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Firm and Technology Dynamics in the Short- and Long-Run

A Macroeconomic Model for Research and Innovation Policy Evaluation

Benedetti Fasil, C.
Impullitti, G.
Licandro, O.
Sedláček, P.

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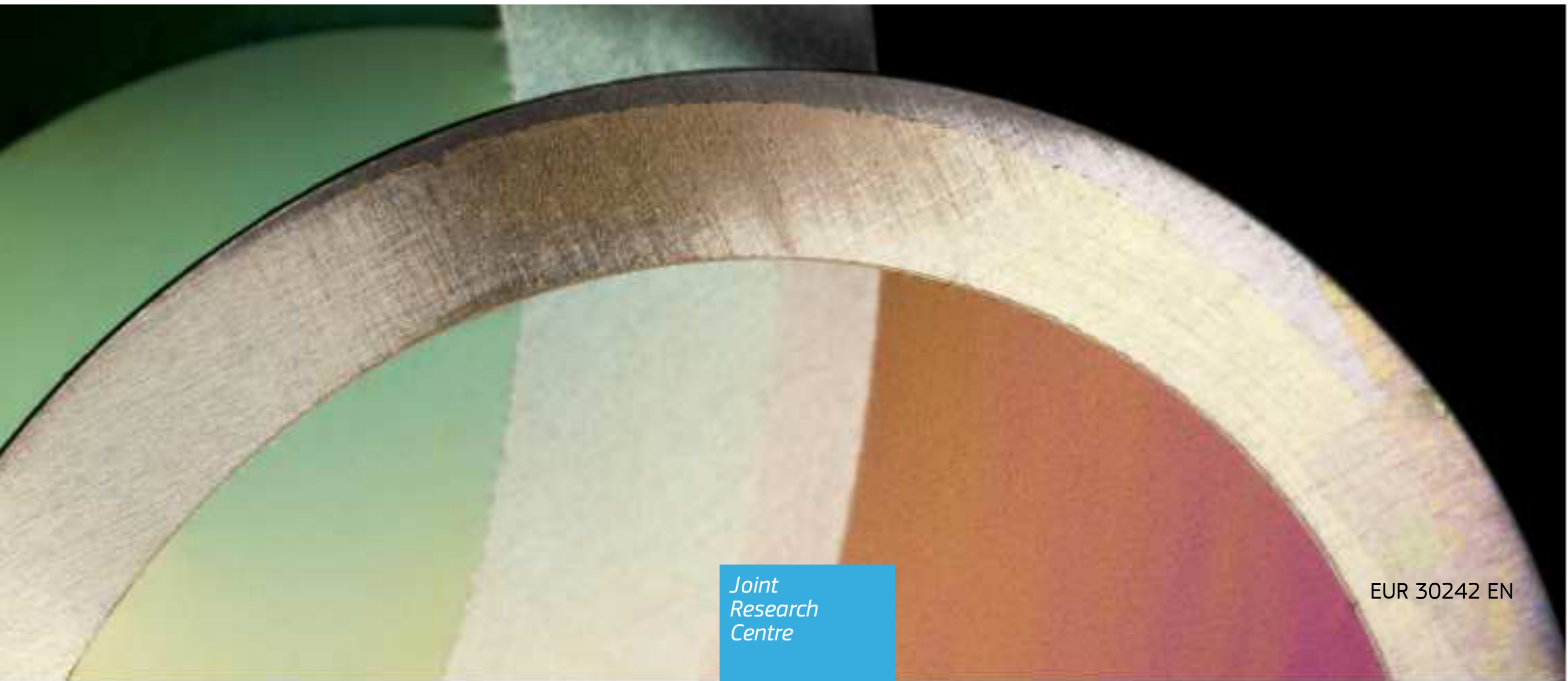

Joint Research Centre

EUR 30242 EN

Contact Information
Name: Cristiana Benedetti Fasil
Address: European Commission, Joint Research Centre, Rue Champ de Mars 21, 1050 Brussels, Belgium
Email: cristiana.benedetti-fasil@ec.europa.eu
Tel.: +44 0229 91111

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Authors

Cristiana Benedetti Fasil, European Commission, Joint Research Centre, Brussels, Belgium
Giammario Impullitti, University of Nottingham, UK & CEP-LSE
Omar Licandro, University of Nottingham, UK & IAE-CSIC and Barcelona GSE
Petr Sedláček, University of Oxford, UK, & CFM-LSE, CEPR

Abstract

We develop a dynamic stochastic general equilibrium model with firm and technology dynamics to assess the impact of a rich set of innovation policies. We explore the aggregate and cross-sectional effects of an R&D tax credit, corporate taxes, and policies affecting firms' access to credit. Two main results emerge. First, the aggregate impact of these policies is driven by general equilibrium effects operating via the government budget, the labor market and via equilibrium entry of firms. In contrast, their stimulating effect on innovation and productivity growth has a negligible impact on aggregate income and employment. Second, we find that uniform policies have heterogeneous effects on firms and their size distribution which generate rich feedbacks to the aggregate economy.

Keywords: Firm dynamics, innovation policy, endogenous growth, business cycles.
JEL: F12, F13, O31, O41.

1 Introduction

Innovation is the key engine of sustained productivity growth. Advanced countries grow by pushing the technological frontier and developing countries grow by catching up with that frontier. However, several economies, including the US and many EU countries, have experienced a substantial slowdown in productivity growth since the late 1970s. A key policy question is therefore whether governments can stimulate innovation and push their countries out of the productivity trap. In this paper we assess the performance of a rich set of innovation policies in a dynamic general equilibrium model with heterogeneous firms.

Allowing for multiple policies operating at the same is important because in reality government interventions do not operate in isolation. Countries are often under the influence of a wide set of policies from tax incentives for R&D to research grants, from policies increasing the supply of human capital to intellectual property rights protection and competition policy. Moreover, governments can also directly contribute to innovation by conducting and funding basic research.

Similarly, it is crucial to analyze the above policies through the lens of a model which allows for heterogeneous firms. There are enormous differences across businesses even within the same industry. Most startups shut down within the first few years of their existence. Most of those that survive do not grow and out of those that do expand, only a fraction regularly invest into R&D. A key advantage of our structural approach is that it allows us to understand how uniform policies, common across all firms, affect different businesses and how this then shapes aggregate economic trends and fluctuations.

We build a dynamic stochastic general equilibrium model with firm dynamics and technology adoption. The economy is characterised by a technology frontier that grows exogenously, firms enter by investing resources to obtain a vintage of the existing technologies and during their life time they keep investing to adopt a better vintage and improve their productivity. If they fail to innovate they eventually exit, as expansions of the technological frontier sustain a process of *creative destruction*.[1] Technology adoption raises firms' productivity which, in turn, leads to a gradual increase in consumption and wages. Therefore, faster technology growth has opposing effects on firms, depending on their technology vintage. On the one hand, firms at the frontier enjoy productivity gains larger than the increase in wage costs prompting them to create jobs. On the other hand, firms which have not adopted the newer vintage experience only a rise in wages and as a result they shrink and shut down more often. Moreover, a shock to aggregate productivity, common to all firms, generates business cycle fluctuations, making the model amenable to analyse the interaction between cycles and innovation policy.

We use this framework to analyse three policies potentially affecting the incentive to adopt new technology. Corporate taxes, an R&D tax credit, granting firm a tax break for their innovation expenditures, and policies aimed at improving access to finance. We assume that firms do not fully fund their entire R&D investment with their cash flow and borrow part of it from financial institutions.[2] The presence of financial frictions imply that firms borrowing to upgrade their technology incur a financing premium, which can be reduced by government policy. We calibrate the model to French firm-level data, matching firm dynamics and aggregate features of the economy, and conduct a set of experiments to explore the effects of these policies on firm-level and aggregate outcomes.[3]

We obtain two main results. First, the aggregate effects of all policies are not driven by their success in stimulating technology adoption and therefore productivity growth but they derive from general equilibrium effects operating via labor supply and business entry. Second, although the policies are common to all firms, the effects on technology adoption and other firm-level outcomes are heterogeneous, affecting firms differently. These heterogeneous firm-level responses have important implications for the transmission mechanisms of aggregate policy outcomes.

The R&D tax credit increases technology adoption and productivity but also reduces tax revenues, leading to lower transfer, lower consumption and, via labor supply, lower wages. The decline in labor cost increases firms' survival rate, thereby reducing the average productivity of the economy. These two forces largely offset each other and average productivity changes little. By reducing exit, higher survival rate leads to an economy populated by larger and older firms which, in turn, produces higher aggregate employment, capital and ultimately output. The reduction in corporate taxes slows down technology adoption, as it operates like a reduction of the tax credit for R&D. Its positive effect on aggregate output is driven by its impact on firm values. Lower taxes increase firm profitability thereby reducing exit rates and shifting the firm distribution toward larger firms. Finally, lower credit frictions increase firms' survival probabilities which depresses average productivity, but also increases firm values producing an effect of the opposite sign on productivity. In our baseline specification, these two forces perfectly offset each other and productivity does not change. Moreover, higher survival rates lead to lower exit rates shifting the firm distribution toward larger, older firms, which as in the case of the R&D tax credit, drives the increase in aggregate output.

[1] We will use innovation and technology adoption interchangeably to indicate a firm's acquisition of a new technology vintage.

[2] Financial system play an important role for innovation as entrepreneurs may lack the wealth to self-finance their innovative ideas or may be reluctant to bear all the risks [Aghion et al. (2018b)].

[3] Since we still miss some French statistics we preliminary complement the calibration using US data.

1.1 Literature review

The paper is related to several lines of research in the literature. Bloom et al. (2019) presents a survey of the empirical literature on innovation policy, condensing it in a *toolkit* for innovation policy makers. The policies are ranked by means of a composite index of the strength and quality of the evidence and the magnitude of the effects. Other criteria are whether the effects are likely to take place in the short or in the long run and whether they will affect inequality. The R&D tax credit and direct public funding of research seem to be more effective in the short run while human capital policies are more effective in the long run. Competition and trade policies seem to have a small impact on innovation but they are cheaper in terms of public budget. The R&D tax credit and trade policy tend to increase inequality, as the boost the relative supply of skilled labor, while human capital policy have the opposite effect. We complement this line of work assessing the impact of different innovation policy in a dynamic general equilibrium framework.

