Capital Replacement and Innovation Dynamics*

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Preliminary and Incomplete

Abstract

We analyze the interactions between the dynamics of capital replacement and the evolution of technology embodied in capital. US data show positive comovement between aggregate investment expenditures and R&D expenditures by capital-goods producers. Motivated by this evidence, we develop an equilibrium model of capital replacement with heterogeneous firms and endogenous technological progress embodied in capital. The model features rich interactions between the distribution of firms and the path of innovations. The mass of firms replacing their capital stock affects the incentives for capital-goods producers to innovate and improve the quality of capital through a market-size effect. In turn, the quality of new capital affects the incentives for final-good producers to scrap and replace their old capital. These feedback effects shape the aggregate dynamics of output and investment both in the long run and in response to transitory shocks.

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1 Introduction

The sluggish recovery of investment and productivity in the aftermath of the Great Recession of 2008-09 has motivated a growing body of work in macroeconomics that investigates the persistent—medium- and long-run—effects of large aggregate shocks on productivity, investment, and output. Several papers analyze the microeconomic drivers of aggregate capital expenditures taking the path of productivity as given, whereas another strand of the literature analyzes endogenous innovation and technology adoption abstracting from the role of the firm distribution for investment.[1]

The goal of this paper is to analyze the *interactions* between firm investment dynamics and the endogenous path of technology embodied in capital goods. We begin our analysis by providing empirical evidence on the comovement between aggregate capital expenditures and expenditures on Research and Development (R&D) in manufacturing sectors that produce capital goods. This comovement suggests that feedback effects between demand and supply in the market for capital goods play an important role for the dynamics of investment and innovation.

Motivated by this observation, our main contribution is to develop an equilibrium framework that combines two building blocks: (i) a capital-replacement model with heterogeneous firms subject to aggregate and idiosyncratic shocks and (ii) a model of endogenous technological innovations embodied in capital goods.

Final-good producers make lumpy investments to update their capital stock in response to idiosyncratic productivity shocks. Capital-good producers invest in R&D to improve the quality of new capital goods and obtain temporary monopoly profits from their innovations. Sustained capital-replacement activity from final-good producers determines a market-size effect that promotes innovation. In turn, growth in the quality of new capital vintages makes installed capital obsolescent, further stimulating capital replacement. The equilibrium feedback effects between these two blocks of the model determine the dynamics of output and investment.

In this preliminary draft, we illustrate this mechanism by calibrating the balanced-growth path of the model and computing its comparative statics with respect to the physical depreciation rate of capital, which constitutes an exogenous driver of capital replacement. As the depreciation rate increases, final-good firms increase the frequency of capital replacement. In turn, this higher demand for capital goods stimulates the innovation activity of

[1] We discuss these strands of the literature in more detail in Section 2.

capital-good producers, which leads to faster growth in capital quality. As a result, the rate of obsolescence of capital is endogenously higher, which further stimulates capital replacement. In future drafts, we will analyze this feedback mechanism in response to transitory shocks to aggregate productivity and discount rates.

The rest of the paper is organized as follows. Section 2 discusses our contributions to the literature. Section 3 presents the empirical evidence on the comovement between investment and R&D in durable-goods manufacturing. Section 4 introduces our model of capital replacement and innovation. Section 5 discusses our calibration and preliminary results on the interactions between capital replacement and embodied technological progress.

2 Related Literature

Our paper contributes to several strands of the literature. First, a growing body of work on investment analyzes the role of the cross-sectional distribution of firms for aggregate capital expenditures and emphasizes the role of non-convex adjustment costs for micro investment dynamics (e.g., Cooper, Haltiwanger, and Power, 1999; Cooper and Haltiwanger, 2006; Khan and Thomas, 2008; Lanteri, 2018; Baley and Blanco, 2021; Winberry, 2021). These models typically assume an exogenous productivity process driving both long-run growth and short-run fluctuations. We contribute to this literature by modeling the endogenous process of innovation that improves the quality of new vintages of capital over time. This feature allows us to analyze the interplay between investment and productivity dynamics both in the long run and in response to aggregate shocks.

