Structural and Investment Funds, which directly finance technological adoption in a broad sense that, by the one side, provide funds to finance private initiatives, and by the other, contribute with public entities by helping to develop applied technologies which are marketable. This is, they both conduct direct investment in adoption of technologies and subsidize this kind of activities. A great example of this is the work done at Fraunhofer Institute in Germany which serves as a good example for the

[2] In the Work Package 3 we study this same problem in a model augmented by human capital accumulation in order to understand the macroeconomic impact of the interaction of these three areas and the policies that help to foster growth in that context.

purposes of this investigation. Our policy exercises are increases of spending in activities like those of Fraunhofer to study its impact on the macroeconomy.

3 Model

Our starting point is a New Keynesian DSGE model similar to Christiano et al. (2005) and Smets and Wouters (2007). We include the standard features useful for capturing the data, including: habit formation in consumption, flow investment adjustment costs, variable capital utilization and "Calvo" price and wage rigidities. In addition, monetary policy obeys a Taylor rule. We follow this approach to analyze our different policies in a context where the economy behaves close to the empirical evidence which derives realistic impulse response functions from known shocks. In Appendix C we eliminate the New Keynesian features building a Real Model and compare these two economies. Furthermore, for the sake of simplicity, we will use the latter for further extensions. However, in our opinion, it is still useful to analyze–and to provide– a model that is close to reality, at least, in its basic setup, that is what we do next.

The key non-standard feature is that total factor productivity depends on two endogenous variables: the creation of new technologies via R&D and the speed of adoption of these new technologies. Skilled labor is used as an input for the R&D and adoption processes. We do not model financial frictions explicitly; however, we allow for a shock that transmits through the economy like a financial shock, as we discuss below.

To study the impact of public investment in this environment, we include an active government that invests in both R&D and adoption activities. In both cases, government investment is complementary to private investment in technology. This government can also spend on goods and is financed aterantively by raising lump-sum or distortionary labor taxes.

We begin with the non-standard features of the model before briefly describing the standard ones:

3.1 Production Sector and Endogenous TFP: Preliminaries

In this section we describe the production sector and sketch how endogenous productivity enters the model. In a subsequent section we present the firm optimization problems.

There are two types of firms: (i) final goods producers and (ii) intermediate goods producers. There are a continuum, measure unity, of monopolistically competitive final goods producers. Each final goods firm i produces a differentiated output Y_t^i. A final good composite is then the following CES aggregate of the differentiated final goods:

$$Y_t = \left(\int_0^1 (Y_t^i)^{\frac{1}{\mu_t}} di \right)^{\mu_t} \tag{1}$$

where $\mu_t > 1$ is given exogenously.

Each final good firm i uses Y_{mt}^i units of intermediate goods composite as input to produce output, according to the following simple linear technology

$$Y_t^i = Y_{mt}^i \tag{2}$$

We assume each firm sets its nominal price P_t^i on a staggered basis, as we describe later.

There exists a continuum of measure A_t of monopolistically competitive intermediate goods firms that each make a differentiated product. The endogenous predetermined variable A_t is the stock of types of intermediate goods adopted in production, i.e., the stock of adopted technologies. Intermediate goods firm j produces output Y_{mt}^j. The intermediate goods composite is the following CES aggregate of individual intermediate goods:

$$Y_{mt} = \left(\int_0^{A_t} (Y_{mt}^j)^{\frac{1}{\vartheta}} dj \right)^{\vartheta} \tag{3}$$

with $\vartheta > 1$.

Let K_t^j be the stock of capital firm j employs, U_t^j be how intensely this capital is used, and L_t^j the stock of labor employed. Then firm j uses capital services $U_t^j K_t^j$ and unskilled labor L_t^j as inputs to produce output Y_{mt}^j according to the following Cobb-Douglas technology:

$$Y_{mt}^j = \theta_t \left(U_t^j K_t^j \right)^{\alpha} (L_t^j)^{1-\alpha} \tag{4}$$

where θ_t is an exogenous random disturbance. As we will make clear shortly, θ_t is the exogenous component of total factor productivity. Finally, we suppose that intermediate goods firms set prices each period. That is, intermediate goods prices are perfectly flexible, in contrast to final good prices.

Let $\overline{Y}_t$ be average output across final goods producers. Then the production function (1) implies the following expression for the final good composite Y_t

$$Y_t = \Omega_t \cdot \overline{Y}_t \tag{5}$$

where Ω_t is the following measure of output dispersion

$$\begin{aligned} \Omega_t &= \left(\int_0^1 (Y_t^i / \overline{Y}_t)^{\frac{1}{\mu_t}} di \right)^{\mu_t} \\ &= 1 \text{ to a 1st order} \end{aligned} \tag{6}$$

In a first order approximation, Ω_t equals unity, implying that we can express Y_t simply as $\overline{Y}_t$.

Next, given the total number of final goods firms is unity, given the production function for each final goods producer (2), and given that Y_t equals $\overline{Y}_t$, it follows that to a first order

$$Y_t = Y_{mt} \tag{7}$$

Finally, given a symmetric equilibrium for intermediate goods (recall prices are flexible in this sector) it follows from equation (3) that we can express the aggregate production function for the final good composite Y_t as

$$Y_t = \left[A_t^{\vartheta - 1} \theta_t \right] \cdot (U_t K_t)^{\alpha} (L_t)^{1-\alpha} \tag{8}$$

where the term in brackets is total factor productivity, which is the product of a term that reflects endogenous variation, $A_t^{\vartheta-1}$, and one that reflects exogenous variation θ_t. Note that equation (8) holds to a first order since we impose Ω_t equals unity.

In sum, endogenous productivity effects enter through the expansion in the variety of adopted intermediate goods, measured by A_t. We next describe the mechanisms through which new intermediate goods are created and adopted.

3.2 R&D and Adoption

The processes for creating and adopting new technologies are based on Comin and Gertler (2006). Let Z_t denote the stock of technologies, while as before A_t is the stock of adopted technologies (intermediate goods). In turn, the difference $Z_t - A_t$ is the stock of unadopted technologies. R&D expenditures increase Z_t while adoption expenditure increase A_t. We distinguish between creation and adoption because we wish to allow for realistic lags in the adoption of new technologies. We first characterize the R&D process and then turn to adoption.

3.2.1 R&D: Creation of Z_t

There are a continuum of measure unity of innovators that use skilled labor to create new intermediate goods. Let L^p_{srt} be skilled labor employed in R&D by innovator p and let φ_t be the number of new technologies at time $t+1$ that each unit of skilled labor at t can create. We assume φ_t is given by

$$\varphi_t = \chi_t Z_t L_{srt}^{\rho_z - 1} L_{purt}^{\gamma_z} \tag{9}$$

where χ_t is an exogenous disturbance to the R&D technology L_{purt} is the number of public R&D labor, and L_{srt} is the aggregate amount of skilled labor working on R&D, which an individual innovator takes as given. Following Romer (1990), the presence of Z_t, which the innovator also takes as given, reflects public learning-by-doing in the R&D process. We assume $\rho_z < 1$ which implies that increased R&D in the aggregate reduces the efficiency of R&D at the individual level. We introduce this congestion externality so that we can have constant returns to scale in the creation of new technologies at the individual innovator level, which simplifies aggregation, but diminishing returns at the aggregate level. Our assumption of diminishing returns is consistent with the empirical evidence (see Griliches (1990)); further, with our specification the elasticity of creation of new technologies with respect to R&D becomes a parameter we can estimate, as we make clear shortly.[3]

The number of technologies depends also in public investment, L_{spurt}. We assume there are decreasing returns to public investment, $\gamma_z < 1$. All this implies that government investment in R&D apart from generating new technologies complement, or facilitates, private investment.

Let J_t be the value of an unadopted technology, $\Lambda_{t,t+1}$ the representative household's stochastic discount factor and w_{st} the real wage for a unit of skilled labor. We can then express innovator p's decision problem as choosing L^p_{srt} to solve

[3]An added benefit from having diminishing returns to R&D spending is that, given our parameter estimates, steady state growth is relatively insensitive to tax policies that might affect incentives for R&D. Given the weak link between tax rates and long run growth, this feature is desirable.

$$\max_{L^p_{srt}} E_t\{\Lambda_{t,t+1} J_{t+1}\varphi_t L^p_{srt}\} - (1-\tau^s_{rt})w_{st}L^p_{srt} \tag{10}$$

where τ^s_{rt} is a R&D subsidy, that can also be considered as a subsidy to the high skilled workers demand. The optimality condition for R&D is then given by

$$E_t\{\Lambda_{t,t+1} J_{t+1}\varphi_t\} - (1-\tau^s_{rt})w_{st} = 0$$

which implies

$$E_t\{\Lambda_{t,t+1} J_{t+1}\chi_t Z_t L^{\rho_z-1}_{srt} L^{\gamma_z}_{purt}\} = (1-\tau^s_{rt})w_{st} \tag{11}$$

The left side of equation (11) is the discounted marginal benefit from an additional unit of skilled labor, while the right side is the marginal cost.

Given that profits from intermediate goods are pro-cyclical, the value of an unadopted technology, which depends on expected future profits, will be also be pro-cyclical. This consideration, in conjunction with some stickiness in the wages of skilled labor which we introduce later, will give rise to pro-cyclical movements in L_{srt}.[4]

Equation (11) also describes how R&D policies stimulate innovation. Due to the existence of spillover externalities, public and private R&D are complements. After an exogenous increase in public R&D, L_{purt}, private R&D increases, because private R&D gets more productive than before. A similar effect will have a subsidy to R&D: an increase in τ^s_{rt} stimulates R&D investment through a fall in the cost of R&D. It is important to emphasize the role of congestion externalities here. The final impact of the policies will depend on the relation between ρ_z and γ_z. If $\rho_z > \gamma_z$ it's better to use subsidies to take advantage of the higher private elasticity rather than invest directly.

Finally, we allow for obsolescence of technologies.[5] Let ϕ be the survival rate for any given technology. Then, we can express the evolution of technologies as:

$$Z_{t+1} = \varphi_t L_{srt} + \phi Z_t \tag{12}$$

where the term $\varphi_t L_{srt}$ reflects the creation of new technologies. Combining equations (12) and (9) yields the following expression for the growth of new technologies:

$$\frac{Z_{t+1}}{Z_t} = \chi_t L^{\rho_z}_{srt} L^{\gamma_z}_{purt} + \phi \tag{13}$$

where ρ_z is the elasticity of the growth rate of technologies with respect to R&D and consequently, γ_z the elasticity of technology growth to public investemt. These parameters are estimated in Work Package 6.

[4]Other approaches to motivating procyclical R&D, include introducing financial frictions Aghion et al. (2010), short term biases of innovators Barlevy (2007), or capital services in the R&D technology function Comin and Gertler (2006).

[5]We introduce obsolescence to permit the steady state share of spending on R&D to match the data.

3.2.2 Adoption: From Z_t to A_t

We next describe how newly created intermediate goods are adopted, i.e. the process of converting Z_t to A_t. Here we capture the fact that technology adoption takes time on average, but the adoption rate can vary pro-cyclically, consistent with evidence in Comin (2009). In addition, we would like to characterize the diffusion process in a way that minimizes the complications from aggregation. In particular, we would like to avoid having to keep track, for every available technology, of the fraction of firms that have and have not adopted it.

Accordingly, we proceed as follows. We suppose there are a competitive group of "adopters" who convert unadopted technologies into ones that can be used in production. They buy the rights to the technology from the innovator, at the competitive price J_t, which is the value of an adopted technology. They then convert the technology into use by employing skilled labor as input. This process takes time on average, and the conversion rate may vary endogenously.