Our paper belongs to the emerging *New Quantitative Growth Theory* literature, where frontier endogenous growth models are taken structurally to micro and macro data and used for quantitative analysis [e.g. Lentz and Mortensen (2008), Akcigit and Kerr (2018)]. Our work is particularly related to Acemoglu et al. (2018) who present a quantitative assessment of the effects of R&D subsidies in an endogenous growth model where firms are heterogeneous in productivity (Klette and Kortum (2004)) and in innovation capacity. Tying the model closely to US micro data and focusing on the steady state equilibrium, they show that R&D subsidies to incumbents achieve modest increase in growth, subsidies to entrants and to fixed operating costs reduce growth.[4] The most effective policy proves to be a tax on the fixed operation costs of incumbents, which reduces the share of low-innovation type of firms and increase the share of high-innovation firms.[5] We complement this analysis focusing on a wider set of policies, casting our experiment in a framework which can be potentially used to analyse the interaction between innovation policies and business cycle fluctuations.

There is surprisingly little work in the endogenous growth literature on the effects of corporate taxation. In a second-generation endogenous growth model that does not feature scale effects, Peretto (2003) shows that only fiscal policies operating via the interest rate affect the long-run growth rate of the economy while those operating via market size do not. Corporate tax cuts are effective in stimulating growth as they operate via the interest rate. Peretto (2007) extends the analysis going more granular on corporate taxation, distinguishing between corporate income taxes, dividend taxes and taxes on capital gains. While these papers focus on theory, recently Ferraro et al. (2011) take this class of models to the data, to capture historical patterns of US tax policies and assess the impact of a rich set of fiscal policies on growth. They show that cutting taxes on capital gains increases long-run growth, while tax cuts on corporate income and dividends have the opposite effects, as they induce more entry thereby reducing innovation per firm, the key variable driving the growth rate. Our contribution is to analyse corporate tax reforms in an economy with firm heterogeneity and business cycle fluctuations, and show that the effects of policy not only on the number but also on the size distribution of firms have important aggregate implications.[6]

We make contact with the literature on the relationship between financial systems and innovation-led growth and in particular with the research on credit frictions in Schumpeterian growth models.[7] Typically, this line of research shows both theoretically and empirically that lower financial frictions, or better access to credit, have an unambiguously positive effect on economic growth and in particular on innovation-driven growth [Levine (2005)]. Recent research incorporating firm-level modelling and data has highlighted a negative effect operating via *selection*. Introducing credit constraints in a simplified version of Klette and Kortum (2004), Aghion et al. (2018a) show that better access to credit has a direct positive effect on firms' innovation incentives and and indirect reallocation effect allowing less innovative firms to survive, which reduces their incentive to innovate. These two offsetting effects generate an inverted-U relationship between credit constraints and productivity growth, which is also uncovered in French firm-level data. Exploiting a policy change that improved access to credit, they show that firms affected by this policy increase their productivity growth but also experience lower exit rates, especially those firms that were less productivie before the policy change. While they focus

[4]The positive direct effect of subsidies to incumbents on their innovation is in part offset by lower entry. First, higher incumbents' innovation increases creative destruction thereby reducing the value of entry; secondly, it increases the demand for skilled workers and their wage, thereby increasing the cost of entry. Subsidising incumbents fixed operating costs reduces the exit rate, thereby producing a negative selection effect which increases the proportion of low-innovation type firms and reduces growth. Finally, subsidising entry has negative effects on growth as it discourages innovation by incumbents.

[5]The analysis is limited to closed economy. For quantitative analyses of R&D subsidies in open economy see Impullitti (2010), Akcigit et al. (2018), and Borota et al. (2019).

[6]Ates and Saffie (2018a) analyse corporate taxation in a Schumpeterian model where firms are heterogeneous in the quality jump produced by innovation, they can be of high or low type. Entry is financed externally and the firm type is unknown at entry. Financial intermediators have access to a screening technology to get a signal of the entrant's type. Higher corporate taxes reduce entry, so the mass of firms is lower but they also trigger stronger selection, as financial screening is more intense. A lower mass of entrant reduces growth, while the more intense screening increases the quality of the entrants, thereby increasing growth. This mass/quality trade off can lead to negligible effects of taxes on growth.

[7]There is an extensive theoretical and empirical literature exploring several channels through which financial frictions can affect innovation and growth. For a recent survey see Aghion et al. (2018b).

on a simple deterministic steady-state model and reduced-form econometric analysis we propose a structural quantitative approach which allows us to asses counterfactual scenarios.

Finally, our work is related to the recent literature bridging the growth and the business cycle approach to macroeconomic analysis [Fatas (2000); Comin and Gertler (2006); Aghion et al. (2009), (2010), and (2014); Nuno (2011); Anzoategui et al. (forthcoming); Bianchi et al. (2019)]. Aghion et al. (2010) study the role of credit in smoothing business cycle fluctuations by facilitating innovation. Financial systems that ease credit constraints allow firms to borrow and make investments during recessions when the costs of investing are low but collateral values are also low. Benigno and Fornaro (2018) provide a Keynesian growth theory, building a New Keynesian model with innovation-driven growth and showing how pessimistic expectations can lead to persistent slumps with high unemployment and weak growth, a 'stagnation trap'. Severe depressions of aggregate demand reduce firms' profits thereby weakening their incentives to innovate and reducing productivity growth. Productivity growth affects households' future income, and a fall in future income generates a further reduction in current aggregate demand. Weak demand pushes the interest rate to the zero lower bound and monetary policy is unable to restore growth and full employment. By affecting expected future growth, substantial subsidies to innovation instead can push the economy out of the stagnation trap. We contribute to this line of research introducing firm heterogeneity and exploring its role in shaping aggregate effects of a rich set of innovation policies.[8] Sedláček (2019) sets up the baseline model on which we build, to show that counter-cyclical uncertainty fluctuations are a by-product of technology growth. We extend this model to incorporate financial frictions and to accommodate several policy instruments and explore their cross-sectional and aggregate implications.

2 Model

This section builds on Sedláček (2019) and provides a tractable general equilibrium growth model with endogenous firm dynamics, technology adoption, credit constraints and a government levying corporate taxes and providing subsidies for technology investment.

In this model firms endogenously enter, exit and conditional on survival they grow over their life-cycle. Throughout their life-cycles firms invest into adopting better production technologies which improve stochastically over time. However, a fraction of these costs must be paid upfront for which firms borrow from financial intermediaries subject to a collateral constraint. Finally, the model also includes a government which levies corporate taxes on firms and in return provides subsidies and tax credits to firms' technology investments.

The main goal of the model is to understand how financial constraints, corporate taxes and R&D subsidies impact firms' decisions. Particular attention is paid to how these economy-wide policies and frictions impact different firms and in turn how they shape the distribution and the aggregate level of R&D spending.

2.1 Household preferences and choices

The representative household chooses consumption, C_t, investment into physical capital I_t, and the supply of labor, N_t on perfectly competitive factor markets.[9] Following the indivisible labor models (see e.g. Hansen, 1985; Rogerson, 1988), labor is assumed to enter linearly into the household's utility function and is interpreted as the employment rate. Formally, the per-period utility of the representative household is given by

$$\ln C - \upsilon N, \tag{1}$$

where $\upsilon > 0$ is the disutility of labor and the preference specification allows for balanced growth. The representative household maximizes the expected present value of life-time utility, subject to its budget constraint

$$C + I = NW + RK + \Pi + T, \tag{2}$$

which states that total income stems from employment (with W being the competitive wage rate), renting out of capital to firms (with R being the competitive interest rate) and from the ownership of firms, where Π are aggregate profits. Finally, households also receive lump sum transfers from the government, denoted by T. This total income is spent on consumption and investment into physical capital, where $I = K' - (1-\delta)K$ and where δ is the depreciation rate, K is the stock of capital and primes indicate next period's values. The resulting optimality conditions are given by

$$W = \upsilon C, \tag{3}$$

$$\frac{1}{C} = \beta \mathbb{E} \frac{1}{C'} \left(R' + 1 - \delta \right). \tag{4}$$

[8] Ates and Saffie (2018b) develop an endogenous growth model with heterogeneous firms and aggregate risk to study the productivity effect of financial crises. They show that credit shortages give rise to a quantity/quality trade off, as firms born during the crises are fewer but produce higher quality goods.

[9] In what follows, aggregate variables are denoted by upper-case letters, while firm-specific variables are denoted by lower-case letters.

2.2 Technology adoption, firm-specific productivity and growth

It is assumed that the frontier technology evolves exogenously according to the following process

$$\ln Z' = \overline{Z} + \ln Z + \epsilon'_Z, \tag{5}$$

where $\overline{Z} > 0$ is a positive drift term and ϵ_Z are iid innovations distributed according to a Normal distribution with zero mean and standard deviation σ_Z.

The productivity level of an individual firm i is denoted by z_i. Each individual firm owns a particular vintage of the frontier technology and therefore we can express individual firm productivity in terms of a particular lag of the frontier technology, $z_{i,t} = v_{j,t} = Z_{t-j}$ with $j \geq 0$. In addition, firms can attempt to improve their prevailing productivity levels by investing into costly adoption of newer technology vintages. Because the frontier is growing over time, an individual firm which fails to adopt newer technologies will experience a gradual decline in relative productivity. At some point, such a firm will become so unproductive that it will no longer be profitable to remain in operation and it will shut down endogenously.

The investment into technology adoption is interpreted broadly, not only as direct costs of purchasing a well-defined technology. In particular, the costs of technology adoption, or implementation, include e.g. those related to identifying best practices, personalizing and implementing such practices at a specific firm, reorganizing existing business procedures or aligning of incentives to use the new technology efficiently (see e.g. Atkin et al., 2017; Comin and Hobijn, 2007; Lientz and Rea, 1998). Because any of the above implementation requirements may fail, investment into technology adoption is inherently uncertain.[10,11]

Following Klette and Kortum (2004), the various costs and resulting benefits of technology adoption are summarized using the following simple function. In particular, a firm investing r units of the final good has a probability p of adopting a newer technology vintage, where

$$p_i = \left(\frac{r_i}{\chi}\right)^{\frac{1}{\eta}} \gamma_i^{1-\frac{1}{\eta}}. \tag{6}$$

In the above expression, χ is a scaling factor, γ_i is the technology gap (or "stock of knowledge") defined as $\gamma_i = z_i/Z$ and $1/\eta$ is a curvature parameter.[12] The associated cost function can be written as

$$Q(p_i, \gamma_i) = \chi\gamma_i \left(\frac{p_i}{\gamma_i}\right)^{\eta}. \tag{7}$$

As explained, if an incumbent firm fails to adopt a newer technology vintage, it retains its prevailing productivity level. Successful adoption attempts may lead to either radical or incremental technological improvements [as in e.g. Akcigit and Kerr (2018)]. In particular, a fraction θ of firms adopting newer vintages adopt the frontier technology, while all other adopting firms obtain the technology of the closest younger technology vintage. Formally, if a firm i in period t has a productivity level of $z_{i,t} = v_{j,t} = Z_{t-j}$, then its productivity in the next period is described by

$$\ln z_{i,t+1} = \begin{cases} v_{j+1,t+1} & \text{with probability } 1 - p_{i,t}, \\ v_{j,t+1} & \text{with probability } p_{i,t}(1-\theta), \\ Z_{t+1} & \text{with probability } p_{i,t}\theta. \end{cases} \tag{8}$$

Finally, it is assumed that the process of technology adoption is the same for potential startups as it is for incumbent firms. As a normalization, the stock of knowledge for potential entrants is assumed to be given by the average stock of knowledge in the economy, $\overline{\gamma}$. Startups are assumed to enter the economy only if they manage to adopt the latest technology vintage.[13]

2.3 Firm behavior

Firm dynamics play a key role in this model. They feature endogenous firm entry and exit, an endogenous firm productivity (and thus size) distribution and firm life-cycle growth. Let us first describe these individual features and then turn to the formal firm maximization problem.