Second, the literature on medium-run business cycles and on the persistent effects of large recessions often emphasizes the roles of investment and of the level of technology for the propagation of aggregate shocks (e.g., Comin and Gertler, 2006; Anzoategui, Comin, Gertler, and Martinez, 2019; Benigno and Fornaro, 2018; Bianchi, Kung, and Morales, 2019; Vinci and Licandro, 2020; Fornaro and Wolf, 2021; Bertolotti, Gavazza, and Lanteri, 2023). The models in this literature introduce elements of endogenous growth theory (e.g., Romer, 1990) into business-cycle analysis, but typically abstract from accounting for the micro dynamics of investment subject to adjustment costs. In a related contribution, Schmitz (2021) analyzes the role of heterogeneity in innovation intensity across firms. We contribute to this literature by analyzing a model of capital replacement with heterogeneous producers. This feature allows us to analyze the role of the cross-sectional distribution of firms for the persistent dynamics of technology in response to business-cycle shocks. Relatedly, Barlevy (2007) analyzes the procyclicality of R&D expenditures. Innovation in durable-goods manufacturing largely accounts for of these dynamics and thus we focus on this channel in our model.

Finally, our paper contributes to the literature on capital replacement and aggregate dynamics when technology is embodied in vintage capital (e.g., Boucekkine, Germain, and Licandro, 1997; Cooley, Greenwood, and Yorukoglu, 1997). In a related contribution, Fiori and Scoccianti (2021) introduces vintage capital with exogenous technical progress in a model of investment with heterogeneous firms subject to adjustment costs. Relative to this literature, our contribution is to analyze the feedback effects between firm capital replacement and the endogenous path of innovations. Our focus on the complementary effects of demand and supply factors for the evolution of technology is consistent with the seminal analyses of Schmookler (1966) and Shleifer (1986).

3 Empirical Evidence

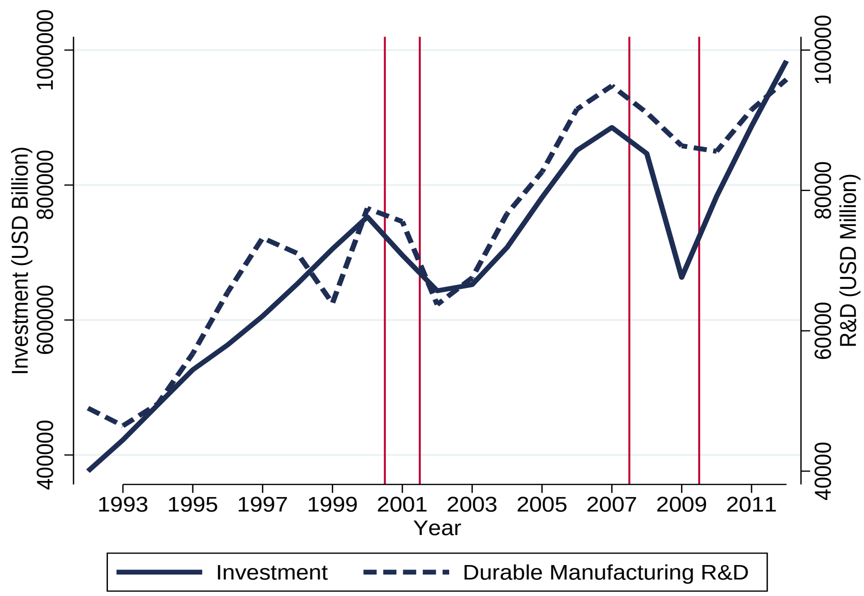
In this section, we describe several empirical patterns on the comovement between investment and R&D expenditures by manufacturers of capital goods. We begin by analyzing the evolution of aggregate investment in equipment and R&D in durable-goods manufacturing. Figure 1 illustrates the dynamics of these variables in the US during 1993-2012. Both investment and R&D expenditures grow over time and decline significantly during the two recessions in our sample, highlighted by red vertical lines. Equipment investment and R&D on equipment and durable goods decrease by approximately 15% and 18% between 2000 and 2002, respectively. During the Great Recession of 2008-09, equipment investment drops by 25% and R&D in durable manufacturing by 9%.

To quantify the comovement between investment expenditures and R&D expenditures, we HP-filter these two series and compute the correlation of their cyclical components. We find a correlation of 0.55 and a relative standard deviation of R&D to investment of approximately 0.63 over the sample period, which confirms the strong comovement illustrated in Figure 1. Among the components of aggregate R&D, durable manufacturing industries displays the strongest correlation with investment.[2]

We further document that R&D by capital-good producers is a key driver of the

[2] Equipment investment has a correlation equal to 0.42 with R&D in nondurable manufacturing and a negligible correlation with R&D in non-manufacturing industries.