In particular, the pace of adoption depends positively on the level of adoption expenditures in the following simple way: an adopter succeeds in making a product usable in any given period with probability λ_t, which is an increasing and concave function of the amount of skilled labor employed, L_{sat}, and L_{puat} is the amount of skilled public R&D workers used in the adoption of the technology:

$$\lambda_t = \bar{\lambda}_0 * (Z_t L_{sat})^{\rho_\lambda} * \left(1 + \bar{\lambda}_{pu} * (Z_t L_{puat})^{\rho_{\lambda pu}}\right) \tag{14}$$

with ρ_λ, $\rho_{\lambda pu} \in (0,1)$ and $(\bar{\lambda}_0, \bar{\lambda}_{pu}) > 0$. We augment L_{sat} by a spillover effect from the total stock of technologies Z_t - think of the adoption process as becoming more efficient as the technological state of the economy improves. The practical need for this spillover is that it ensures a balanced growth path: as technologies grow, the number of new goods requiring adoption increases, but the supply of labor remains unchanged. Hence, the adoption process must become more efficient as the number of technologies expands. Unlike the specification used for R&D, there is no separate shock to the productivity of adoption activities in (14). We are constrained to introduce this asymmetry because we do not have a direct observable to measure adoption labor or λ_t. The identified series of adoption hours, L_{sat}, can be interpreted as the effective number of adoption hours.

Our adoption process implies that technology diffusion takes time on average, consistent with the evidence. If λ is the steady state value of λ_t, then the average time it takes for a new technology be adopted is $1/\lambda$. Away from the steady state, the pace of adoption will vary with skilled input L_{sat}. We turn next to how L_{sat} is determined.

Once in usable form, the adopter sells the rights to the technology to a monopolistically competitive intermediate goods producer that makes the new product using the production function described by equation (8). Let Π_{mt} be the profits that the intermediate goods firm makes from producing the good, which arise from monopolistically competitive pricing. The adopter sells the new technology at the competitive price V_t, which is the present discounted value of profits from producing the good, given by

$$V_t = \Pi_{mt} + \phi E_t\{\Lambda_{t,t+1} V_{t+1}\} \tag{15}$$

Then we may express the adopter's maximization problem as choosing L_{sat} to maximize the value J_t of an unadopted technology, given by

$$J_t = \max_{L_{sat}} E_t\{-(1-\tau^s_{at})w_{st}L_{sat} + \phi\Lambda_{t,t+1}[\lambda_t V_{t+1} + (1-\lambda_t)J_{t+1}\} \tag{16}$$

subject to equation (14). The first term in the Bellman equation reflects total adoption expenditures that considers a subsidy to technological adoption τ^s_{at} (which can also be considered as a subsidy to high skilled workers demand, similar to τ_{rt}), while the second is the discounted benefit: the probability weighted sum of the values of adopted and unadopted technologies.

The first order condition for L_{sat} is

$$\lambda'_t \cdot \phi E_t\{\Lambda_{t,t+1}[V_{t+1} - J_{t+1}]\} = (1-\tau^s_{at})w_{st} \tag{17}$$

The term on the left is the marginal gain from adoption expenditures: the increase in the adoption probability λ_t times the discounted difference between an adopted versus unadopted technology. The right side is the marginal cost.

The term $V_t - J_t$ is pro-cyclical, given the greater influence of near term profits on the value of adopted technologies relative to unadopted ones. Given this consideration and the stickiness in w_{st} which we alluded to earlier, L_{sat} varies pro-cyclically. The net implication is that the pace of adoption, given by λ_t, will also vary pro-cyclically.

The effect of public adoption is through λ' that increases when L_{spuat} goes up. This also implies that L_{sat} rises for the same reasons it increases with $[V_{t+1} - J_{t+1}]$. Adoption subsidies have similar effects and the difference between innovating directly and subsidizing it depends on the difference between ρ_λ and $\rho_{\lambda pu}$. We analyze this extensively in the results section.

Given that λ_t does not depend on adopter-specific characteristics, we can sum across adopters to obtain the following relation for the evolution of adopted technologies

$$A_{t+1} = \lambda_t\phi[Z_t - A_t] + \phi A_t \tag{18}$$

where $Z_t - A_t$ is the stock of unadopted technologies.

3.3 Households

The representative household consumes and saves in the form of capital and riskless bonds which are in zero net supply. It rents capital to intermediate goods firms. As in the standard DSGE model, there is habit formation in consumption. Also as is standard in DSGE models with wage rigidity, the household is a monopolistically competitive supplier of differentiated types of labor.

The household's problem differs from the standard setup in two ways. First it supplies two types of labor: unskilled labor L^h_t which is used in the production of intermediate goods and skilled labor which is used either for R&D or adoption, L^h_{st}.

Second, we suppose that the household has a preference for the safe asset, which we motivate loosely as a preference for liquidity and capture by incorporating bonds in the utility function, following Krishnamurthy and Vissing-Jorgensen (2012). Further, following Fisher (2015), we introduce a shock to liquidity demand $\varrho_t > 0$. As we show, the liquidity demand shock transmits through the economy like a financial shock. It is mainly for this reason that we make use of it, as opposed to a shock to the discount factor.[6]

Let C_t be consumption, B_t holdings of the riskless bond, Π_t profits from ownership of monopolistically competitive firms, K_t capital, Q_t the price of capital, R_{kt} the rate of return, and D_t the rental rate of capital. Then the households' decision problem is given by

$$\max_{C_t,B_{t+1},L_t^h,L_{st}^h,K_{t+1}} E_t \sum_{\tau=0}^{\infty} \beta^\tau \left\{ \log(C_{t+\tau} - bC_{t+\tau-1}) + \varrho_t B_{t+1} - \left[\frac{\upsilon(L_t^h)^{1+\varphi} + \upsilon_s(L_{st}^h)^{1+\varphi}}{1+\varphi} \right] \right\} \tag{19}$$

subject to

$$C_t = (1-\tau_t^l)\left[w_t^h L_t^h + w_{st}^h L_{st}^h\right] + \Pi_t + R_{kt}Q_{t-1}K_t - Q_tK_{t+1} + R_tB_t - B_{t+1} + T_t \tag{20}$$

with

$$R_{kt} = \frac{D_t + Q_t}{Q_{t-1}} \tag{21}$$

$\Lambda_{t,t+1}$, the household's stochastic discount factor, is given by

$$\Lambda_{t,t+1} \equiv \beta u'(C_{t+1})/u'(C_t) \tag{22}$$

where $u'(C_t) = 1/(C_t - bC_{t-1}) - b/(C_{t+1} - bC_t)$. In addition, let ζ_t be the liquidity preference shock in units of the consumption good:

$$\zeta_t = \varrho_t / u'(C_t) \tag{23}$$

Then we can express the first order necessary conditions for capital and the riskless bond as, respectively:

$$1 = E_t\{\Lambda_{t,t+1} R_{kt+1}\} \tag{24}$$

$$1 = E_t\{\Lambda_{t,t+1} R_{t+1}\} + \zeta_t \tag{25}$$

As equation (25) indicates, the liquidity demand shock distorts the first order condition for the riskless bond. A rise in ζ_t acts like an increase in risk: given the riskless rate R_{t+1} the increase in ζ_t induces a precautionary saving effect, as households reduce current consumption in order to satisfy the first order condition (which requires a drop in $\Lambda_{t,t+1}$). It also leads to a drop in investment demand, as the decline in $\Lambda_{t,t+1}$ raises the required return on capital, as equation (24) implies. The decline in the discount factor also induces a drop in R&D and investment.

Overall, the shock to ζ_t generates positive co-movement between consumption and investment similar to that arising from a monetary shock. To see, combine equations (24) and (25) to obtain

$$E_t\{\Lambda_{t,t+1}(R_{kt+1} - R_{t+1})\} = \zeta_t \tag{26}$$

[6] Another consideration is that the liquidity demand shock induces positive co-movement between consumption and investment, while that is not always the case for a discount factor shock.

To a first order an increase in ζ_t has an effect on both R_{kt+1} and $\Lambda_{t,t+1}$ that is qualitatively similar to that arising from an increase in R_{t+1}. In addition, note that an increase in ζ_t raises the spread $R_{kt+1} - R_{t+1}$. In this respect it transmits through the economy like a financial shock. Indeed, we show later that our identified liquidity demand shock is highly correlated with credit spreads.

Since it is fairly conventional, we defer until later a description of the household's wage-setting and labor supply behavior.

3.4 Firms

3.4.1 Intermediate goods firms: factor demands

Given the CES function for the intermediate good composite (3), in the symmetric equilibrium each of the monopolistically competitive intermediate goods firms charges the markup ϑ. Let p_{mt} be the relative price of the intermediate goods composite. Then from (3) and the production function (4), cost minimization by each intermediate goods producer yields the following standard first order conditions for capital, capital utilization, and unskilled labor:

$$\alpha \frac{p_{mt} Y_{mt}}{K_t} = \vartheta [D_t + \delta(U_t) Q_t] \tag{27}$$

$$\alpha \frac{p_{mt} Y_{mt}}{U_t} = \vartheta \delta'(U) Q_t K_t \tag{28}$$

$$(1-\alpha) \frac{p_{mt} Y_{mt}}{L_t} = \vartheta w_t \tag{29}$$

3.4.2 Final goods producers: price setting

Let P_t^i be the nominal price of final good i and P_t the nominal price level. Given the CES relation for the final good composite, equation (1), the demand curve facing each final good producer is:

$$Y_t^i = \left(\frac{P_t^i}{P_t} \right)^{-\mu_t/(\mu_t - 1)} Y_t \tag{30}$$

where the price index is given by:

$$P_t = \left(\int_0^1 (P_t^i)^{-1/(\mu_t - 1)} di \right)^{-(\mu_t - 1)}, \tag{31}$$

Following Smets and Wouters (2007), we assume Calvo pricing with flexible indexing. Let $1 - \xi_p$ be the i.i.d probability that a firm is able to re-optimize its price and let $\pi_t = P_t / P_{t-1}$ be the inflation rate. Firms that are unable to re-optimize during the period adjust their price according to the following indexing rule:

$$P_t^i = P_{t-1}^i \pi_{t-1}^{\iota_p} \pi^{1-\iota_p} \tag{32}$$

where π is the steady state inflation rate and ι_p reflects the degree of indexing to lagged inflation.

For firms able to re-optimize, the optimization problem is to choose a new reset price P_t^* to maximize expected discounted profits until the next re-optimization, given by

$$E_t \sum_{\tau=0}^{\infty} \xi_p^{\tau} \Lambda_{t,t+\tau} \left(\frac{P_t^* \Gamma_{t,t+\tau}}{P_{t+\tau}} - p_{mt+\tau} \right) Y_{t+\tau}^i \tag{33}$$

subject to the demand function (30) and where

$$\Gamma_{t,t+\tau} \equiv \prod_{k=1}^{\tau} \pi_{t+k-1}^{\iota_p} \pi^{1-\iota_p} \tag{34}$$

The first order condition for P_t^* and the price index that relates P_t to P_t^*, P_{t-1} and π_{t-1} are then respectively:

$$0 = E_t \sum_{\tau=0}^{\infty} \xi_p^{\tau} \Lambda_{t,t+\tau} \left[\frac{P_t^* \Gamma_{t,t+\tau}}{P_{t+\tau}} - \mu_{t+\tau} p_{mt+\tau} \right] Y_{t+\tau}^i \tag{35}$$

$$P_t = \left[(1-\xi_p) \left(P_t^*\right)^{-1/(\mu_t - 1)} + \xi_p \left(\pi_{t-1}^{\iota_p} \pi^{1-\iota_p} P_{t-1} \right)^{-1/(\mu_t - 1)} \right]^{-(\mu_t - 1)} \tag{36}$$

Equations (35) and (36) jointly determine inflation. In the loglinear equilibrium, current inflation is a function of current real marginal cost p_{mt}, expected future inflation, and lagged inflation.

3.4.3 Capital producers: investment

Competitive capital producers use final output to make new capital goods, which they sell to households, who in turn rent the capital to firms. Let I_t be new capital produced and p_{kt} the relative price of converting a unit of investment expenditures into new capital (the replacement price of capital), and γ_y the steady state growth in I_t. In addition, following Christiano et al. (2005), we assume flow adjustment costs of investment. The capital producers' decision problem is to choose I_t to solve

$$\max_{I_t} E_t \sum_{\tau=0}^{\infty} \Lambda_{t,t+\tau} \left\{ Q_{t+\tau} I_{t+\tau} - p_{kt+\tau} \left[1 + f \left(\frac{I_{t+\tau}}{(1+\gamma_y) I_{t+\tau-1}} \right) \right] I_{t+\tau} \right\} \tag{37}$$

where the adjustment cost function is increasing and concave, with $f(1) = f'(1) = 0$ and $f''(1) > 0$. We assume that p_{kt} follows an exogenous stochastic process.