[10] The assumption of gradual adoption of (frontier) technology is related to Comin and Gertler (2006). In contrast to the latter study which assumes homogeneous firms (and competitive technology adopters), the primary focus of this paper is the time-varying *distribution* of technology vintages across firms.

[11] An alternative interpretation of the uncertainty surrounding technology adoption is that in addition to expected adoption costs, firms face heterogeneous and stochastic implementation costs. As new information about these costs emerges, firms may choose to abandon adopting a technology that was profitable in expectation (see e.g. Jack et al., 2015).

[12] An alternative modelling choice would be to assume that technology adoption costs are specified in labor units.

[13] Alternatively, it is possible to assume that startups are characterized by a particular distribution of initial technology levels.

Incumbent firms differ in terms of their productivity levels which they can improve as described in Section 2.2. However, investment into technology adoption is hindered by financial frictions. In particular, following Manova (2013) it is assumed that a fraction of a firm's technology adoption costs must be paid upfront. These costs are then borrowed from a financial intermediary subject to a collateral constraint.

In addition, firms must pay corporate taxes on their profits. They do, however, receive (potentially size-dependent) tax credits on their technology adoption costs from the government.

Conditional on their productivity level, firms produce output using labor and capital in a decreasing-returns-to-scale production technology. The gradual nature of technology adoption together with the presence of decreasing returns to scale in production result in a non-degenerate endogenous firm-level productivity (and thus size) distribution.

In the data, however, productivity gaps alone cannot account for the observed average size differences between young and more mature firms (see e.g. Foster et al., 2016). Therefore, to generate a realistic firm size distribution, which will be quantitatively important for the aggregate dynamics of the economy, firms in this model also grow over their life-cycles independent of their productivity levels.

In particular, it is assumed that firms accrue efficiency gains, ψ, through learning-by-doing. These gains are proportional to firm size and can be rationalized by for instance established long-term relationships, well-developed distribution networks or better management practices (see e.g. Stein, 1997). This makes more mature businesses, which do not necessarily operate cutting-edge technologies, competitive and able to fend off more innovative newcomers.[14]

Finally, in addition to variable costs, firms must also pay stochastic fixed costs of operation, ϕ. Businesses endogenously shut down when the realization of the fixed cost is too high rendering them unprofitable.[15]

Formally, after observing aggregate shocks but prior to the realization of idiosyncratic operational costs, an incumbent firm i of age a maximizes its discounted stream of all future profits ($\mathbb{V}_a(z_i, \mathcal{F})$) by choosing employment ($n_{i,a}$), capital ($k_{i,a}$) a technology adoption probability ($p_{i,a}$) and by deciding whether or not to remain in operation

$$\mathbb{V}_a(z_i, \mathcal{F}) = \max_{n_{i,a}, k_{i,a}, p_{i,a}} \int_{\phi} \max\left[0, \widetilde{\mathbb{V}}_a(z_i, \phi, \mathcal{F})\right] dH(\phi), \tag{9}$$

where $\mathcal{F}$ is the aggregate state and $\widetilde{\mathbb{V}}_a(z_i, \phi, \mathcal{F})$ is the value of a firm conditional on a particular draw of operation costs defined as

$$\begin{aligned}\widetilde{\mathbb{V}}_a(z_i, \phi, \mathcal{F}) =& (1-\tau)\begin{pmatrix} Az_i\left(k_{i,a}^{\alpha} n_{i,a}^{1-\alpha}\right)^{\kappa} - Wn_{i,a} - Rk_{i,a} - \phi \\ -Q(p_{i,a}, \gamma_i)(1+\widetilde{r}d) + \psi_a n_{i,a} \end{pmatrix} \\ &+ Q(p_{i,a}, \gamma_i)(1+\widetilde{r}d)\varphi(n_{i,a}) + \mathbb{E}\beta\frac{C}{C'}\mathbb{V}_{a+1}(z_i', \mathcal{F}'),\end{aligned} \tag{10}$$

where α and κ lie between 0 and 1 with the latter controlling the returns to scale in production and where $\varphi(n_{i,a})$ is a size-dependent tax-credit factor. Aggregate TFP, which affects all firms symmetrically, is given by

$$A' = (1-\rho)\overline{A} + \rho A + \epsilon_A.$$

In addition, the term $(1+\widetilde{r}d)$ reflects costs of technology adoption resulting from financial frictions. Specifically, firms face liquidity constraints and they must obtain outside capital to fund a fraction $d \in (0,1)$ of their technology adoption costs. Therefore, firms borrow $dQ(p_{i,a}, \gamma_i)$ from financial intermediaries. A fraction ζ of these costs is assumed to be invested in tangible capital and this fraction is pledged as collateral for the loan, with $\zeta < d$.

Because of imperfect contractability, firms will repay their loans only with probability $\mu \in (0,1)$. In this case, the lender receives $\Gamma(Q(p_{i,a}, \gamma_i)) = \Gamma_{i,a}$. With the complement probability $1-\mu$, firms default on their loans in which case the lender is able to recover the collateral $\zeta Q(p_{i,a}, \gamma_i)$. Therefore, the total costs of technology adoption can be written as

$$(1-d)Q(p_{i,a}, \gamma_i) + \mu\Gamma_{i,a} + (1-\mu)\zeta Q(p_{i,a}, \gamma_i). \tag{11}$$

In order for lenders to be willing to participate, it must be that the repayment $\Gamma_{i,a}$ is sufficiently large. In particular, it must be that the returns from lending to firms are at least as large as the returns from investing in the market at a rate $\widetilde{r}$. Formally, this results in the following incentive compatability constraint

$$dQ(p_{i,a}, \gamma_i)(1+\widetilde{r}) \leq \mu\Gamma_{i,a} + (1-\mu)\zeta Q(p_{i,a}, \gamma_i). \tag{12}$$

[14] In addition, modeling life-cycle growth using such deterministic efficiency gains greatly simplifies the computation of the model. The reason is that it does not introduce additional state variables as would be the case with e.g. labor or capital adjustment costs at the firm level.

[15] Note that as with expenditures on technology adoption, also ψ and ϕ are assumed to be paid in units of the final good and therefore they grow at the same rate as the rest of the economy.

In equilibrium, free entry of financial intermediaries results in (12) holding with equality which yields the following expression for the value of the loan

$$\mu\Gamma_{i,a} = dQ(p_{i,a},\gamma_i)(1+\widetilde{r}-(1-\mu)\zeta/d). \tag{13}$$

Combining (13) with (11) results in the firm value expression in (10).

Given the perfectly competitive nature of the factor markets, the optimal firm-specific employment and capital decision boil down to factor prices being equal to marginal products. In the case of the optimal employment choice, firms also take into account efficiency gains from learning-by-doing and the marginal change tax credits

$$R = \alpha\kappa y_{i,a}/k_{i,a}, \tag{14}$$

$$W = (1-\alpha)\kappa y_{i,a}/n_{i,a} + \psi_a + \frac{\tau}{1-\tau}\frac{\partial\varphi(n_{i,a})}{\partial n_{i,a}}Q(p_{i,a},\gamma_i)(1+\widetilde{r}d). \tag{15}$$

where individual firm output is given by $y_{i,a} = Az_i\left(k_{i,a}^{\alpha}n_{i,a}^{1-\alpha}\right)^{\kappa}$.

The point at which firms decide to shut down, $\widetilde{\phi}_{i,a}$, is defined by the liquidity constraint faced by firms. Specifically, in order to continue operating, firms must be able to repay their lenders

$$y_{i,a} - Wn_{i,a} - Rk_{i,a} - \phi - (1-d)Q(p_{i,a},\gamma_i) + \psi_a n_{i,a} + \mathbb{E}\beta\frac{C}{C'}\mathbb{V}_{a+1}(z_i',\mathcal{F}') \geq \Gamma_{i,a}. \tag{16}$$

Notice that the liquidity constraint applies to before-tax revenues.[16] Using (13) results in the following definition of the cutoff value for operational costs above which firms decide to shut down

$$\widetilde{\phi}_{i,a} = y_{i,a} - Wn_{i,a} - Rk_{i,a} - Q(p_{i,a},\gamma_i)(1+\lambda) + \psi_a n_{i,a} + \mathbb{E}\beta\frac{C}{C'}\mathbb{V}_{a+1}(z_i',\mathcal{F}'), \tag{17}$$

where $\lambda = [(1-\mu)(d-\zeta)+d\widetilde{r}]/\mu$ is the lending premium derived by combining the liquidity constraint (16) and the participation constraint (12).

Finally, optimal technology adoption, both for incumbent firms and potential new entrants, equates the marginal costs to the marginal benefits of investing into newer technology vintages

$$\chi\eta\left(\frac{p_{i,a}}{\gamma_i}\right)^{\eta-1}(1+\widetilde{r}d) = \frac{1}{1-\tau(1+\varphi(n_{i,a}))}\frac{\partial\mathbb{E}\beta C/C'\mathbb{V}_{a+1}(z_i',\mathcal{F}')}{\partial p_{i,a}}, \tag{18}$$

$$\chi\eta\left(\frac{p_e}{\overline{\gamma}}\right)^{\eta-1}(1+\widetilde{r}d) = \frac{1}{1-\tau(1+\varphi(n_e))}\theta\mathbb{V}_0(Z,\mathcal{F}). \tag{19}$$

In the above, p_e is the probability a potential entrant successfully adopts a newer technology, n_e is startup size and $\mathbb{V}_0$ represents the firm value of startups.[17] Note that $\mathbb{V}_{a+1}(z_i',\mathcal{F}')$ incorporates the endogenous evolution of firm-specific productivity as described by (8). To ease the exposition, formulas making this explicit are presented only in the Appendix.