Figure 1: Equipment Investment



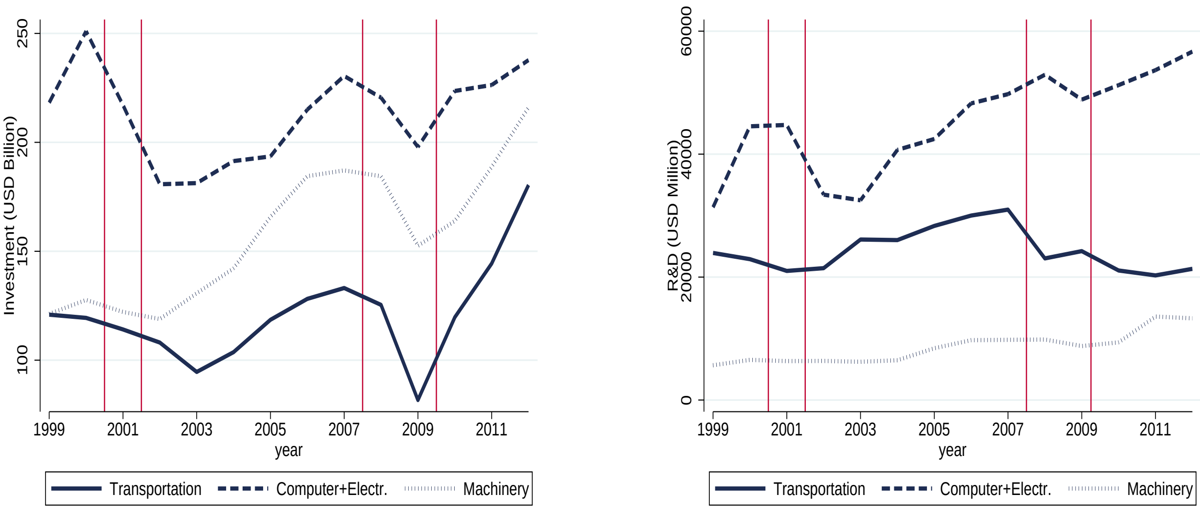
Notes: The figure displays the evolution of US private nonresidential investment in equipment from the Bureau of Economic Analysis and US private R&D expenditures in durable manufacturing industries from the National Science Foundation. Horizontal axes report years (1993-2012); vertical lines highlight recession periods (2001, and 2008-2009).

pro-cyclical behavior of aggregate R&D expenditures, which Barlevy (2007) documents. Durable manufacturing R&D is the largest component of total R&D in our sample, accounting for 39% of the aggregate on average. Moreover, durable manufacturing R&D generates the bulk of the observed positive covariance between GDP and total R&D over the business cycle.[3] The correlation between the cyclical component of R&D in durable-good manufacturing and GDP is 0.58 and this component of R&D expenditures is three times as volatile as GDP over the business cycle. Nondurable manufacturing R&D and nonmanufacturing R&D have a larger relative volatility but a lower correlation with GDP.

Next, we show that the comovement between investment and durable R&D observed in the aggregate data is also relevant at a more disaggregated level. We analyze investment and R&D expenditures for three distinct categories of equipment: Transportation equipment; Computers and electronics; and Machinery. The left panel of Figure 2 displays the evolution of investment for each category, excluding investment expenditures by firms in the industries producing the same equipment types. The right panel of the figure displays R&D expenditures at the same level of aggregation.

[3] R&D in nondurable manufacturing and nonmanufacturing industries constitute on average 28% and 33% of total R&D between 1992 and 2012.

Figure 2: Durable Categories and Recessions



(a) Investment

(b) R&D in Durable Manuf.

Notes: The figure displays the evolution of private nonresidential investment across different types of equipment from the Bureau of Economic Analysis (left panel) and US private R&D expenditures in durable manufacturing industries from the National Science Foundation (right panel) during two recession episodes. Horizontal axes report years (1993-2012); vertical lines highlight recession periods (2001, and 2008-2009).