The first order condition for I_t the relates the ratio of the market value of capital to the replacement price (i.e. "Tobin's Q") to investment, as follows:

$$\begin{aligned} \frac{Q_t}{p_{kt}} = 1 + f \left(\frac{I_t}{(1+\gamma_y) I_{t-1}} \right) + \frac{I_t}{(1+\gamma_y) I_{t-1}} f' \left(\frac{I_t}{(1+\gamma_y) I_{t-1}} \right) \\ - E_t \Lambda_{t,t+1} \left(\frac{I_{t+1}}{(1+\gamma_y) I_t} \right)^2 f' \left(\frac{I_{t+1}}{(1+\gamma_y) I_t} \right) \end{aligned} \tag{38}$$

3.4.4 Employment agencies and wage adjustment

As we noted earlier, the household is a monopolistically competitive supplier of labor. Think of the household as supplying its labor to form a labor composite. Firms then hire the labor composite. The only difference from the standard DSGE model with wage rigidity, is that households now supply two types of labor, skilled and unskilled. It also sets wages for each type.

Let $X_t = \{L_t, L_{st}\}$ denote a labor composite. As is standard, we assume that X_t is the following CES aggregate of the differentiated types of labor that households provide:

$$X_t = \left[\int_0^1 X_t^{h\,\frac{1}{\mu_{wt}}} dh\right]^{\mu_{wt}}. \tag{39}$$

where $\mu_{wt} > 1$ obeys an exogenous stochastic process[7].

Let W_{xt} denote the wage of the labor composite and let W_{xt}^h be the nominal wage for labor supplied of type x by household h. Then profit maximization by competitive employment agencies yields the following demand for type x labor:

$$X_t^h = \left(\frac{W_{xt}^h}{W_{xt}}\right)^{-\mu_{wt}/(\mu_{wt}-1)} X_t, \tag{40}$$

with

$$W_{xt} = \left[\int_0^1 W_{xt}^{h\,-\frac{1}{\mu_{wt}-1}} dh\right]^{-(\mu_{wt}-1)}. \tag{41}$$

As with price setting by final goods firms, we assume that households engage in Calvo wage setting with indexation. Each period a fraction $1-\xi_w$ of households re-optimize their wage for each type. Households who are not able to re-optimize adjust the wage for each labor type according to the following indexing rule:

$$W_{xt}^h = W_{xt-1}^h \pi_{t-1}^{\iota_w} \pi^{1-\iota_w} \gamma. \tag{42}$$

where γ is the steady state growth rate of labor productivity.

The remaining fraction of households choose an optimal reset wage W_{xt}^* by maximizing

$$E_t \left\{\sum_{\tau=0}^{\infty} \xi_w^\tau \beta^\tau \left[u'(C_{t+\tau}) \frac{(1-\tau_{t+\tau}^l) W_{xt}^* \Gamma_{wt,t+\tau}}{P_{t+\tau}} X_{t+\tau}^h - \upsilon \frac{X_{t+\tau}^{h\;1+\varphi}}{1+\varphi}\right]\right\} \tag{43}$$

subject to the demand for type h labor and where the indexing factor $\Gamma_{xt,t+\tau}$ is given by

$$\Gamma_{wt,t+\tau} \equiv \prod_{k=1}^{\tau} \pi_{t+k-1}^{\iota_w} \pi^{1-\iota_w} \gamma \tag{44}$$

The first order condition for the re-set wage and the equation for the composite wage index as a function of the reset wage, inflation and the lagged wage are given, respectively, by

[7] In estimating the model we introduce wage markup shocks to the wage setting problem of unskilled labor only, so the markup for skilled labor is constant at its steady state level.

$$E_t \left\{ \sum_{\tau=0}^{\infty} \xi_w^{\tau} \Lambda_{t,\tau} \left[\frac{(1-\tau_{t+\tau}^{l}) W_{xt}^{*} \Gamma_{wt,t+\tau}}{P_{t+\tau}} - \mu_{wt} \upsilon \frac{X_{t+\tau}^{h}{}^{\varphi}}{u'(C_{t+\tau})} \right] X_{t+\tau}^{h} \right\} = 0 \tag{45}$$

$$W_{xt} = \left[(1-\xi_w) \left(W_{xt}^{*} \right)^{-1/(\mu_{wt}-1)} + \xi_p \left(\gamma \pi_{t-1}^{\iota_w} \pi^{1-\iota_w} W_{xt-1} \right)^{-1/(\mu_{wt}-1)} \right]^{-(\mu_{wt}-1)} \tag{46}$$

3.4.5 Fiscal and monetary policy

We take two approaches when including government, lump-sum or distortionary taxes. If we assume that government activities G_t, L_{purt}, L_{puat}, κ_{rt}, and κ_{at} are financed with lump sum taxes T_t, government's budget constraint is

$$G_t + w_{st}(L_{purt} + L_{puat}) + w_{st}(\tau_{rt}^{s} L_{srt} + \tau_{at}^{s} L_{sat}) = T_t \tag{47}$$

while with distortionary taxes it writes

$$G_t + w_{st}(L_{purt} + L_{puat}) + w_{st}(\tau_{rt}^{s} L_{srt} + \tau_{at}^{s} L_{sat}) = \tau_t^{l}(w_t L_t + w_{st} L_{st}) \tag{48}$$

Further, the (log) deviation of G_t, L_{purt}, L_{puat}, τ_{rt}^{s}, and τ_{at}^{s} from the deterministic trend of the economy follows AR(1) processes. Formally, for each $\mathcal{X}_t \in \{G_t, L_{purt}, L_{puat}, \tau_{rt}^{s}, \tau_{at}^{s}\}$, we have

$$\log(\mathcal{X}_t/(1+\gamma_y)^t) = (1-\rho_{\mathcal{X}})\bar{\mathcal{X}} + \rho_{\mathcal{X}} \log(\mathcal{X}_{t-1}/(1+\gamma_y)^{t-1}) + \epsilon_t^{\mathcal{X}} \tag{49}$$

Next, we suppose that monetary policy obeys a Taylor rule. Let R_{nt+1} denote the gross nominal interest rate, R_n the steady state nominal rate, π^0 the target rate of inflation, L_t total employment and L^{ss} steady state employment. The (nonlinear) Taylor rule for monetary policy that we consider is given by

$$R_{nt+1} = \left[\left(\frac{\pi_t}{\pi^0} \right)^{\phi_\pi} \left(\frac{L_t}{L^{ss}} \right)^{\phi_y} R_n \right]^{1-\rho} \cdot R_{nt}^{\rho} \tag{50}$$

where the relation between the nominal and real rate is given by the Fisher relation:

$$R_{nt+1} = R_{t+1} \cdot \pi_{t+1} \tag{51}$$

and where ϕ_π and ϕ_y are the feedback coefficients on the inflation gap and capacity utilization gap respectively. We use the employment gap to measure capacity utilization as opposed to an output gap for two reasons. First, Takahashi et al. (2016) show that measures of employment are the strongest predictors of changes in the Fed Funds rate. Second, along these lines, the estimates of the Taylor rule with the employment gap appear to deliver a more reasonable response of the nominal rate to real activity within this model than does one with an output gap.[8]

In addition, we impose the zero lower bound constraint on the net nominal interest rate, which implies that the gross nominal rate cannot fall below unity.

$$R_{nt+1} \geq 1 \tag{52}$$

[8] Part of the problem may be that the behavior of the flexible price equilibrium output is quite complex in the model, particularly given the endogenous growth sector. As a robustness check on our specification of the Taylor rule, we estimate a version of the model in which we adjust the employment gap for demographic effects on the size of the labor force; our estimation results are robust to this change.

3.5 Resource constraints and equilibrium

The resource constraint is given by

$$Y_t = C_t + p_{kt}\left[1 + f\left(\frac{I_{t+\tau}}{(1+\gamma_y)I_{t+\tau-1}}\right)\right] I_t + G_t \tag{53}$$

Capital evolves according to

$$K_{t+1} = I_t + (1 - \delta(U_t))K_t \tag{54}$$

The market for skilled labor must clear:

$$L_{st} = (Z_t - A_t) * (L_{sat} + L_{puat}) + L_{srt} + L_{purt} \tag{55}$$

Finally, the market for risk-free bonds must clear, which implies that in equilibrium, risk-free bonds are in zero net supply

$$B_t = 0$$

This completes the description of the model.

3.6 Calibration

We take the calibration of the basic parameters from Anzoategui et al. (2015). They conduct a mix between calibration and Bayesian estimation of the parameters. We follow them except for those parameters that are absent from their paper or we re-estimate in other Work Packages. As we will explain, most of these parameters are in line with the standard RBC literature (see Christiano et al. (2005) and Smets and Wouters (2007)). We refer to Anzoategui et al. (2015) for more details on the way these parameters are set.

Some parameters are set to match steady state variables. The steady state depreciation rate δ and the steady state ratio of government expenditures are set to match their respective values in the data. Markups on final μ and intermediate goods ς are set to 1.1 and 1.18 respectively. The former is close to the lower and the latter to the middle values estimated in the literature.[9] Markups need to be calibrated conservatively low because the R&D share of GDP is increasing in markups and decreasing in ρ_λ. Hence, setting markups low makes the estimation of ρ_λ more conservative. ϑ is set to 1.35 to produce an elasticity of substitution between intermediate goods equal to 3.85, in line with Broda and Weinstein (2006). The steady state liquidity demand shock is set to get an annual liquidity premium of 50 bps, consistent with estimates in Negro et al. (2017).

We calibrate the technology parameters as follows. The elasticity of λ to private adoption activities ρ_λ is set to 0.95 to induce a ratio of private R&D to GDP consistent with post-1970 U.S. data (approximately 1.8% of GDP) and $\rho_{\lambda_{pu}}$ to 0.7, which is close to the estimates of Work Package 6. $\overline{\lambda}$ is set to produce an average adoption lag of 5 years

[9] Jaimovich (2007) reports markup estimates in gross output data between 1.05 and 1.15 and in value added data from 1.2 to 1.4.

which is consistent with the estimates in Cox and Alm (1996), Comin and Hobijn (2010) and Comin and Mestieri (2018).

The obsolescence rate $(1-\phi)$ is to 8% yearly, which is the average of the estimates of the obsolescence rate that come from the rate of decay of patent citations (Caballero and Jaffe (1993)) and patent renewal rates (Bosworth (1978)). We also use the estimates of Work Package 6 to calibrate the parameters in φ_t. The private technological parameter ρ_z is set to 0.38 and the public technological elasticity to 0.29. Given this calibration, Anzoategui et al. (2015) estimate the remain parameters with Bayesian methods. Table (4) summarizes the parameters in the model. These parameters are in line with the estimates in the literature as they extensively discuss in their paper.

Also, table (5) in the appendix describes the calibration of the parameters for the stochastic processes where we also borrow from the estimations conducted by Anzoategui et al. (2015). Finally, table (6) in the appendix shows the calibration of the steady state parameters for fiscal policy.

Parameter	Description	Value
α	Capital share	1/3
φ	Inv. Frisch elasticity	3.381
$\frac{G}{Y}$	SS govt. consumption/output	0.2
γ_y	SS output growth	1.87%
μ	SS final goods mark-up	1.1
ϑ	Intermediate goods mark-up	1.35
$1-\phi$	Obsolescence rate	0.08/4
$\overline{\lambda}$	SS adoption lag	0.15/4
ρ_λ	Private adoption elasticity	0.95
ρ_z	Private R&D elasticity	0.38
	Anzoátegui et al. (2015) Estimates	
ρ	Taylor rule smoothing	0.805
ϕ_π	Taylor rule inflation	1.571
ϕ_y	Taylor rule labor	0.47
f''	Investment adj. cost	1.386
$\frac{\delta'(U)}{\delta}$	Capital utiliz. Elast.	3.868
ξ_p	Calvo prices	0.927
ξ_w	Calvo wages	0.87
ι_p	Price indexation	0.276
ι_w	Wage indexation	0.338
μ_w	SS wage mark-up	1.87%
b	Consumption habit	0.389
δ	Capital depreciation	0.02
β	Discount factor	0.995
γ_y	SS output growth	1.87%

Table 4: Calibration.