2.4 The firm distribution, market clearing, balanced growth and equilibrium

We can now define $\omega_{j,a}$ as the beginning-of-period mass of firms of age a and productivity vintage z_j. In addition, let there be a fixed mass $\overline{E}$ of potential startups attempting to enter the economy in each period. The distribution of firm masses across frontier technology vintages ($j \geq 0$) and firm ages ($a \geq 0$) can be described

[16] This assumption is made for computational convenience. If, instead, the liquidity constraint was on after-tax revenues, then all firm decisions would depend on the particular realization of operational costs ϕ. This additional layer of heterogeneity would greatly complicate the solution method.

[17] Notice that startups have exactly the same financial constraint as incumbent firms. It is straightforward to assume that financial frictions are harsher for startups. This can be done by assuming that the fraction of technology adoption costs requiring external funding is larger for startups than for incumbents, $d_e > d$.

by

$$\begin{aligned}
\omega_{0,0} =& \overline{E} p_e \theta, \\
\omega'_{0,a+1} =& \sum_a \sum_j \int^{\widetilde{\phi}_{j,a}} p_{j,a} \theta \omega_{j,a} dH(\phi) \\
&+ \sum_a \sum_{j \leq a} \int^{\widetilde{\phi}_{0,a}} p_{0,a}(1-\theta)\omega_{0,a} dH(\phi) \\
\omega'_{j+1,a+1} =& \sum_a \sum_j \int^{\widetilde{\phi}_{j,a}} (1-p_{j,a})\omega_{j,a} dH(\phi) \\
&+ \sum_a \sum_{j \leq a} \int^{\widetilde{\phi}_{j+1,a}} p_{j+1,a}(1-\theta)\omega_{j+1,a} dH_t(\phi)
\end{aligned} \tag{20}$$

In the above, the first expression describes the mass of startups entering the economy in each period. The second expression gives the mass of firms older than one year, but which are nevertheless at the technological frontier. Such firms are either last period's surviving adopters with radical improvements from any part of the firm distribution (first summation) or last period's surviving frontier firms which managed to adopt the next younger vintage enabling them to keep up with technology growth (second summation). Finally, the third expression defines the mass of firms at productivity levels below the frontier. These businesses are either last period's surviving firms with productivity z_j which did not adopt newer technologies (first summation) or the mass of last period's surviving firms with productivity z_{j+1} which adopted the next younger technology vintage enabling them to keep up with technology growth (second line).

The labor and capital market clearing conditions and the aggregate resource constraint can be written, respectively, as

$$N = \sum_j \sum_a \int^{\widetilde{\phi}_{j,a}} \omega_{j,a} n_{j,a} dH(\phi), \tag{21}$$

$$K = \sum_j \sum_a \int^{\widetilde{\phi}_{j,a}} \omega_{j,a} k_{j,a} dH(\phi), \tag{22}$$

$$Y = C + I + \Xi, \tag{23}$$

where aggregate production $Y = \sum_a \sum_j \int^{\widetilde{\phi}_{j,a}} \omega_{j,a}(y_{j,a} + n_{j,a}\psi_a) dH(\phi)$, which includes efficiency gains from learning-by-doing, is spent on consumption, investment into physical capital and aggregate costs $\Xi = \sum_a \sum_j \int^{\widetilde{\phi}_{j,a}} \omega_{j,a} \left(\phi + Q(p_{j,a}, \gamma_j)\right) dH(\phi)$. The latter include operational costs and technology adoption expenditures. Aggregate profits are then defined as $\Pi = (1-\tau)[Y - WN - RK - \Xi] + \Theta$, where $\Theta = \tau \sum_a \sum_j \int^{\widetilde{\phi}_{j,a}} \omega_{j,a} \varphi(n_{j,a}) Q(p_{j,a}, \gamma_j)(1+\widetilde{r}d) dH(\phi)$. Finally, the government is assumed to run a balanced budget

$$T + \Theta = \tau \sum_a \sum_j \int^{\widetilde{\phi}_{j,a}} \omega_{j,a} \pi_{j,a} dH(\phi), \tag{24}$$

where individual firm profits are defined as $\pi_{j,a} = (y_{j,a} - Wn_{j,a} - Rk_{j,a} - \phi - Q(p_{j,a}, \gamma_j)(1+\widetilde{r}d) + \psi_a n_{j,a})$.

Note that the frontier technology is the only source of growth and therefore the economy fluctuates around the stochastic trend Z.[18] The aggregate state $\mathcal{F}$ consists of not only the aggregate capital stock K and the two aggregate shocks A and Z, but also of the entire joint distribution of firm age and productivity vintages $\omega_{j,a}$. The reason for the latter is that aggregate factor demands depend on the distribution of workers and capital across firms with different productivity vintages and efficiencies of operation (learning-by-doing gains) which are age-dependent.

Definition 1 (Equilibrium). *A competitive equilibrium for this economy is characterised by individual firms' policy rules for employment ($n_{i,a}$), capital ($k_{i,a}$), technology adoption probabilities ($p_{i,a}$) and firm exit ($\widetilde{\phi}_{i,a}$), potential entrants' policy rules for technology adoption probabilities (p_e), household's policy rules for aggregate consumption (C), employment (N) and investment (I), the wage (W), interest rate (R) and the distribution of firms across technology vintages and ages ($\omega_{j,a}$), the financial intermediaries' required loan repayment value ($\Gamma_{i,a}$), which satisfy the following conditions: (i) firms' optimal labor, capital, technology adoption and exit conditions (14) to (18), (ii) the free entry condition (19), household's optimal labor supply and Euler equations*

[18] Only firm-level and aggregate employment are stationary. All other variables can be stationarized by dividing them with Z.

(3) and (4), (iii) the aggregate resource constraint (23), which clear the labor and capital markets (21) to (22), which satisfy the incentive compatability constraint (12) and which are consistent with the law of motion for the distribution of firms across frontier technology vintages and ages (20).

3 Parametrization

The following paragraphs first describe the model's calibration and then evaluate its performance on dimensions not considered in the parametrization. In order to ease the exposition of the calibration strategy, we discuss the calibrated parameters in relation to specific targets even though individual parameters typically influence the behavior of the entire model. All parameter values and the associated targets are presented in Table 1.[19]

In order to be consistent with the establishment-based uncertainty measure, the targeted moments are computed using French establishment data taken from the ORBIS dataset using the period between 2009 and 2017. Following the frequency of the ORBIS data, the model period is therefore assumed to be one year.[20]

Let us start by discussing the parameters pertaining directly to the household. The discount factor, β, is set to 0.97 corresponding to an annual interest rate of 3%. The disutility of labor, ν, is set such that the steady state (stationarized) wage rate is normalized to one. The depreciation rate of physical capital is set to 10%, consistent with U.S. values found in Cooper and Haltiwanger (2006).

The parameters governing the process of technology adoption include the normalization constant χ, the curvature parameter η and the probability of radical technology improvements θ. The normalization constant affects the level of technology adoption costs. Proxying adoption costs with expenditures spent on research and development, χ is set such that average adoption costs are 2.2% of output as in the data. The curvature parameter is set to 2 implying a 0.5 elasticity of the probability of adopting a new technology vintage with respect to the associated expenditures. This is consistent with estimates in Acemoglu et al. (2018). Finally, θ is set to 0.1 following Akcigit and Kerr (2018) who estimate that roughly 10% of all innovations open up new technologies.

Next, turning to the production function, $\alpha = 0.33$ while the returns to scale parameter is set to $\kappa = 0.8$ which falls within the values estimated in Basu and Fernald (1997). The efficiency gains from learning-by-doing, ψ_a, directly affect establishments' life-cycle growth. To ease the computational burden, we consider four age categories: startups, young (one to five years), medium-aged (six to ten years) and old establishments (11 years and more).[21] Efficiency gains are then set in order to match average establishment size by age, relative to the economy's average (with efficiency gains of old establishments normalized to zero). The distribution of the operational costs, H, controls the extent to which establishments exit the economy. It is assumed that H is logistic with mean μ_H and scaling parameter σ_H. The former is set such that the average establishment exit rate is 25%. The latter, which controls the dispersion of of operational costs and which in turn shapes the relation between exit rates and firm-specific productivity, is pinned down by targeting the relative exit rate of startups and young establishments of 1.5 observed in the data.

Financial frictions in the model are governed by $\widetilde{r}$, d and ζ. To simplify the analysis, however, we assume that financial intermediaries have no outside option for their capital, i.e. $\widetilde{r} = 0$. This greatly simplifies the analysis, because what remains to be determined is the financing premium λ, rather than d and ζ separately. We set λ to 2% as in the data. The corporate tax rate is set to 28%, the statutory rate in France. The tax credit factor is set to 1.32 as given by OECD data.

Finally, let us turn to the calibration of the aggregate shocks (A and Z). Aggregate TFP is characterized by a level $\overline{A}$, persistence ρ and standard deviation of productivity shocks σ_A. Frontier technology grows over time with a positive drift $\overline{Z}$ and dispersion of frontier technology shocks σ_Z. These five parameters are chosen such that the model replicates the average establishment size, the persistence and volatility of real GDP, average labor productivity growth and the reallocation that is attributable to entry and exit.

4 Results

This section uses the developed model to investigate the effects of three different scenarios: an increase in R&D tax credits, a reduction in corporate taxes and a reduction in financial frictions. All three scenarios are conducted such that the change in the relevant parameter in the model is 5 percent. For example, the tax credit is goverend by φ in the model. The baseline specification assumes that the credit is 32 percent, i.e. $\varphi = 1.32$. Therefore, in our quantitative exercise we increase this to $\varphi_{\text{new}} = \varphi + 0.05(\varphi - 1) = 1.336$.

[19] The solution method follows Sedláček and Sterk (2017) and its description is deferred to the Appendix.

[20] When computing business cycle statistics, the data is logged and HP filtered with a smoothing coefficient 100.

[21] While startups become young establishments in the next period (conditional on survival), young (medium-aged) establishments become medium-aged (old) establishments with a probability $\delta = 1/5$ ensuring an "expected duration" of five years within these age categories (conditional on survival).