We highlight two empirical patterns. First, there is substantial heterogeneity in the evolution of investment both across equipment categories and across recession episodes. During the 2001 recession, investment on computers and electronic equipment entirely drives the aggregate decline observed in Figure 1. In contrast, during the Great Recession investment falls markedly across all equipment categories, with transportation declining the most both in absolute value as well as in percentage terms.

Second, the cyclical behavior of R&D expenditures varies across equipment categories and recessions consistently with the heterogeneity observed for equipment investment. The 2000-2002 decline in durable manufacturing R&D is almost entirely driven by computers and electronics, which were also responsible for the entire investment drop. During the Great Recession, the largest and most persistent R&D decline happens for transportation equipment, where investment shrinks the most. Consistent with this observation, Bertolotti, Gavazza, and Lanteri (2023) document a decline in the quality of new vehicles sold during 2008-09 relative to expansion years.

Finally, we provide suggestive evidence that the age distribution of capital may play an important for the response of investment expenditures to aggregate shocks. To this end, we analyze the investment patterns across equipment categories before recessions. We find that the largest declines in investment are for types of equipment that display large expansions before the recession hits. Investment in computers and electronics was 14% higher than its HP trend in 2000, while the same deviation was smaller for machinery and transportation equipment (4.3% and 6.7%, respectively). In 2007, investment in transportation equipment was 12% above trend (7% for machinery and 8% for computers and electronics).

Overall, the empirical evidence suggests the presence of interactions between the dynamics of investment expenditures and the dynamics of R&D by capital-goods producers. This evidence motivates us to develop a model of investment and endogenous innovation embodied in capital.

4 Model

In this section, we describe and analyze our model of capital replacement and innovation.

4.1 Environment

Time is discrete and infinite, $t = 0, 1, ...$ The economy is populated by a representative household with linear preferences over streams of consumption and discount factor B. The household owns a continuum of final-good producing firms indexed by $i \in \mathcal{I} \equiv [0, 1]$ and a continuum of capital-good producing firms indexed by $j \in \mathcal{J} \equiv [0, 1]$. Final-good firms produce output using capital goods, which depreciate and can be replaced subject to the payment of fixed costs. Capital-good producers' innovations determine the path of technology ("quality") embodied in capital goods.

4.2 Final-Good Producers: Capital Replacement

We begin by describing the capital-replacement problem of final-good producers taking as given the innovation process, building on Cooper, Haltiwanger, and Power (1999). Each final-good firm produces a homogenous output good with a linear technology that employs capital:

$$y_{i,t} = z_t s_{i,t} K_{i,t-1}, \tag{1}$$

where z_t denotes an aggregate productivity shock and $s_{i,t}$ denotes an idiosycratic productivity shock. Capital $K_{i,t-1}$ is subject to a one-period time to build and depreciates at rate

δ. At each date t, firms face a discrete choice on their production capacity for the following date: They can either let their capital depreciate or they can replace it, in which case their new capacity is given by $\bar{K}_t \equiv \kappa \bar{q}_t$, where $\kappa > 0$ is a parameter and $\bar{q}_t$ denotes the average quality of capital goods produced at date t. The evolution of the capital stock thus given by

$$K_{i,t} = \begin{cases} (1-\delta) K_{i,t-1} & \text{if } \; x_{i,t} = 0 \\ \bar{K}_t = \kappa \bar{q}_t & \text{if } \; x_{i,t} = 1 \end{cases} \tag{2}$$

Capital replacement requires paying a cost F_t, which we further specify below. Firms solve the following dynamic capital-replacement problem:

$$\max_{x_{i,t}} \mathbb{E}_0 \sum_{t=0}^{\infty} B^t \left(z_t s_{i,t} K_{i,t-1} - x_{i,t} F_t \right), \tag{3}$$

subject to (2), where $x_{i,t} \in \{0, 1\}$ denotes the discrete capital replacement choice.

Upon replacement, the old capital stock is worthless due to irreversibility and the new capital stock is given by a bundle of capital goods $j \in \mathcal{J}$. The efficiency of this bundle depends on both the quantity $v_{i,j,t}$ and the *quality* $q_{j,t}$ of the capital goods purchased, according the following technology:

$$\bar{K}_t = \int_{j \in \mathcal{J}} q_{j,t}^{\gamma} v_{i,j,t}^{1-\gamma} dj, \tag{4}$$

with $\gamma \in (0, 1)$. Hence, when firm i replaces its capital stock, it solves the following static expenditure minimization problem:

$$\min_{\{v_{i,j,t}\}_j} \int_j p_{j,t} v_{i,j,t} dj, \tag{5}$$

subject to (4).