4 The effect of Aggregate Shocks

Figure (1) depicts the IRF for one standard deviation of a monetary shock and to an exogenous TFP shock. Our results resemble the results on Anzoategui et al. (2015) and Comin and Gertler (2006). First, the economy with endogenous technology is more volatile than without it. The last is true for both monetary and TFP shocks. Second, all the responses–in this case to demand and supply shocks– are more persistent with endogenous technology.

Finally, it is worth to notice a key feature of our model: R&D and diffusion investment are both procyclical; the responses of L_{sat} and L_{srt} follow the response of GDP. The implication of this is that adoption of technology is procyclical as well. When there is a positive shock to the exogenous technological factor, adoption A_t (the second component of the aggregate TFP) goes up. This is because after a TPF shock, profits go up and wages go down, which makes investment in adoption and R&D to increase. Hence, total TFP increases endogenously. In particular, the growth rate of TFP expands/declines transitorily causing a permanent impact on the level of TFP.

5 Government investment in Innovation

In this section, we show the response of the economy to government spending on investment in R&D and Adoption. The goal os this section is to understand how can we better target an increase in innovation spending (European Union objective for H2020). Hence, we expand investment in R%D or Adoption separately. In the following, we analyze two cases: first we assume that government finances spending with lump-sum taxes, and second with distortionary labor taxes as described in the exposition of the model. The goal of these exercises is to study the general equilibrium effects of different policies, to highlight the importance of second-order effects of policies in which the way innovation is financed matters, since it raises resources from the economy by affecting other margins, like consumption.

5.1 Lump-sum taxes

Figures (2) and (3) show the IRF's for one standard deviation shock to diffusion public investment (left), R&D public investment (center), and R&D subsidies (right) of a government that finances its activities with lump-sum taxes. To show the relevance of the different elasticities for our different policies, we consider two alternative calibrations. First, we consider the benchmark calibration (blue-dashed line). Second, we show a case with high elasticity of adoption and R&D to public investment (pink-solid line). In the latter, the influence of public investment on λ_t and φ_t are equivalent to private activities. Recall that in the baseline calibration, the government is less efficient in both the probability of adopting a new technology λ_t and in the productivity of R&D φ_t.

Figure (2) suggests that first-order effects happen mainly through labor markets. As in this model investment in technology is made with skilled labor, government activities push skilled labor markets by demanding a higher quantity of skilled labor, and hence pushing wages up (see Figure (3)). The increase in wages is slow due to the wage rigidities. Left panel of Figure (2) shows an increase in public adoption L_{puat}. After a shock to L_{puat}, skilled wages also go up, so households start supplying more skilled labor overall.

This additional labor supply has to be distributed among the different private activities. This increases both private investment in adoption, L_{sat}, and private R&D investment, L_{srt}, constituting a spillover from public to private activities. Also, there is an increase in unskilled labor, that is due to the–expected– increase in aggregate productivity and investment, which raises unskilled wages. Hence, as a result of the combination of the increase in investment, productivity, and labor, GDP increases immediately and persistently. Consumption sustains this growth as wages and firm's earnings soar. This is the contribution of public investment to medium-term business cycles.

However, investment in R&D doesn't have the same effect of adoption activities. Center panels of Figures (2) and (3) show the IRF's to a one standard deviation of public R&D investment, L_{purt}. Recall that R&D activities don't translate to productivity immediately, it is adoption which does the job of materializing ideas into goods. That is why there are huge differences between the two cases.

When public R&D increases, agents know that the level of technology will be higher in the medium term. As a result, they want to consume more because, they are wealthier. This reaction triggers an increase in interest rates which lowers the value of adopted technologies. As a result, adoption declines upon impact. R&D instead increases because public R&D enhances the productivity of private R&D. Hence the different evolution of private R&D and adoption investments.

Finally, the right panel of Figures (2) and (3) show the response of the economy to an innovation subsidy shock. An important feature of innovation subsidies is that they can take advantage of the different impacts public and private investment have. In our baseline calibration, government investment in innovation has a lower elasticity, so it would be optimal to raise–lump-sum– taxes and then subsidize private innovation activities instead of spending directly on innovation.

Figures (2) and (3) show that a shock to R&D subsidy, in our calibration, resembles the response of the economy to R%D as if the public investment had high elasticity. This means that the rise in subsidy is enough to induce high investment in R&D and take advantage of the higher productivity the private activities have. The only difference would be the response of labor markets. As these shocks are transmitted through private demand for labor, L_{srt} expands more than for public R&D, and its impact on the rest of labor variables is essentially the same. An interesting result is that for our calibration, the impact on λ_t is equivalent to investment in R&D. This implies that the response on diffusion A_t is the same as in the high elasticity case. As a consequence, GDP and consumption follow the response of A_t on the best case.

In summary, a subsidy or tax to innovation is more useful when the differences in decreasing returns of public and private investment are higher, this is, when private investment is more productive than public investment. This also implies that having accurate estimates of these elasticities is key in order to evaluate the impact of the different possible policies governments can undertake in order to generate sustained growth.

5.2 Returns and the Skill Premium

Since in this economy there are many agents that have different roles, it is useful to analyze the effect of shocks on the returns of the different activities. Therefore, we study the effect of our policies on the return to R&D and Adoption. These returns are computed as follows:

$$E_t\left[\Lambda_{t+1}R^A_{t+1}\right] = E_t\left[\Lambda_{t+1}\phi\frac{V_{t+1}}{V_t-\pi_t}\right] = 1 \text{ and } E_t\left[\Lambda_{t+1}R^Z_{t+1}\right] = E_t\left[\Lambda_{t+1}\frac{J_{t+1}\varphi_t}{(1-\tau^s_{rt})w_{st}}\right] = 1.$$

Additionally, we compute worker's inequality responses to our policies, by analyzing the skill premium w_{st}/w_t.

Figure (4) shows the response of returns and the skill premium to a TFP shock and also to our policies. The four left panels show R^A_{t+1} and R^Z_{t+1}, while the four right left panels show the skill premium. Unsurprisingly, direct investment in diffusion and R&D increase their respective returns. This is because of the complementarity between public and private activities. Through the returns, we can understand the differences between investing in R&D and adoption. The return to adoption is much more volatile (for any shock), this is because they are more exposed to short- and medium-run fluctuations, while the return to R&D only reacts some periods after the policy. This is due to the adoption lag. In the early periods after the policy, there are no incentives to invest in R&D privately. However, the final effect is positive and highly persistent in the medium-run as technologies become more profitable. The latter is the main mechanism present in the process of R&D activities, which are active in the long-run, but depend heavily on current profits.

The skill premium also responds strongly to our policies. In fact, all these policies, even with lump-sum taxes generate inequality in the short-run. This is more pronounced for R&D policies because of the adoption lag. Surprisingly, the subsidy has a longer effect on inequality, that may be due to the higher impact of this policy on Z_t. However, all our policies impact the skill premium negatively generating more equality in the long-run. This is, innovation policies demand more skilled labor in the short-run, increasing the skill premium. But as the innovation process is effective in improving technology, in the long-run the additional demand for skilled labor disappears while the technological improvement doesn't, that's why the skill premium declines.

5.3 Distortionary taxation and the role of wage rigidities

In this section we explore the impact of wage rigidities and how they determine the effect of our policies. We do this to show that the way government is financed matters, but in our setup it could be camouflaged by this feature. The fact that we are taxing only labor in order to finance or subsidy skilled labor demand turns rigidities to be key in our results.

In what follows, we study the effects of innovation policies financed with distortionary taxation, but we set the probability of not adjusting wages to be 75% lower than in the baseline calibration and maintain the rest of the parameters fixed. Figures (5) and (6) show this case. The pink solid line shows the response of the economy with distortionary taxes and the blue dashed with lump-sum (that is, essentially, the baseline calibration).

Now the joint role of distortionary taxes and wage rigidities shows up, and it seems to be important. In this case, our policies trigger an increase in taxes, but the dynamics of the economy differ greatly between the two ways of financing, as expected. This, because in a low rigidity case, wages respond significantly to labor taxes not as with high rigidities. Hence, both the supply of labor and consumption will be changed with respect to the baseline, generating differences between distortionary and non-distortionary taxation.

Two forces now affect labor dynamics if government investment is financed with distortionary taxes. By the one side, our three policies demand skilled labor; by the other, taxes must increase in order to finance these policies, which distorts the labor supply of both types of labor. These two forces are present only in skilled labor after a shock to any of our policies, implying that its effects on skilled labor will be ambiguous. However, on impact, unskilled labor should decrease due to the raise in labor tax rates, while there is not an exogenous force demanding more unskilled labor. This happens in the short term, but while adoption of technology takes place, labor recovers. Hence, it follows that the response of labor depends on the response of labor taxes: the higher the latter increases, the lower labor falls. Thing that takes place after a shock to any of our three policies, with a significant impact on the real economy.

Moreover, the response of the real economy is very different as well. In the case of a shock to diffusion, GDP and consumption reach a maximum that is a third of the lump-sum case. This is because rigidities keep labor costs constant relative to the low case so the economy experiences an accentuated boom that follows the development of labor markets and the expansion of adoption. In the medium term the expansion of GDP and consumption is determined by the effect of distortionary taxes, by having a lower increase than when spending is financed with lump-sum taxes. For the case of our R&D policies, the pattern is similar. A subsidy calls for a bigger increase in taxes, which dampen the effect of subsidy policies, as can be seen by the stronger negative response of consumption and GDP than the case of lump-sum taxes and in public R&D. Actually, with distortionary taxation it would be better to use pubic R&D than subsidize it, at least in the short-run. Therefore, the way government finances its investment in innovation matters.

Finally, all our three policies are capable of generating the medium term business cycles shown above. Even though their effects depend on the way government finances them, in any case they are capable of expand the economy in the medium term. However, their effects crucially depend on the calibration of key parameters, especially those related to labor markets.

5.4 Alternative policies: Government spending v/s a reduction in corporate taxes

The final exercise is to show what kind of macroeconomic policy has a better performance. To do this, we include a corporate tax (or subsidy) and government spending shock. We take the case of a lump-sum tax for comparison and calibrate both shocks to have the same size and persistence (although they are not equivalent). Figure (7) shows the result.

This exercise constrasts the role of real and short-term policies. In our model, government spending is not productive, it is only final goods consumption, hence it won't have effects in the long-run. This generates big differences in the responses of both policies. Although a 1% increase in government spending expands GDP by almost a double of a reduction in corporate taxes on impact, the long-term effect is negative. This because government spending triggers a sizable crowding-out effect on consumption and investment because the interest rate goes up after a government spending shock. The increase in the interest rate affects investment in adoption and R&D by depressing them as well. Therefore, the economy contracts in the medium-run.

The opposite happens after a reduction of profits taxes. In fact, the economy sees a long-run expansion (of about 1%). This is due to the increase in investment (in capita and innovation) after the reduction in corporate taxes. The reason is that the driver of innovation are profits. As after tax profits increase, there is room for increasing innovation, which implies an increase in demand for capital and, of course R&D and adoption. All this, plus wage ridigities, implies a boom in innovation (in high skilled workers hired) which lasts enough to expand both A_t and Z_t, fact that finishes in the important expansion of consumption and GDP.[10]

Something to take in count when we analyze profit tax policies respect to sectoral (R&D or adoption) policies is that its effects are more long-lasting and more equilibrated than the adoption and/or R&D investments. In fact this policy seems to be counterweighting the trade-offs appeared from adoption or R&D policies alone, because there isn't a fall on A_t or Z_t at any term. This follows from the fact that net profits is the variable taken in consideration when agents decide to invest both in R&D or adoption, so it is the relevant margin to target. Therefore, any policy (in absence of more frictions) that targets profits is able to overcome the term trade-offs implied by the decision of investing in Adoption or R&D.