Table 1: Model parameters

	parameter	value	target/source
β	discount factor	0.97	annual interest rate 3%
υ	disutility of worker labor	0.01	wage normalization, $W_{ss} = 1$
δ_k	capital depreciation rate	0.10	Cooper, Haltiwanger (2006)
χ	technology adoption costs, normalizing constant	354	R&D costs as a share of output 2.2%
η	technology adoption costs, curvature	2	Acemoglu et al. 2013
θ	probability of radical improvements	0.10	Akcigit & Kerr (2016)
κ	returns to scale	0.80	Basu and Fernald (1997)
ψ_s	learning-by-doing efficiency gains, startups	-1.94	rel. average size of startups 12%, BDS
ψ_y	learning-by-doing efficiency gains, young establishments	-1.61	rel. average size of young establishments 15%, BDS
ψ_m	learning-by-doing efficiency gains, medium-aged establishments	-1.14	rel. average size of medium-age establishments 28%, BDS
ψ_o	learning-by-doing efficiency gains, old establishments	0	normalization
μ_H	operational cost mean	0.001	0 average paid operational costs, normalization
σ_H	operational cost distribution, scale	4.089	average establishment exit rate of 11%, BDS
$\overline{E}$	mass of potential entrants	57.9	firm mass of 1, normalization
λ	lending premium	0.02	average lending premium of 2%
τ	corporate tax rate	0.28	statutory corporate tax rate of 28%
φ	tax credit factor	1.3	average R&D tax credit of 32%, OECD
$\overline{Z}$	frontier technology shocks, drift	0.02	average labor productivity growth
σ_Z	frontier technology shocks, standard deviation	0.006	reallocation rate volatility 0.079
$\overline{A}$	aggregate TFP shocks, mean	4.440	average establishment size 69
ρ_A	aggregate TFP shocks, persistence	0.625	real GDP autocorrelation 0.58
σ_A	aggregate TFP shocks, volatility	0.004	real GDP volatility 0.019

Notes: The table reports model parameters and their respective targets or sources. Relative average size is defined as average size of the given firm category relative to the economy-wide average. The reallocation rate is the number of jobs created by startups and destroyed by exiting businesses relative to total employment.

Table 2: Partial equilibrium impact of higher tax credits on business outcomes (in $\%$ relative to baseline)

	simple	n-weighted
$\overline{p}$	$+4.7$	$+3.5$
$\overline{z}$	$+0.1$	$+0.2$
$\overline{n}$	$+4.4$	$+1.5$
$\overline{k}$	$+3.6$	$+1.4$
$\overline{y}$	$+3.6$	$+1.4$
$\overline{c}_{\text{R\&D}}$	$+9.4$	$+6.3$

Notes: average firm-level outcomes (simple and employment-weighted) with p, z, n, k, y and $c_{\text{R\&D}}$ denoting, respectively, probability of technology adoption, firm-specific productivity, employment, capital, output and costs related to technology adoption. All values are in percent relative to the baseline.

4.1 Higher R&D tax credits

We begin with a description of the effects of imposing higher tax credits for R&D expenditure of firms. The mechanisms described here operate in similar fashion under the other two policy changes and we will therefore devote more time to them here. In particular, it is instructive to separately discuss the effects of the tax credit increase under *partial* and *general* equilibrium. In the former, we let firms change their individual choices of employment, capital and investment into technology adoption, but we assume that exit decisions and in particular the aggregate wage and the number of potential entrants remain fixed at the values in the baseline economy. In the latter, all endogeneous variables are allowed to adjust.

4.1.1 Partial equilibrium

Following an increase in tax credits to individual firms, businesses have higher incentives to invest into technology adoption. This can be directly seen from (18) which allows us to derive the elasticity of the probability of innovation with respect to the tax credit as[22]

$$\epsilon_{p,\varphi} = \frac{\partial p_i}{\partial \varphi}\frac{\varphi}{p_i} = \frac{\varphi\chi\eta\tau}{(\eta-1)\chi\eta(1-\tau(1+\varphi))} > 0. \tag{25}$$

All else equal (and in particular, holding the wage and exit decisions fixed), higher tax credits lead to more technology investment, and in turn a higher rate of technology adoption. This, in turn, shifts the distribution of firms towards more productive businesses. This distributional change has large effects on average firm-level outcomes, as summarized in Table 2. Now that firms adopt newer vintages of technology more frequently (top row), average firm productivity increases (second row). The shift towards more productive firms also means that businesses are on average larger and utilize more capital (third and fourth rows), which in turn raises average output (fifth row). However, these increases come at substantial costs. Because of increased incentives to invest into technology adoption, the costs of doing so rise substantially (last row). Therefore, the net effect is not immediately obvious and this is precisely what we discuss in the next subsection.

However, before moving on, it is worth highlighting the large differences between the simple and employment-weighted averages in Table 2. The fact that employment-weighted averages are substantially smaller indicates that much of the changes following the tax credit increase occur at small businesses. The fact that an economy-wide policy has heterogeneous effects across businesses of different sizes is something that we will revisit below.

4.1.2 General equilibrium

Let us start by going back to the last two rows of Table 2 which show that while the partial equilibrium increase in average output is substantial, the associated costs are much larger.[23] This is simply due to the fact that technology adoption is not a bet on certainty. Only with an average probability of about 20 percent do businesses adopt newer vintages of technologies (and this probability differs across firm size and age). Therefore, the change in tax credits is likely to not be neutral from the point of view of the government budget. This spills over into the

[22] In the derivation we assume that the continuation value $\partial\mathbb{V}_{a+1}(z_i', \mathcal{F}')/\partial p_i$ is invariant to p. While this assumption is a good approximation for a given age, the continuation value does increase between age groups with older firms have higher incentives to invest into technology adoption simply because of their larger firm values. Nevertheless, the elasticity is positive for all age groups and roughly constant across the productivity distribution.

[23] This result is likely sensitive to the assumption of exogenous growth. Under endogenous growth, extended tax credits may indeed increase the overall growth rate and in turn raising tax income for the government.

Table 3: General equilibrium impact of higher tax credits (in % relative to baseline)

Firm-level outcomes					
$\overline{p}$	$\overline{z}$	$\overline{n}$	$\overline{k}$	$\overline{y}$	$\overline{c}_{\text{R\&D}}$
$+0.8$	$+0.0$	$+2.4$	$+1.7$	$+1.7$	$+2.0$
Aggregate outcomes					
W	E	Ω	N	K	Y
-0.7	$+1.4$	$+1.0$	$+0.3$	$+0.1$	$+0.1$

Notes: Top panel shows firm-level averages, with p, z, n, k, y and $c_{\text{R\&D}}$ denoting, respectively, probability of technology adoption, firm-specific productivity, employment, capital, output and costs related to technology adoption. Bottom panel shows aggregate outcomes with W, E, Ω, N, K, and Y denoting, respectively, the wage rate, number of startups, number of firms, aggregate employment, aggregate capital and aggregate output. All values are in percent relative to the baseline.

household decision making through the lump-sum transfers which, in turn, will affect the (general) equilibrium wage rate. Indeed, under the current calibration the net tax change is negative implying that the lump-sum transfers to the household drop (see equation 2). This directly impacts household consumption which, due to the assumption of infinitely-elastic labor supply implies that the wage rate also falls (see equation 3).

The decline in the wage rate has multiple effects on individual firms: i) it makes incumbents more inclined to create jobs, ii) it makes it easier for incumbents to survive in the market, iii) it increases firm values and in turn raises firm entry, iv) it makes labor relatively cheaper compared to physical capital. All these changes come together and impact the equilibrium distribution of firms and in turn shape the aggregate economy. Table 3 presents the aggregate results, in percent relative to the baseline.

The top panel of Table 3 shows again firm-level (employment-weighted) averages. It shows that even though the probability of technological innovation goes up, average firm-level productivity barely increases. This is because of two opposing effects. On the one hand, the partial equilibrium impact of the increased probability of technological adoption raises average firm productivity (as is apparent from Table 2). However, the reduced wage means that now even relatively less productive firms are able to survive. This weakened selection process leads to a lower average firm productivity. These two effects almost exactly cancel out in the current parametrization.[24]

Nevertheless, the overall effect on the aggregate economy is positive. This does not operate through improved productivity, but rather through *general equilibrium* effects. In particular, the decreased wage makes firms operate at a larger scale. Average firm size increases, as does the amount of firm-level capital (even though capital intensity declines due to a shift towards the cheaper factor of production). As a result, average firm output increases. However, this is not the only effect. The lower variable costs and improved chances of survival (partly due to higher probabilities of adopting new technologies) result in firm entry becoming more attractive. The number of businesses increases further raising aggregate output.[25,26]

4.1.3 Heterogeneous effects of homogeneous policies

In this subsection, we return to the topic of heterogeneous effects of an economy-wide policy. The difference between the changes in simple- and employment-weighted averages already hints at the fact that different firms are being affected in different ways by the common policy change. To visualize this, Figure 1 shows the percent changes in several firm-level outcomes as a function of relative productivity ($\gamma_i = z_i/Z$).

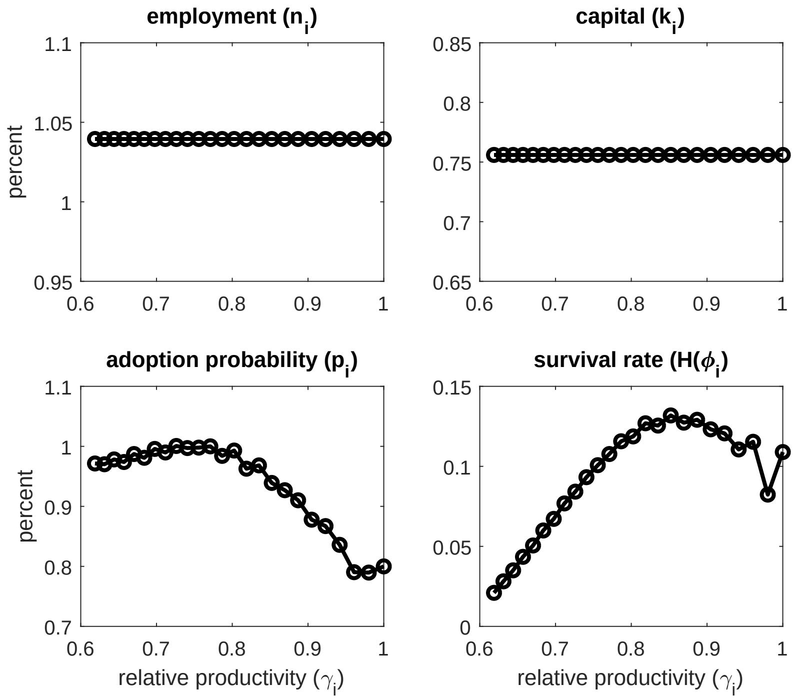
The top panels of Figure 1 show the change in firm-level employment and capital following the increase in tax credits. Firms across the productivity spectrum choose to increase both employment and capital. Since these decisions are static, they are not a result of greater chances of productivity growth in the future. Instead, this increase is a result of the lower wage, an indirect general equilibrium effect. The fact that firms are all reacting to the same drop in variable costs also explains why firms across the productivity distribution raise their factor inputs by the same percent amounts. The fact that employment rises by more than capital input is a result of a relative price change. Due to the drop in wages (and an unchanged cost of capital), labor becomes relative cheaper and firms substitute towards it in their production mix.