Because all final-good firms face the same expenditure-minimization problem, the solution is independent of i and the resulting expenditure determines the capital-replacement cost: $F_t = \int_{j \in \mathcal{J}} p_{j,t} v_{j,t} dj$. We denote by λ_t the Lagrange multiplier on constraint (4), which is also common across replacing firms. The cost-minimizing quantity of variety j demanded by each replacing firm is given by

$$v_{j,t} = \lambda_t^{\frac{1}{\gamma}} (1-\gamma)^{\frac{1}{\gamma}} p_{j,t}^{-\frac{1}{\gamma}} q_{j,t} \tag{6}$$

and aggregate demand for variety j is given by $M_t v_{j,t}$, where M_t is the mass of firms replacing their capital at date t: $M_t \equiv \int_{i\in\mathcal{I}} x_{i,t} di$.

4.3 Capital-Goods Producers: Innovation

Next, we describe the profit-maximization and innovation problem of capital-goods producers, which builds on a quality-ladder model of technological progress (Grossman and Helpman, 1991; Aghion and Howitt, 1992).

Capital-goods producers invest to improve the quality of their products, which they sell to final-good producers. The success of their innovation effort is stochastic. Upon a successful innovation, the quality of variety j increases by an exogenous factor $\eta > 1$, $q_{j,t} = \eta q_{j,t-1}$, and capital-good producers enjoy profits from monopolistic competition. Specifically, their technology requires c units of final output to produce one unit of capital, giving the following profit-maximization problem:

$$\max_{v_{j,t}} M_t v_{j,t} \left(p_{j,t} - c\right) \tag{7}$$

subject to the demand function given by (6). The optimality condition implies that capital-goods producers charge a constant markup, $p_{j,t} = \frac{c}{1-\gamma}$, and their optimal quantity produced satisfies

$$v_{j,t} = (1-\gamma)^{\frac{2}{\gamma}} c^{-\frac{1}{\gamma}} \lambda_t^{\frac{1}{\gamma}} q_{j,t}. \tag{8}$$

Thus, profits for successful innovators are linear in quality $q_{j,t}$ and given by

$$\pi_{j,t} = \gamma \left(1-\gamma\right)^{\frac{2-\gamma}{\gamma}} c^{\frac{\gamma-1}{\gamma}} \lambda_t^{\frac{1}{\gamma}} M_t q_{j,t}. \tag{9}$$

In contrast, when innovation is not successful, the quality of variety j remains constant, $q_{j,t} = q_{j,t-1}$, and capital-goods producers sell their output at a price equal to their marginal cost c, because their predetermined quality level can be freely imitated by a competitive fringe.

To innovate, capital-goods producers invest $R_{j,t}$ units of the final good. We define the innovation intensity of firm j as $\psi_{j,t} \equiv \frac{R_{j,t}}{\eta q_{j,t-1}}$. Innovation is successful with probability

$\phi(\psi_{j,t})$, with $\phi(0) = 0$, $\phi' > 0$, $\phi'' < 0$, and $\lim_{\psi \to +\infty} \phi(\psi) = 1$.

The optimal expenditures on $R\&D$ for variety j solves

$$\max_{R_{j,t}} \phi\left(\frac{R_{j,t}}{\eta q_{j,t-1}}\right) \Pi_{j,t} - \chi_0 e^{\chi_1(\bar{q}_t - \vec{q}_t)} R_{j,t}, \tag{10}$$

where the term $\chi_0 e^{\chi_1(\bar{q}_t - \vec{q}_t)}$, where $\bar{q}_t$ denotes average capital quality and $\vec{q}_t \equiv (1+g)^t$, with $\chi_0 > 0$ and $\chi_1 > 1$, scales the cost of $R\&D$ to ensure that the model dynamics are stationary around the Balanced-Growth Path with a constant growth rate of output equal to g.