6 Conclusion

In this First Work Package we develop a baseline model which serves to analyze the impact of several public innovation policies on the evolution of the economy.

We follow Anzoategui et al. (2015) by including an active role of government policies in the process of R&D and adoption of technologies. We include direct public innovation investment, innovation subsidies, and analyze their effects along with the way they are financed in order to get an intuition of their impact in general equilibrium as well.

We find that public innovation in the form of any of our policies (direct investment or innovation subsidies) expand the economy in the medium term. This implies that it can serve as a substitute for private investment in innovation. We also show that their effects on the economy depend crucially on some parameters, in particular those related with labor markets. We showed that a great degree of wage rigidities hide the aggregate trade-

[10] We consider these two exercises as extreme cases of the policies analyzed. By the one hand, government spending could be productive and help build capital. By the other hand, profit taxes have a strong effect because in this model there aren't important frictions when building productivity. The latter fact will be analyzed further but it is out of the scope of this paper.

offs generated by labor tax raises. However, even with these trade-offs acting, innovation policies have a positive impact in the aggregate economy, wealth, consumption, and GDP.

This analysis can be extended in several ways. Two important extensions are the following: first, the distributional features of different policies. As they affect different labor markets differently, they have distributional effects; at least in the short term, the skill premium diverges due to these policies. Second, as there are trade-offs of these policies, the evaluation of optimal policy is a natural extension of this framework.

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A Tables

Parameter	Description	Value
ρ_θ	TFP	0.91
ρ_{pk}	Investment	0.87
ρ_ϱ	Liquidity demand	0.91
ρ_{mp}	Monetary	0.57
ρ_μ	Mark-up	0.38
ρ_g	Govt. expenditures	0.99
ρ_{μ_w}	Wage mark-up	0.26
ρ_χ	R&D	0.84
σ_θ	TFP	0.51
σ_{pk}	Investment	0.74
σ_ϱ	Liquidity demand	0.23
σ_{mp}	Monetary	0.1
σ_μ	Mark-up	0.1
σ_g	Govt. expenditures	2.87
σ_{μ_w}	Wage mark-up	0.3
σ_χ	R&D	2.13

Table 5: Calibration of stochastic processes.

Parameter	Description	Value
$\overline{\lambda}_{pu}$	SS public adoption lag	0.2
$\rho_{\lambda_{pu}}$	Public adoption elasticity	0.7
γ_z	Public R&D elasticity	0.29
ρ_{lr}	Persistence in Pub Inv in Adoption	0.9
ρ_{la}	Persistence in Pub Inv in R&D	0.9
ρ_{κ_r}	Persistence Pub subsidies in Adoption	0.9
ρ_{κ_a}	Persistence Pub subsidies in R&D	0.9
σ_{lr}	Pub Inv in Adoption	0.01
σ_{la}	Pub Inv in R&D	0.01
σ_{κ_r}	Pub subsidies in Adoption	0.01
σ_{κ_a}	Pub subsidies in R&D	0.01
$G/Earnings$	SS gov spending share	0.8
$L_{spua}/Earnings$	SS adoption inv share	0.05
$L_{spur}/Earnings$	SS R&D inv share	0.05
$\kappa_a/Earnings$	SS adoption subsidy share	0.05
$\kappa_r/Earnings$	SS R&D subsidy share	0.05

Table 6: Calibration of government parameters.

B Figures

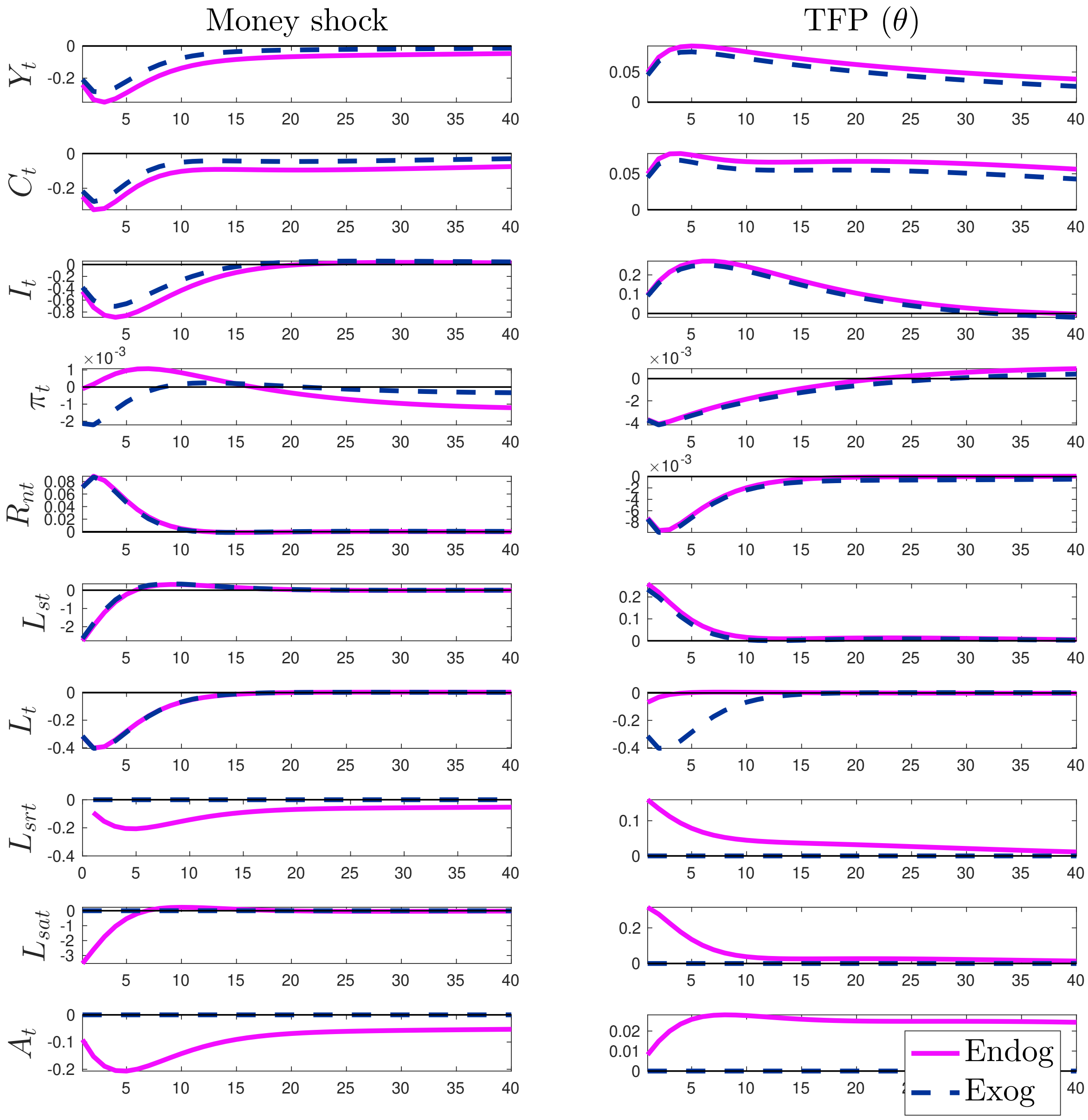

Figure 1: IRF's for a TFP shock with (red) and without (blue) endogenous technology.

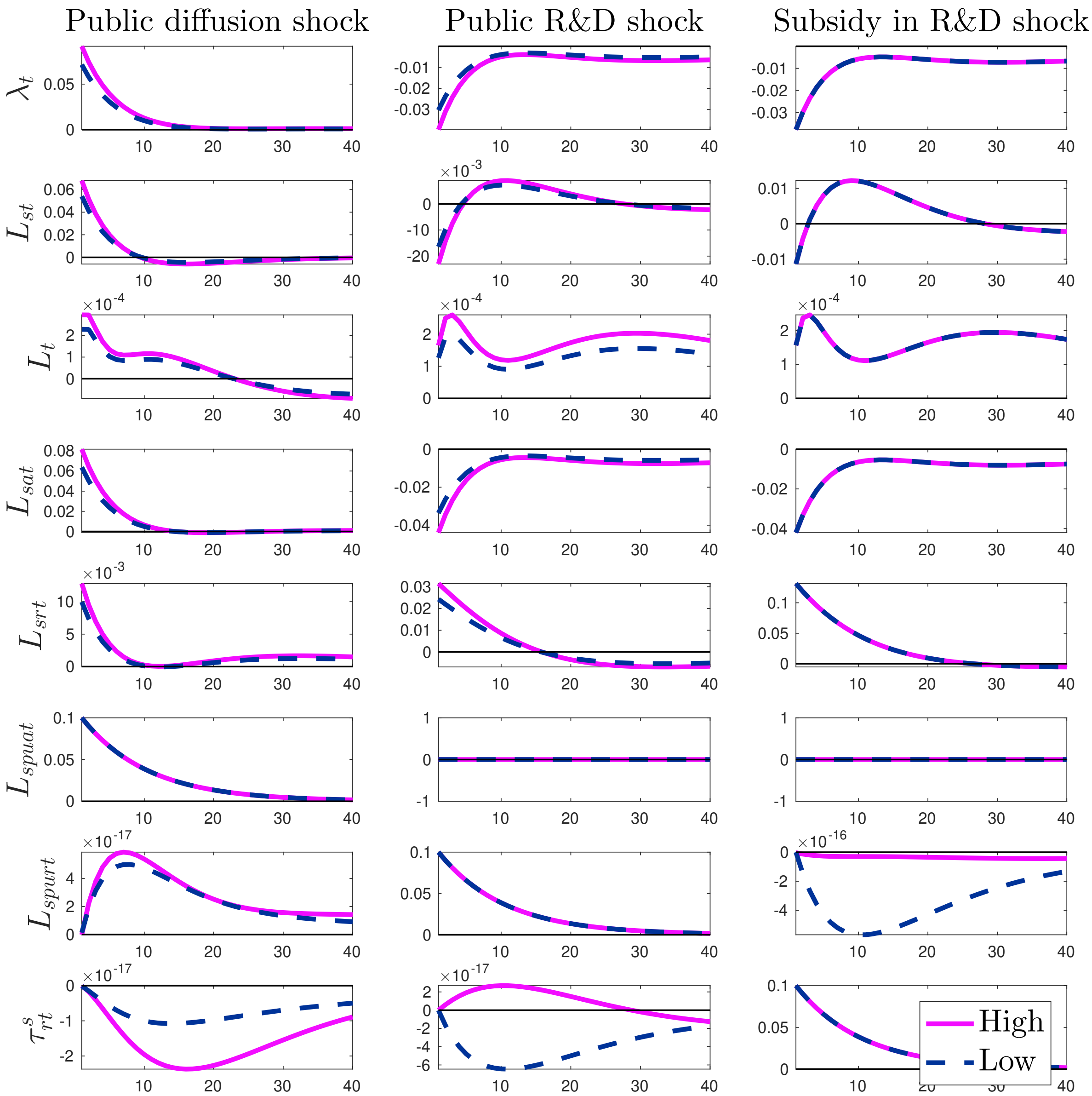

Figure 2: IRF's for shocks to public investment with lump-sum taxes. Pink-solid: high elasticities of government investment in innovation. Blue-dashed: baseline.