[24] By increasing firm values, lower wages also produce an additional incentive to increase innovation which in the benchmark economy is not strong enough to overturn the negative selection effect.

[25] The reason why aggregate output increases by less than average firm-level production is that aggregate output is net of all paid costs which also increase.

[26] The fact that increasing tax credits raises aggregate output is a result of government taxes being a distortion. Reducing government taxes, and tax credits, to zero increases aggregate output considerably more than the analyzed scenario. This is despite the presence of the financial friction.

Figure 1: Heterogeneous effects of the R&D tax credit



Notes: the panels show changes (in percent) in firm-level employment (n_i), capital (k_i), the probability of adopting newer vintages of technology (p_i) and the survival rate ($H(\widetilde{\phi}_i)$) as a function of the distance from the frontier, or relative productivity $\gamma_i = z_i/Z$.

The bottom panels show the changes in the probability of adopting newer vintages of technologies and the survival rates by firm-level productivity. In contrast to the top panels, these variables highlight the clearly heterogeneous effects a rise in tax credits, which is common to all firms, has on different firms. The reason for the difference between the variables in the top and bottom panels comes from the fact that while employment and capital are static decisions, investment and exit decisions are dynamic and take into account future chances of survival and productivity growth. The latter are then heterogeneous across firms, depending on their relative position in the productivity distribution. Survival rates depend on the expected *level* of firm values (see eq. 17) which increase with productivity. In contrast, the probability of adopting newer technologies depends on the expected *difference* in firm values when successful and when not (see eq. 18). The latter generally decreases with productivity as the potential improvements upon successful technology adoption decrease the closer a firm is to the frontier to begin with.[27] Therefore, the impact of higher tax credits is increasing (decreasing) in relative productivity for survival rates (adoption probabilities).

The increase in R&D tax credit then produces a stronger stimulus to innovate for less productive (and small) firms than for large, productive, firms. Recall that the former, on the one hand, have more ground to cover as they are further behind the technology frontier, so they can potentially obtain larger innovations. On the other hand, their innovation intensity (R&D to sales ratio) is smaller compared to more productive firms. This tension between *innovation potential* and *innovation scale* is a key determinant of the role of firm heterogeneity in shaping the aggregate effects of innovation policy. In our benchmark economy, the tax credit shifts the firm distribution toward small, less productive, firms thereby increasing their innovation relatively more than for more productive firms. The negligible effect on productivity then suggests that the innovation scale margin prevails. Consequently a policy that shifts the firm distribution toward firms with lower innovation expenditure is unlikely to stimulate productivity growth.

The figure highlights two important points. First, even economy-wide policy changes which are common to all firms may have heterogeneous effects. Hence, a country's firm size and productivity distribution represents an important statistics guiding policy decisions. The results of our benchmark simulations suggest, for example, that an R&D tax credit is more likely to be effective in enhancing productivity in a country mostly populated by small and young firms. Second, firm-level changes, which eventually shape the aggregate response, are driven by indirect, general equilibrium, effects (in this case a change in the wage rate).

[27] This result would change in the case of endogenous growth where even the most productive firms can grow further.

Table 4: General equilibrium impact of lower corporate taxes and financial frictions (in $\%$ relative to baseline)

	Firm-level outcomes					
	$\overline{p}$	$\overline{z}$	$\overline{n}$	$\overline{k}$	$\overline{y}$	$\overline{c}_{\text{R\&D}}$
corporate taxes	-3.8	$+0.0$	-10.1	-7.2	-7.2	-8.8
financial frictions	$+0.2$	$+0.0$	$+0.1$	$+0.1$	$+0.1$	$+0.3$
	Aggregate outcomes					
	W	E	Ω	N	K	Y
corporate taxes	$+3.5$	-6.8	-4.1	$+0.6$	$+1.3$	$+1.3$
financial frictions	$+0.1$	-0.1	-0.0	$+0.1$	$+0.1$	$+0.1$

Notes: Top panel shows firm-level averages, with p, z, n, k, y and $c_{\text{R\&D}}$ denoting, respectively, probability of technology adoption, firm-specific productivity, employment, capital, output and costs related to technology adoption. Bottom panel shows aggregate outcomes with W, E, Ω, N, K, and Y denoting, respectively, the wage rate, number of startups, number of firms, aggregate employment, aggregate capital and aggregate output. All values are in percent relative to the baseline. "Corporate taxes" denote the case of a 5% decrease in the corporate tax rate τ, while "finanical frictions" denote the case of a 5% decline in the external financing premium λ.

4.1.4 Robustness

Next, we check the robustness of our results to larger changes in the tax credit. We report the results in Figures C.1 to C.3 in the Appendix. All results are essentially confirmed, the only non linerity can be observed with the effect on the average productivity which is slightly U-shaped. This result hinges on the opposite forces operating on productivity discussed above. For larger increases in R&D tax credit the general equilibrium effects via goverment tax revenues becomes stronger, thereby producing a larger decline in transfer, consumption and ultimately wages. This in turn increses entry and the distribution of firms shifts towards younger firms. However, while startups are on average more productive, they are small. The largest employment weight in the economy is held by old firms. These firms are actually relatively productive compared to young/medium-aged firms, as the reason for making to old age is that they were successful in innovating. So, the shift away from these to younger firms is driving the employment-weighted decline in productivity.

4.2 Lower corporate taxes

Let us now turn to the case of lowering corporate taxes. The mechanisms described in the previous section all work in the same way. However, lower corporate taxes have two opposing (direct) effects on firms. On the one hand, they increase after-tax profits and in turn (all else equal) they raise firm values. However, lower corporate taxes also reduce the effective tax credits, since they are not only proportional to the amount spent on technology adoption but also on the corporate tax rate itself. Therefore, lowering of corporate taxes also has the opposite effects of decreasing tax credits. It is a quantitative question which of these two effects dominates.

In *partial equilibrium* (holding wages and exit decisions constant), a decrease in corporate taxes reduces investment into technology adoption. Once again, this can be seen from (18). Lowering taxes has essentially the same effect as reducing tax credits. Lower chances of adopting newer vintages of technology then results in a shift of the distribution of firms towards less productive businesses. This, in turn, reduces all firm-level outcomes despite the fact that static decisions, such as hiring of labor and capital is unaffected by the policy change (see equations 14).

The case of *general equilibrium* is somewhat more complex. In response to lowering taxes, expenditures on technology adoption also fall (both in terms of governmental transfers and in terms of the magnitude of resources spent by firms). This leads to an increase in consumption and through the household's optimal labor supply also a rise in the wage rate. The latter, however, then makes firms shrink their size (see top row of Table 4).

There are countervailing forces on firm values. While higher wages help decrease firm values, lower corporate tax rates serve to increase them. Under the current calibration, firm values indeed increase across the firm distribution. This means that firm exit rates fall, resulting in a shift towards older, larger businesses. This shift in the firm distribution is crucial for the aggregate results, where aggregate employment, capital and output all increase (see Table 4).[28,29]

[28] Despite the drop in exit rates, the number of firms falls because firm entry also declines. Even though the value of startups rises because, as incumbents, also potential entrants find it harder to adopt new technologies (enter).

[29] Note that Table 4 reports employment-weighted firm-level averages. Unweighted average employment, capital and output increase explaining the rise in aggregate employment, capital and output despite the fall in the number of firms.

4.3 Lower financial frictions

Finally, we discuss the case of lowering financial frictions. All else equal, financial frictions only affect firms' exit decisions. A lower external financing premium makes it easier for firms to survive. However, this *partial equilibrium* effect is not the only consequence of the change. In general equilibrium, the wage rate increases. The reason for this is that with fewer firms shutting down, the firm distribution shifts towards older, larger, firms (see second row of Table 4). This raises output and in turn consumption. The latter increases the wage rate via the household's optimal labor supply decision. Despite the increase in survival rates, the higher variable costs are quantitatively more important for young firms and therefore startups are somewhat discouraged from entry. These two opposite forces, lower exit and entry rates, offset each other, leaving the number of firms essentially unchanged (last row of Table 4).[30]

Once again, the positive effect of the policy on output does not operate via the technology adoption and productivity channel. There are two opposite effects on productivity essentially offsetting each other. First, by increasing firms survival rates, the cheaper access to credit allows less productive firms to survive thereby reducing aggregate productivity. Second, the increase in survival rates also prop up firms values thereby raising the incentives to adopt new technologies which impact average productivity positively. The positive effect of reducing the credit frictions on aggregate output is driven by its effect on firms' survival probability which shifts the distribution toward older, larger firms.

5 Taking stock and future research

Our results show that all three policies we have analysed can help the economy reach higher levels of activity but, interestingly, not via a faster pace of innovation. The R&D tax credit has positive direct impact on firms technology adoption and productivity which is offset by its general equilibrium effect on tax revenues. Lower tax revenues imply lower transfer leading to lower consumption and, via labor supply, to lower wages. The reduction in the cost of labor increases firms' survival rate, thereby reducing the average productivity of the economy. The positive effect on income derives from the increase in firm size and age, brought about by the higher survival rate. The reduction in corporate taxes has a negative effect on the adoption of new technologies as it essentially operates as a reduction of the tax credit for R&D. The positive effect on aggregate output comes from its impact on firm values. Lower taxes increase firms values thereby reducing exit rates and shifting the firm distribution toward larger firms. Finally, lower credit frictions increase firms' survival probabilities which depresses average productivity, but also increases firm values producing an effect of the opposite sign on productivity.

Although in part due to the specific parametrization, the *neutrality result* of these different policy with respect to productivity is stimulating starting point for future research. Below, we discuss some of the results from a modelling perspective and propose extensions which could overturn the policy neutrality. The key features of the model, through which much of the effects operate, include the labor supply elasticity, the entry elasticity, and the way we model R&D expenditure and growth. Let us briefly discuss each of these.

5.1 Labor supply and firm entry elasticities

From the results it is apparent that much of the effects operate through general equilibrium effects. One such channel works through the equilibrium price of labor which, in turn, determines relative costs of inputs in production but also firm values. The latter affects exit rates, incentives for innovation and entry.

The current model assumes an infinite labor supply elasticity, making the wage sensitive to changes in consumption. Alternative assumptions, ideally grounded in empirical evidence on responses of employment to similar policy changes, may be a fruitful avenue for future research.

The same can be said about the elasticity with which firms enter the economy. The model assumes free entry, albeit with an endogenous probability. Allowing for instance for a financial friction parameter for startups which differs from that of incumbents is yet another realistic extension to the current framework.

5.2 Technology investment and growth

Costs of investing into newer technology vintages are assumed to be paid in units of the final good. In reality, these costs are often in terms of (research) labor units. Therefore, allowing for (part) of these costs to be counted as employment is a useful extension. Quantitatively, this may also prove to be important because of the important role the labor market plays in the indirect general equilibrium effects discussed above.

Finally, let us discuss the modelling of aggregate growth. The baseline model is based on *exogenous* growth as the frontier technology level evolves exogenously according to (5). In what follows we describe how this

[30] This result could be different if would have different policies for incumbents and entrants. We plan to implement this extension in future research.

assumption can be relaxed and instead growth can be endogenized via firms' decisions to invest in productivity enhancing R&D activities.

5.2.1 Innovation

The majority of the baseline setup can be retained. However, it is useful to redefine $\gamma_i = z_i/\overline{z}$ as the firm specific productivity level relative to *average* firm-specific productivity $\overline{z} = 1/\Omega \sum_i z_i$, where Ω is the mass of all active firms.

In addition, the main difference being that instead of investing into technology adoption, firms invest into innovation. The cost of R&D can have the same functional form as described in (7) which we repeat here for convenience

$$Q(p_i, \gamma_i) = \chi\gamma_i \left(\frac{p_i}{\gamma_i}\right)^{\eta}. \tag{26}$$

In return for investing $Q(p_{i,a}, \gamma_i)$ units of the final good into R&D, firms have a probability $p_{i,a}$ of *innovating* upon their current productivity level. Specifically, with probability $p_{i,a}$ the firm specific productivity level becomes $z_i' = z_i(1+\lambda)$, where λ is the growth rate in firm-level productivity or the so-called innovation "step size". With the complement probability $1 - p_{i,a}$ firms retain their previous productivity level. Therefore, the evolution of firm-specific productivity can be summarized by

$$z_{i,t+1} = \begin{cases} z_{i,t}(1+\lambda) & \text{with probability } p_{i,t}, \\ z_{i,t} & \text{with probability } 1 - p_{i,t}. \end{cases} \tag{27}$$

As before, potential entrants face the same innovation technology as incumbents. However, only those that successfully innovate enter the market. In addition, it is assumed that potential entrants innovate upon the average productivity level $\overline{z}$. Therefore, the free entry condition becomes

$$\chi\eta \left(\frac{p_e}{\overline{\gamma}}\right)^{\eta-1} (1+\widetilde{r}d) = \frac{1}{1-\tau(1+\varphi(n_e))} \mathbb{V}_0(\overline{z}(1+\lambda), \mathcal{F}) \tag{28}$$

5.2.2 Balanced growth

Assuming that the economy is on a balanced growth path, we can express the economy-wide growth rate as

$$1 + g = \frac{\overline{z}'}{\overline{z}} = \frac{1}{\Omega}\left[\sum_i \sum_{a>0} H_{i,a}(1+\lambda p_{i,a}) + \sum_i \sum_{a=0} H_{i,0} p_e (1+\lambda)\right]. \tag{29}$$

The above states that average productivity increases because of incumbents' R&D efforts (first term) and because of successful startups (second term). The former can be seen from the fact that expected firm-level productivity next period is given by $\mathbb{E}[z'_{i,a+1}] = p_{i,a}z_{i,a}(1+\lambda) + (1-p_{i,a})z_{i,a} = z_{i,a}(p_{i,a} + p_{i,a}\lambda + 1 - p_{i,a}) = z_{i,a}(1 + p_{i,a}\lambda)$.

Finally, because firm-level innovation is the only source of growth, it can be shown that all growing variables grow at the same rate g defined above.

5.3 Further extensions

5.3.1 Innovation policy and the business cycle

Our model is rich enough to allow us analyse the interaction between growth and business cycle. A further avenue for future research is then to study the interplay of structural policies, such as those analysed here, and business cycle fluctuations. Innovation can make firms more resilient in turbolent times. There is a growing literature on firm characteristics fostering resilience to shocks.[31] A few recent papers focus on the role of innovation. Hombert and Matray (2018) show that R&D intensive US manufacturing firms downsized relatively less in response to increasing Chinese import competition. Gupta (2019) find that more innovative Spanish firms were less affected by the recent crisis compared to non-innovative firms.

Innovation can strengthen firm resilience to shocks by allowing smaller cuts in profit margin to stay competitive, differentiation via the introduction of new products and more in general by being more flexible and adaptable to new market scenarios. In future research we plan to explore the potential role of the several innovation policies implemented by the EU in shaping firms' and aggregate response to short to medium-run fluctuations.

[31] Chodorow-Reich (2014) shows that access and quality of available credit were key in allowing firms to weather the Great Recession. Aghion et al. (2017), find that more decrentralised firms took smaller hits in the same recession. Other firm characteristics such as size (Fort et al. (2013)), ownership and governance structures (Alviarez et al. (2018), Alfaro and Chen (2012)) have been shown to be important in shaping firms' response to large negative shocks.

5.3.2 Granular policies

We have only focused on uniform policies which do not differentiate by firm size, productivity or age. In future research we plan to explore *state-dependent policies* which will be differentiated according to the firm characteristics they are designed to target. Financial constraints are often considered a key market failure mainly affecting young and small firms. Therefore, credit policies aimed at mostly, or exclusively, these types of firms might be more desirable. The R&D tax credit in many countries treats small firms more generously (OECD (2018)). Small firms seem to be more responsive to innovation policy than other firms (Criscuolo et al. (2019)). Size-dependent policies though carry their own specific problems. They discourage firms from growing and they often target size and not age which is arguable the more relevant feature for growth (Bloom et al. (2019)). The model can already deal with tax and tax heterogeneity across firms and differentiating the credit frictions between entrants (young firms) and incumbents is a straightforward extension.

6 Conclusion

In this paper we have developed a dynamic stochastic general equilibrium model with firm and technology dynamics to analyse a rich set of innovation policies. Technology dynamics is produced by firms' decision to adopt new technologies that are periodically available in the economy thanks to an exogenously growing technology frontier. We used this framework to explore the aggregate and cross-sectional effects of an R&D tax credit, corporate tax cuts, and policies aimed at improving firms' access to credit. We show that aggregate effects of these policies are driven by general equilibrium effects operating via government budget, the labor market and via equilibrium entry. While their stimulating effect on innovation has a negligible impact on aggregate income and employment. Moreover, we find that uniform policies have heterogeneous effects on firms and their size distribution which generate rich feedbacks to the aggregate economy.

The R&D tax credit increases innovation but since it is financed by a reduction in government transfers it depresses wages which, in turn, increase firms survival rate, thereby producing a negative effect on productivity. Its stimulating effect on output is obtained through a shift in the firm size distribution toward older and large firms. Corporate tax cuts and improved access to credit broadly affect the economy via similar mechanisms. Common to all policies are two general equilibrium mechanisms. The first is a *mass-productivity* trade-off, as by reducing firms' costs or increasing the after-tax firms' value government intervention increase the survival rate thereby reducing average productivity and, on the other end, it reduces entry shifting mass toward the right tail of the firm size distribution. The second is produced by the assumption that government budget is always balanced, and any change in innovation policies is sterilised with an opposite and equivalent change in lump-sum transfers. This sterilisation via transfer impacts wages via labor supply with produces rich general equilibrium feedbacks.

The model is amenable to many extensions. The wage is very sensitive to policy due to our assumption of infinite labour supply elasticity. Removing this assumption and disciplining this elasticity with the data we can give us a more accurate quantitative wage response. Introducing an endogenously growing technology frontier will possibly strengthen the direct effect of policy-induced firms' increase in innovation on aggregate income level and growth rate. The model can also already be used to analyse the interaction between policies and business cycle fluctuations and, with some minor changes, to move from uniform to state-dependent policies. Finally, an interesting line of future research could explore different sterilisation mechanisms for the government budget (e.g. other types of taxes instead of transfers) and also explore the implication of temporarily financing the innovation policies with budget deficit.

Appendix

A Solution method

The structural model is a general equilibrium framework with heterogeneous firms. Individual businesses must know the entire distribution of firm productivity and employment levels in order to be able to forecast the development of the wage rate, a key variable in their optimization decisions. In addition, the presence of an aggregate shock makes these firm distributions time-varying rendering the solution of the model challenging.

The method employed in this paper follows that developed in Sedláček and Sterk (2017). The procedure is based on first-order perturbation along the stationary steady state life-cycle dynamics of individual firms, which depend on the evolution of their firm-specific productivity values. Notice that without persistent idiosyncratic shocks and without adjustment costs, all firms with the same productivity level will make the same decisions. Therefore, it is possible to treat a particular distance from the technological frontier as a separate "firm type". To economize on notation, we can express the model compactly as:

$$\mathbb{E}_t f\left(y_{t+1}, y_t, x_{t+1}, x_t; \Upsilon, \zeta\right) = 0$$

where x_t is a vector containing the state variables (all variables in $\mathcal{S}_t$) and y_t is a vector containing the non-preditermined variables, Υ is a vector containing all parameters of the model and ζ is a scalar parameter pre-multiplying the covariance matrix of the shock innovations, as in Schmitt-Grohé and Uribe (2004). Importantly, the above is system of a finite number of expectational difference equations.

A.1 Solving for the steady state without aggregate uncertainty

One first solves for the equilibrium of a version of the model without aggregate uncertainty. That is, I find vectors $\overline{y}$ and $\overline{x}$ that solve $f\left(\overline{y}, \overline{y}, \overline{x}, \overline{x}; \Upsilon, 0\right) = 0$. As described in the main text, the calibration targets various parameters to match long-run statistics. The calibration procedure has the following steps:

1. given values for the technology types (i.e. technology gaps), the aggregate wage rate (W), the technology adoption probability (p) and the distribution of firm-specific operational and adjustment costs ($H(\mu_h, \sigma_H)$ and ψ), one can calculate the growth paths of firm-level employment, firm values and the endogenous exit rates.

2. given firm values and exit rates from (1.) and a normalization of the mass of entrants, it is possible to back out the entry cost and to compute the distribution of firm masses across technology types.

3. given the mass of firms in all technology types from (2.) and their optimal choices from (1.) and (2.), it is possible to compute all aggregate variables.