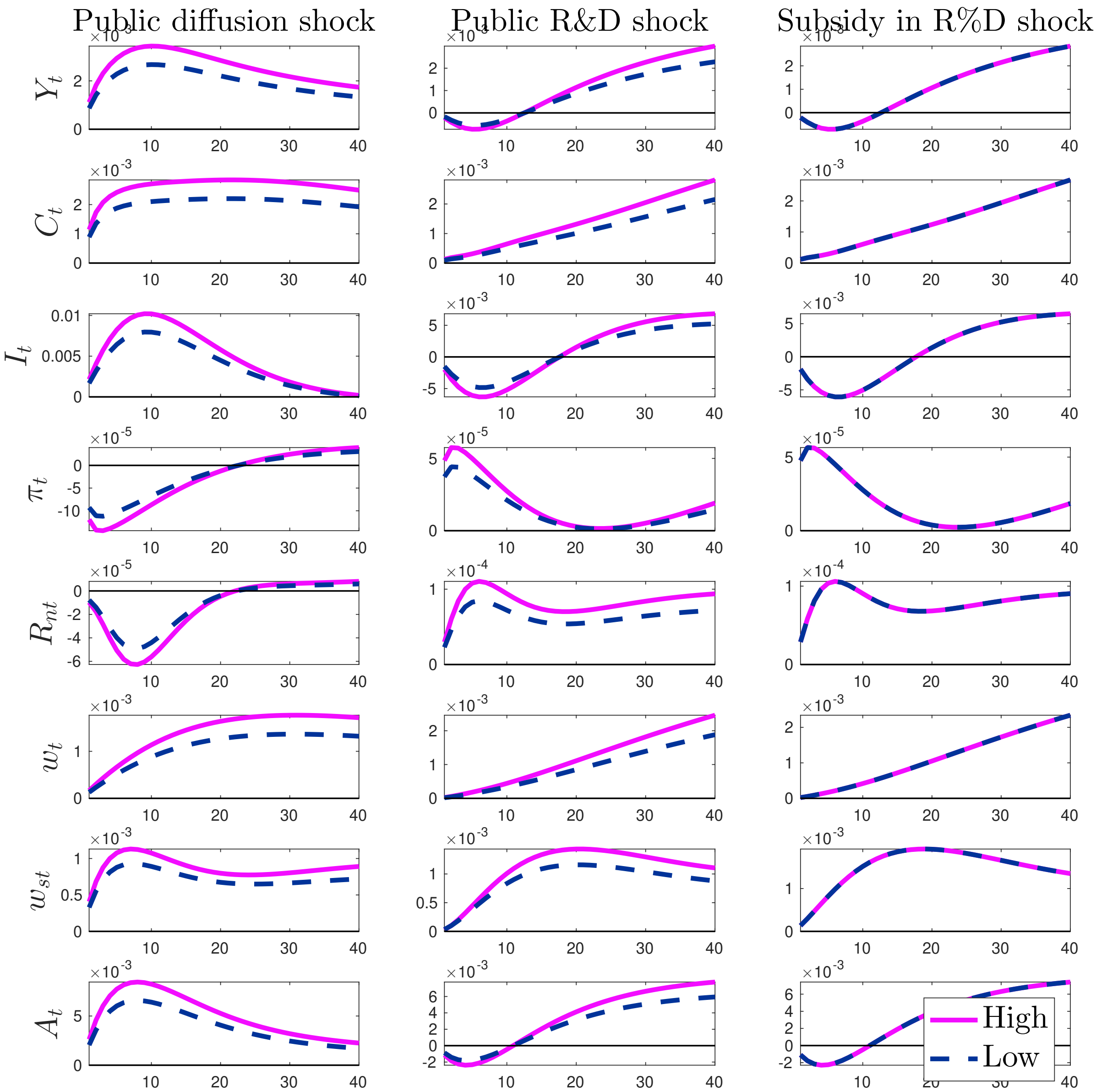

Figure 3: IRF's for shocks to public investment with lump-sum taxes. Pink-solid: high elasticities of government investment in innovation. Blue-dashed: baseline.

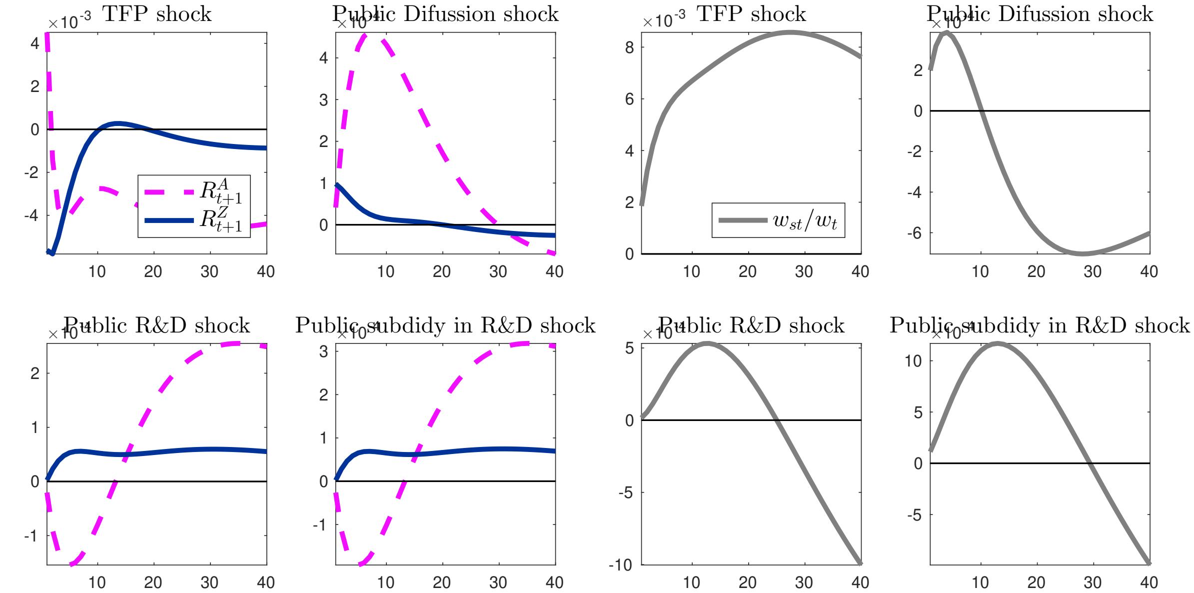

Figure 4: The effect of policies on returns to technology (four left panels) and on the skill premium (four right panels).

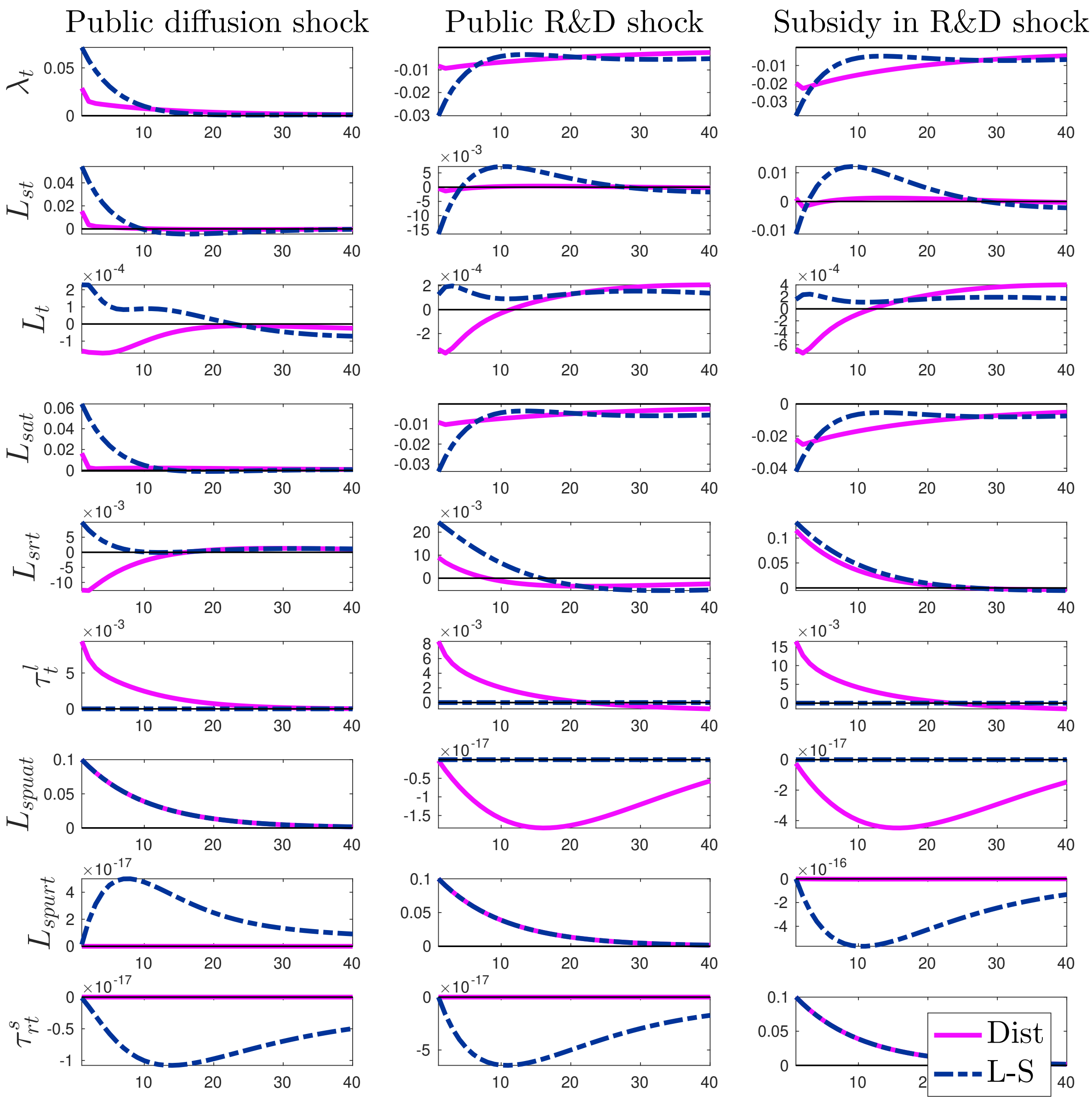

Figure 5: IRF's for shocks to public investment with distortionary taxes and low rigidities ($\xi_w^* = 0.25\xi_w$). Pink solid: distorsionary labor taxes. Blue dashed: lump-sum taxes.

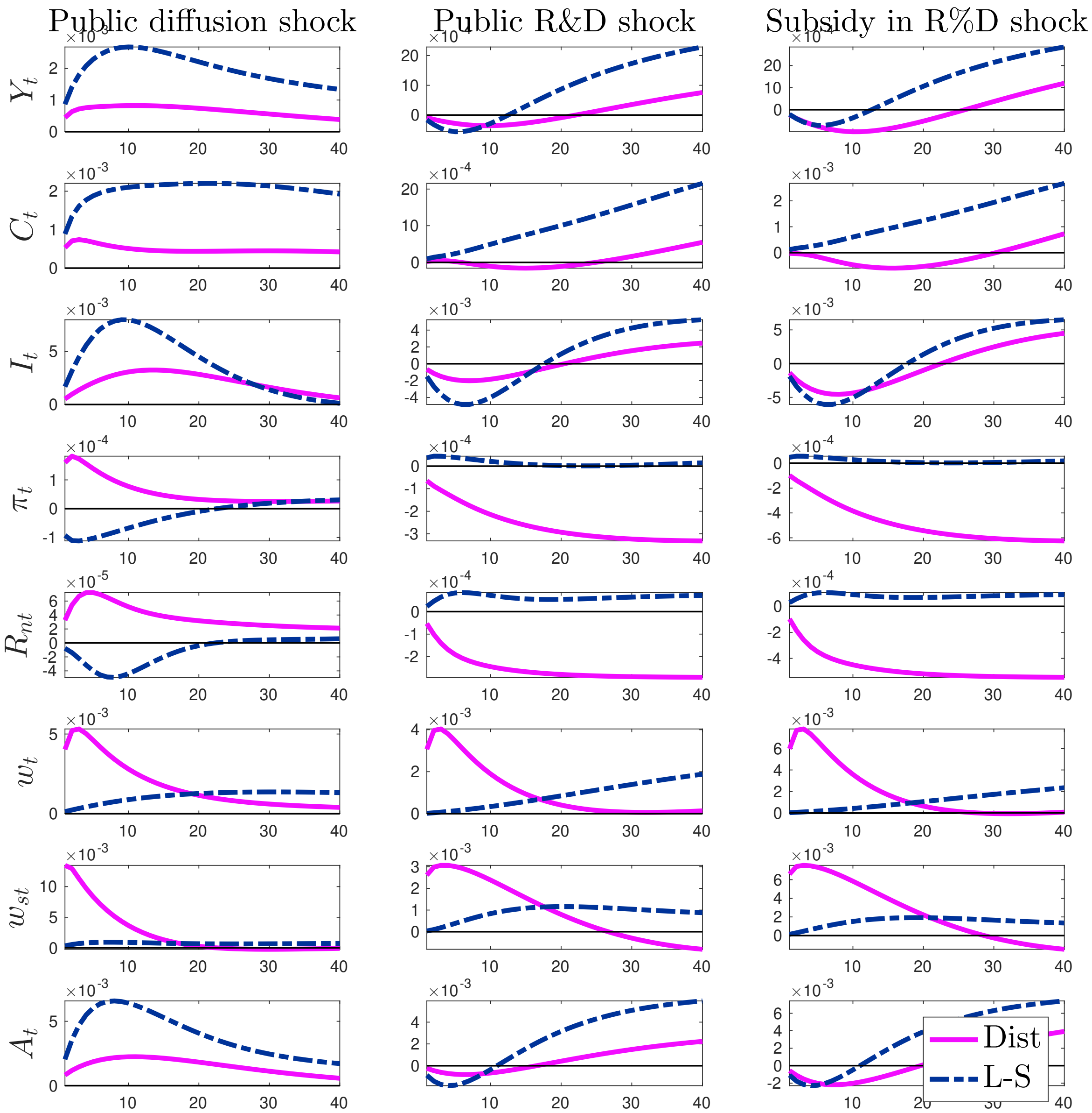

Figure 6: IRF's for shocks to public investment with distortionary taxes and low rigidities ($\xi_w^* = 0.25\xi_w$). Pink solid: distorsionary labor taxes. Blue dashed: lump-sum taxes.