A.2 Solving for the equilibrium with aggregate uncertainty

Next, one can solve for the dynamic equilibrium using first-order perturbation around the stationary steady state (including the steady state life-cycle patterns of firms) found in the previous step. The first-order approximated solutions, denoted by hats, have the following form:

$$\begin{aligned}\widehat{x}_{t+1} &= \overline{x} + \Theta^* \left(\widehat{x}_t - \overline{x}\right) \\ \widehat{y}_{t+1} &= \overline{y} + \Phi^* \left(\widehat{x}_t - \overline{x}\right)\end{aligned}$$

where Θ^* and Φ^* are matrices containing the coefficients obtained from the approximation. The perturbation procedure is standard and carried out in one step.

An advantage of perturbation methods is that the computational speed is relatively high and many state variables can be handled. An important prerequisite for perturbations to be accurate, however, is that deviations from the steady-state are not too large. For firm dynamics models like the one in this paper it may seem problematic because differences in employment levels across firms may be very large. The solution method adopted here, however, overcomes this problem since the steady state we perturb around contains the entire life-cycle profiles of firms. These growth paths, captured by the constants in the above equations, are themselves non-linear functions of technology types.

Hence, the fact that most newborn firms starts off much below their eventual sizes does not involve large accuracy losses since the same is true for the steady-state sizes of newborn firms. Similarly, the fact that the equilibrium features various firm types with very different optimal sizes does not reduce accuracy since we perturb around the growth path for each individual firm type.

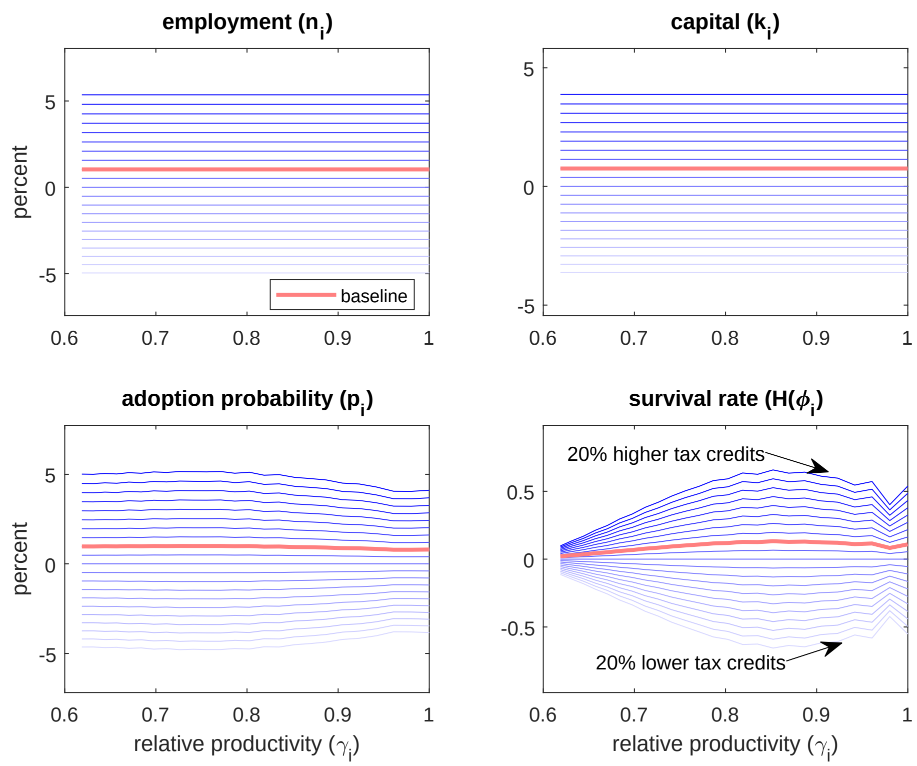
B Details of firms' first order conditions

This subsection provides more detailed expressions for the firms' first order conditions presented in the main text. Specifically, it makes explicit the evolution of firm specific productivity. Let us rewrite the first order conditions in terms of firm-specific productivity levels defined by the age of the technology vintage operated by the firm, $z_{j,t} = Z_{t-j}$. The optimal expenditures on R&D for incumbent and potential new firms, respectively, are given by

$$\chi\eta\left(\frac{p_{i,a}}{\gamma_i}\right)^{\eta-1}(1+\widetilde{r}d) = \frac{1}{1-\tau(1+\varphi(n_{i,a}))}\mathbb{E}_t\beta_t\left(\begin{array}{c}\theta\mathbb{V}_{a+1}(Z_{t+1},\mathcal{F}_{t+1})\\ +(1-\theta)\mathbb{V}_{a+1}(z_{j,t+1},\mathbb{F}_{t+1})\\ -\mathbb{V}_{a+1}(z_{j+1,t+1},\mathbb{F}_{t+1})\end{array}\right),$$

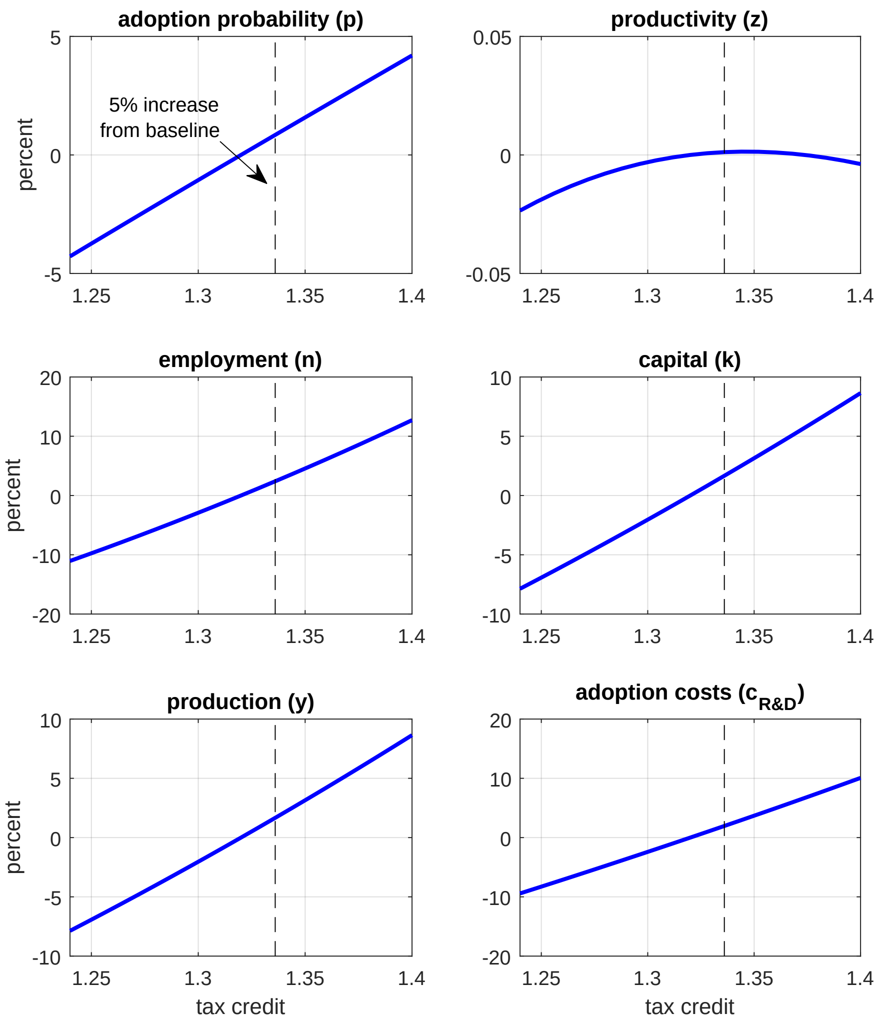
C Robustness

Figure C.1: R&D tax credit and firm-level outcomes



Notes: Changes in firm-level variables (in percent) as a function of firm-level productivity.

Figure C.2: R&D tax credit and average firm-level outcomes



Notes: Changes in firm-level variables (in percent).

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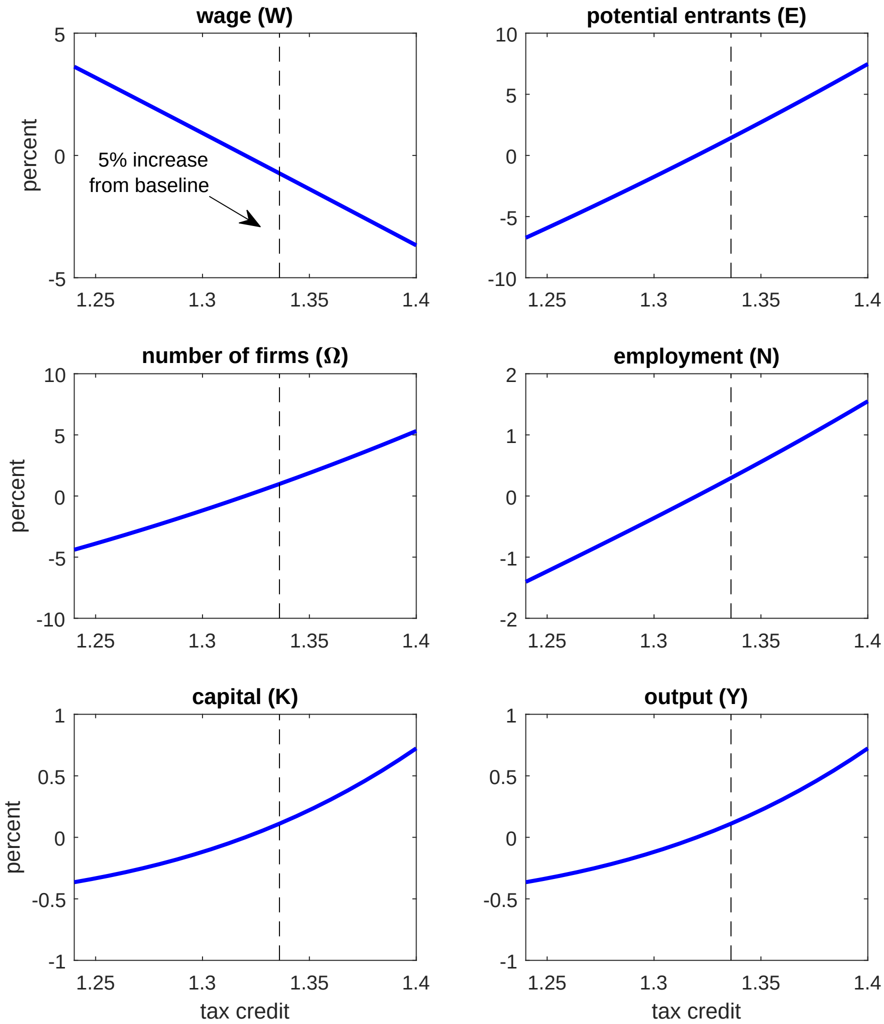
Figure C.3: R&D tax credit and aggregate outcomes)



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