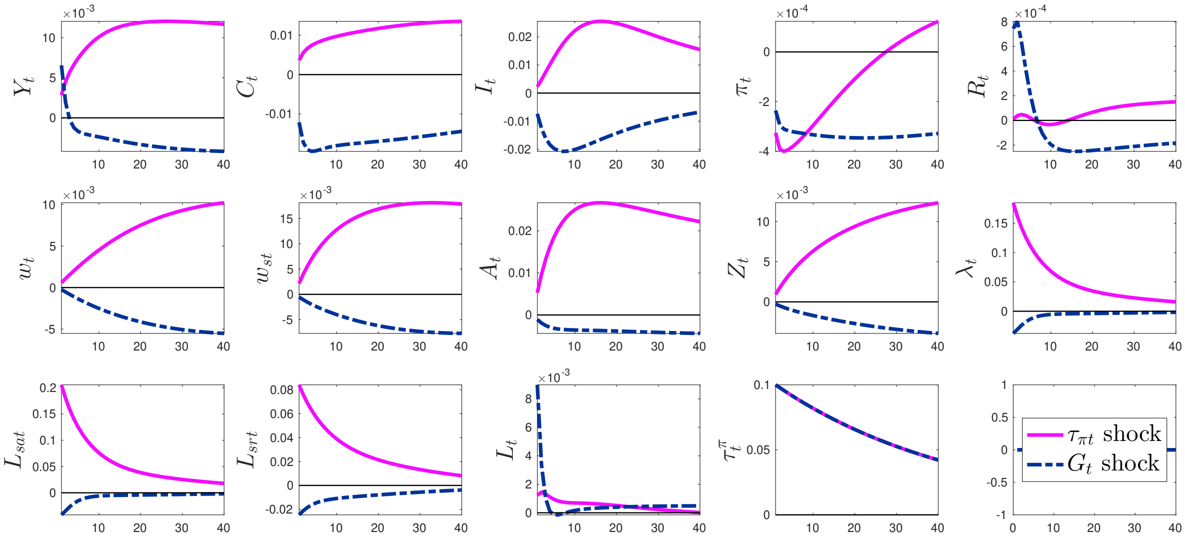

Figure 7: IRF's for a government spending shock and a reduction of corporate taxes.

C The Real Model

In the body of the paper, we build a New Keynesian model that its goal was to generate realistic responses of the economy to known shocks. We stressed the role of nominal– price and wage– rigidities because we wanted to have the best description of the reality both in the short- and the long-run. In this section, we depart from that and show the model results for a real model, which is a model without New Keynesian features. However, we maintain real rigidities like consumption habits, capital adjustment costs, and capital utilization. We take this route in order to understand and provide a simple model to analyze the different policies, but also, and more importantly, to build on the extensions. Therefore, this section shows the results of the model turning off prices–the Phillips curve, wage rigidities–the laws of motion of wages (equation (46)), and the Taylor rule, essentially. In what follows, we show the comparison between the New Keynesian (NK henceforth) and the Real models with both lump-sum and distortionary taxation.

Figures (8) and (9) show the IRF's of the economy to our three policy shocks for both the NK and the Real approaches with lump-sum taxes. First of all, we should note the different response of wages, especially skilled wages. When there is a positive innovation shock, that is a skilled labor demand shock, wages are pushed up in the Real model, while due to the sticky wages they don't react in the short-term. This has an important effect on equilibrium labor. As expected, skilled labor (L_{st}) reacts positively–and strongly– in the NK while it doesn't change much on the Real model, due to income effects. All this implies that the effect on λ_t and on φ_t is softer, implying that technology reacts less stronger, hence technology doesn't push GDP so high.

Recall that nominal rigidities work in the short run. However, the inclusion of them have long-term effects, this, because nominal rigidities, and monetary policy affect the incentives to invest in assets. Even though this is true, we don't see great differences on the impact of R&D policies in the Real and NK models, apart from the response of labor. Actually, as a consequence of the response of wages, labor in adoption in Real model the don't fall as much as in the NK model but the fall is more steady. This implies that technology is less likely to be adopted for longer, implying losses in GDP.

Finally, to illustrate the effect of our New Keynesian features, we analyze the implications of the interaction between the Taylor rule and the return to capital. In both models the expected return to capital increases, pushing investment up, that implies an additional increase in GDP. In the NK model, after a shock to diffusion, inflation goes down as this is a shock that pushes marginal costs down. This triggers the response of the Taylor rule, hence the nominal interest rate falls, that is an additional push to investment in capital and technology. That's why GDP increases by so much respect to the Real model after a diffusion shock.

Figures (8) and (9) show the IRF's of the economy to our three policy shocks for both the NK and the Real approaches with distortionary taxes. Comparing with the results in the body, these results are strikingly different. The first to note is that in our baseline calibration, after any of our policies, taxes go up. This happens in both the NK and Real model. The main differences is that wages don't react in the short-run in the NK model, while in the Real model they do by increasing. This generates a plunge in any kind of labor in equilibrium implying a fall in all kind of economic activity.

The increase in taxes is greater in the Real model because they have to finance the same amount of investment with a smaller taxable base implying an additional fall in labor. As any activity is affected negatively, technology gets damaged (both A_t and Z_t fall) making investment to fall. Hence, the economy experiences a complete contraction, and a recession.

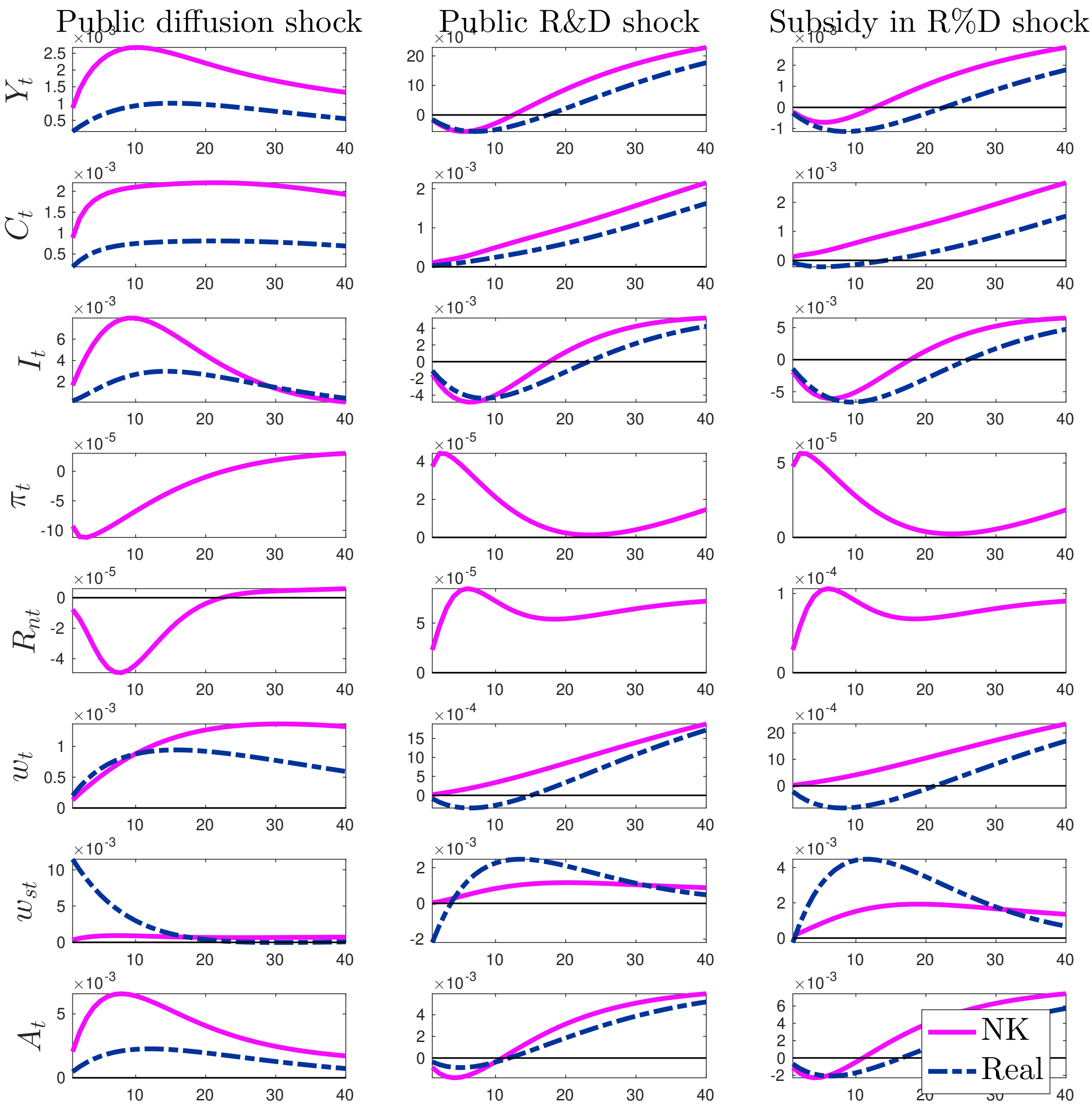

Figure 8: IRF of the economy to innovation policies in the New Keynesian and the Real models with Lum-sum taxes.

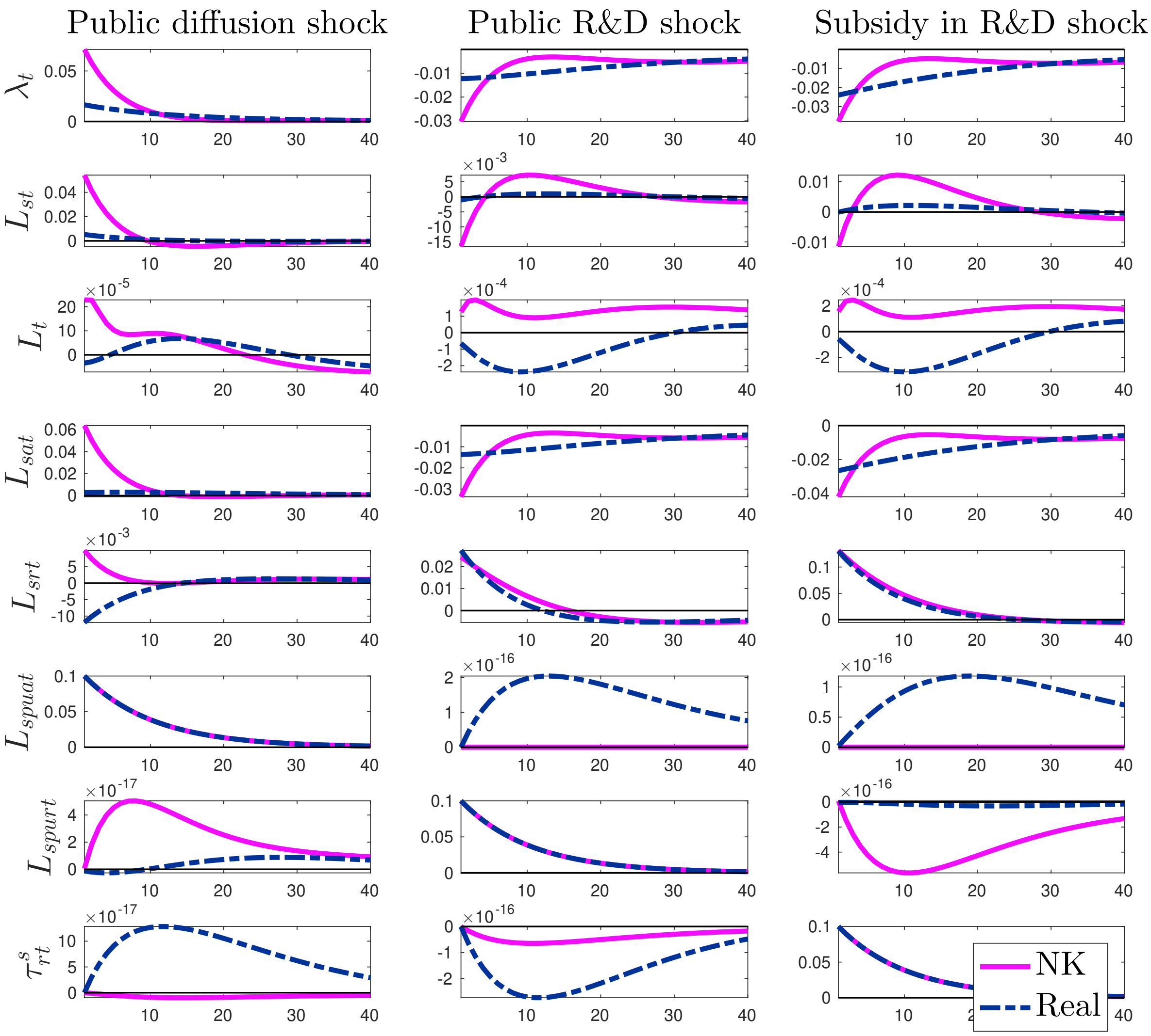

Figure 9: IRF of the economy to innovation policies in the New Keynesian and the Real models with Lum-sum taxes.

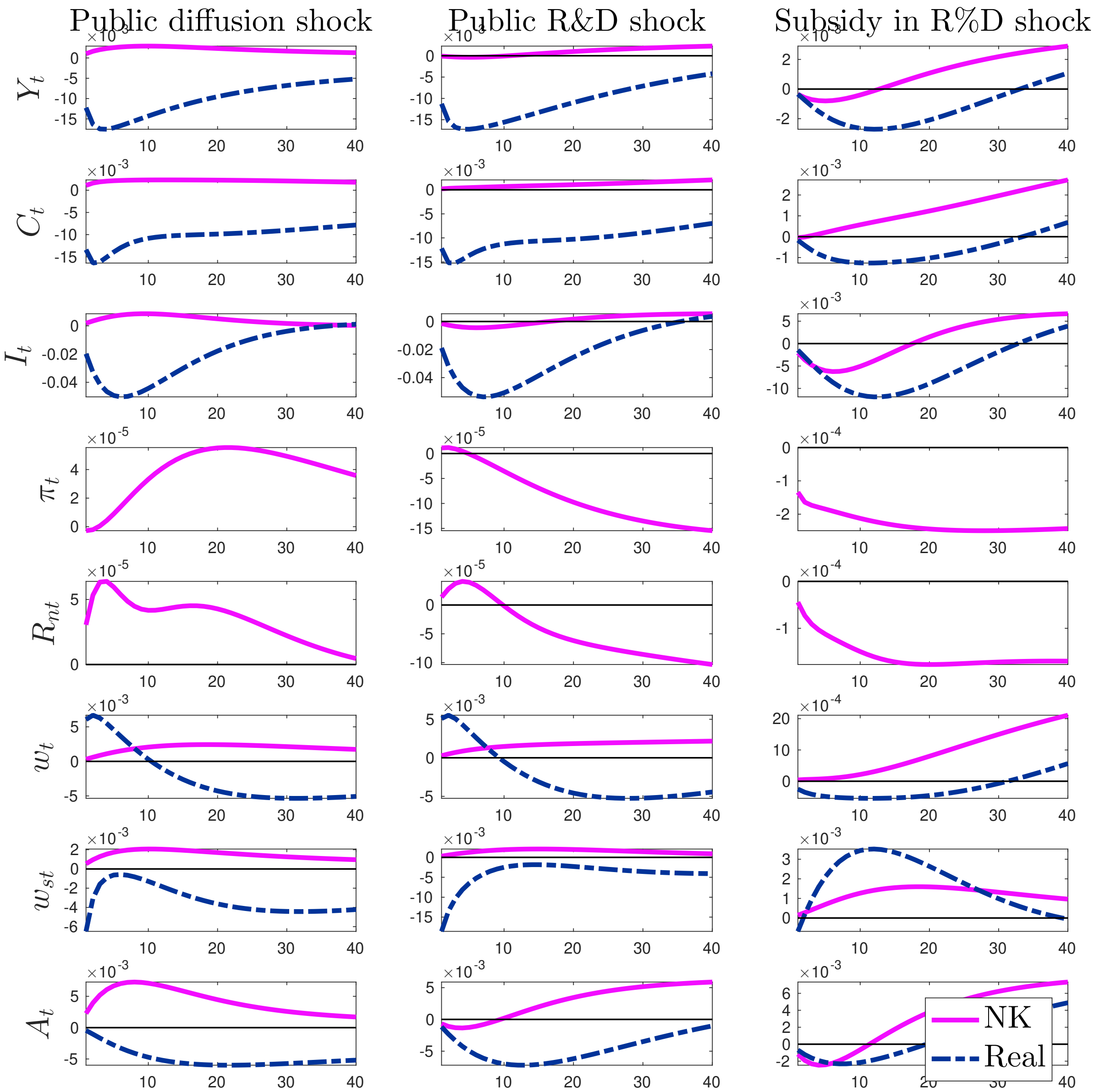

Figure 10: IRF of the economy to innovation policies in the New Keynesian and the Real models with distortionary taxes.

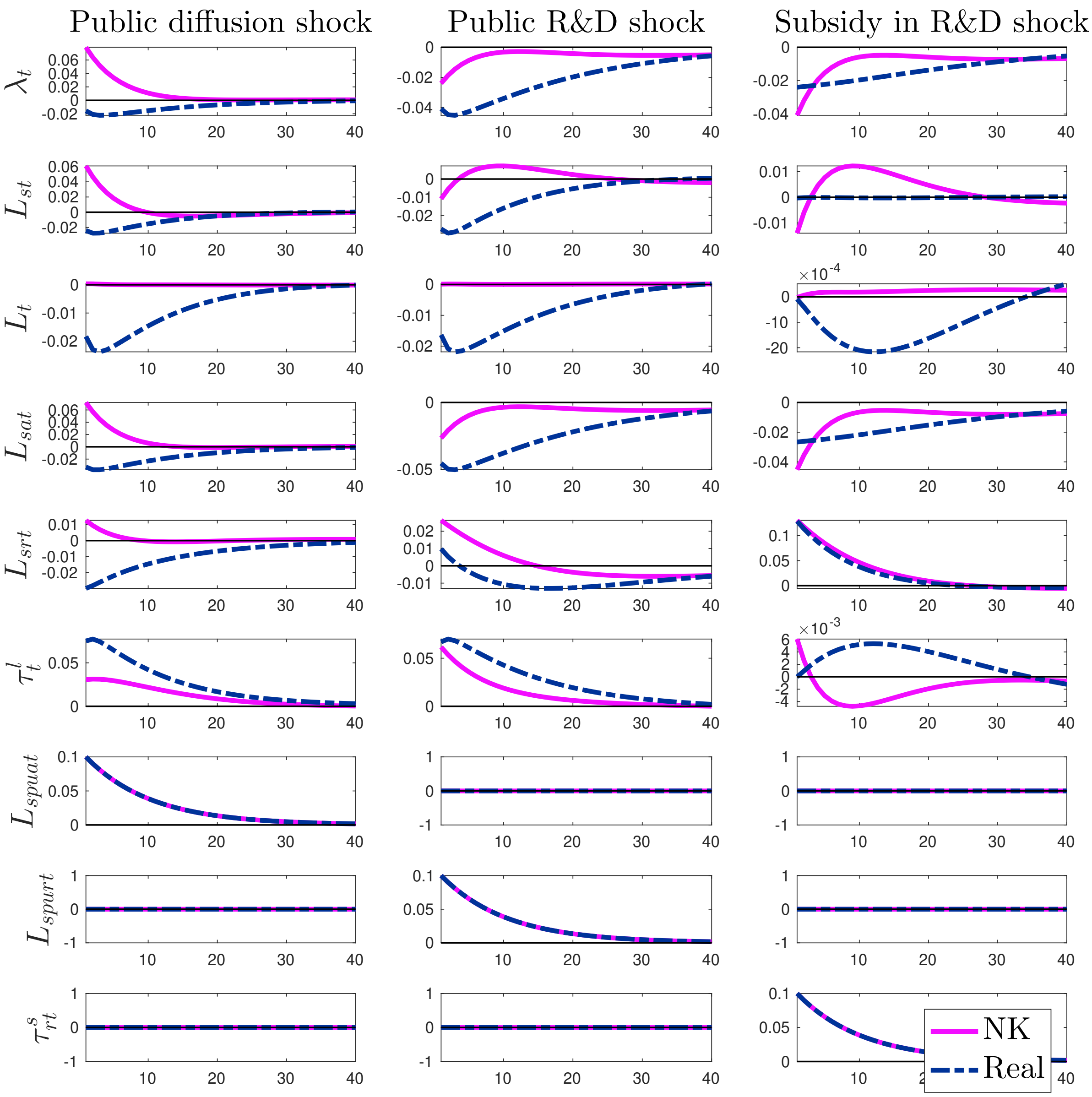

Figure 11: IRF of the economy to innovation policies in the New Keynesian and the Real models with distortionary taxes.

D Log-linearization of returns

The return to R&D, R^Z_{t+1}. The return to R&D can be obtained from the free-entry condition

$$E_t\left[\Lambda_{t+1}R^Z_{t+1}\right] = E_t\left[\Lambda_{t+1}\frac{J_{t+1}\varphi_t}{(1-\tau^s_{rt})w_{st}}\right] = 1$$

That loglinearized and detrended is (with $\hat{x}_t = \log x_t - \log x$):

$$\hat{R}^Z_{t+1} = \hat{J}_{t+1} + \hat{\varphi}_t + \tau^s_{rt} - \hat{w}_{st} - \hat{Z}_t + \hat{Z}_{t+1}$$

The return to Diffusion, R^A_{t+1}. The return to Adoption can be obtained from the value of a new technology:

$$V_t = \pi_t + \phi E_t\{\Lambda_{t+1}V_{t+1}\}$$

The return becomes:

$$E_t\left[\Lambda_{t+1}R^A_{t+1}\right] = E_t\left[\Lambda_{t+1}\phi\frac{V_{t+1}}{V_t - \pi_t}\right] = 1$$

So

$$R^A_{t+1} = \frac{\phi V_{t+1}}{V_t - \pi_t}$$

Which loglinearized and detrended is

$$\hat{R}^A_{t+1} = \hat{V}_{t+1} - \frac{1}{1 - \frac{\pi}{v}}\hat{V}_t + \frac{\frac{\pi}{v}}{1 - \frac{\pi}{v}}\hat{\pi}_t - \hat{A}_t + \hat{A}_{t+1}$$