The first-order condition of this problem implies that the optimal $R\&D$ intensity is constant across varieties and satisfies

$$\phi'(\psi_t)\gamma\,(1-\gamma)^{\frac{2-\gamma}{\gamma}}\,c^{\frac{\gamma-1}{\gamma}}\lambda_t^{\frac{1}{\gamma}} M_t = \chi_0 e^{\chi_1(\bar{q}_t - \vec{q}_t)}. \tag{11}$$

Accordingly, average capital quality evolves as follows:

$$\begin{aligned} \bar{q}_t &= \int_{j \in \mathcal{J}} \left(\phi(\psi_t)\eta q_{j,t-1} + (1-\phi(\psi_t))q_{j,t-1}\right) dj \\ &= \bar{q}_{t-1} + \phi(\psi_t)(\eta - 1)\bar{q}_{t-1}. \end{aligned} \tag{12}$$

4.4 Balanced Growth

We focus on a balanced-growth path, along which average capital quality grows at constant rate g and at each date there is a constant mass of final-good firms M replacing their capital. On the balanced-growth path, we can formulate the capital replacement problem of final-good firms recursively as follows:

$$V(k,s) \equiv \max_{x \in \{0,1\}} sk - xf + \beta \mathbb{E} V\left[(k', s')\,|s\right], \tag{13}$$

subject to the transition

$$k' = \begin{cases} \frac{1-\delta}{1+g}k & \text{if } x = 0 \\ \frac{\kappa}{1+g}q & \text{if } x = 1, \end{cases}$$

where $\beta \equiv \frac{B}{1+g}$, we use lower-case variables to denote upper-case variables divided by the growth rate $(1+g)^t$, such as $k \equiv \frac{K_t}{(1+g)^t}$, and q is the average quality of capital, $q \equiv \frac{\bar{q}_t}{(1+g)^t}$.

We obtain the balanced-growth path by solving this problem jointly with the innovation problem. Specifically, given a level of growth g, the stationary replacement problem gives an optimal fraction of replacing firms M for which $x = 1$. In turn, given a mass of replacers M, the innovation problem of capital producers gives the associated optimal innovation intensity, which solves (11), and the associated growth rate of average quality from (12).

5 Quantitative Analysis

In this section, we perform a preliminary calibration of the model and illustrate the key mechanism relating capital replacement and innovation activity.

5.1 Calibration

We begin by describing our choices of functional forms and parameter values, which we report in Table 1.

We calibrate the parameters of the final-good firms' capital replacement problem borrowing from the literature on investment dynamics with heterogeneous firms. We then assume that the innovation probability function takes the form $\phi(\psi) \equiv \phi_0 \left(1 - e^{-\phi_1 \psi}\right)$, with $\phi_0 \in [0, 1]$ denoting the upper bound on the innovation probability and $\phi_1 > 0$ governing the curvature of this probability with respect to R&D intensity. We parameterize this function to obtain an average growth rate close to 2%.

We calibrate γ to obtain a markup on monopolistic capital varieties of $1/(1-\gamma) = 1.3$, which lies between the 1.2 and 1.5 markup values implied by the estimates of the elasticity of substitution across varieties in Akcigit, Hanley, and Serrano-Velarde (2021) (5.863) and in Acemoglu, Akcigit, Alp, Bloom, and Kerr (2018) (2.9), respectively. We calibrate the innovation step-size η consistently with Acemoglu, Akcigit, Alp, Bloom, and Kerr (2018).

5.2 Preliminary Results

We now use the calibrated model to provide a graphical representation of the balanced growth path equilibrium. Figure 3 represents the two key equations that determine the growth rate of capital quality g and the mass of firms replacing their capital M in the balanced growth path equilibrium. The blue solid line represents the demand for new capital—i.e., the fraction of firms that optimally choose to replace their capital as a function of quality growth. As the quality of new capital grows at a faster rate, effective

Table 1: Parameters Values

	Parameter	Symbol	Value
Capital Replacement	Discount factor	B	0.96
	Physical depreciation	δ	0.085
	Aggregate productivity level	z	1
	Investment fixed scale	κ	0.8
	Persistence of s_i shocks	ρ_s	0.7
	Variance of s_i shocks	σ_ε^2	0.12
Innovation	Investment quality weight	γ	0.23
	Maximum innovation prob.	ϕ_0	0.71
	Curvature of innvation prob.	ϕ_1	4
	Scale of R&D marginal cost	χ_0	0.036
	Convexity of R&D marginal cost	χ_1	1
	Intermediate marginal cost	c	1
	Innovation step-size	η	1.132

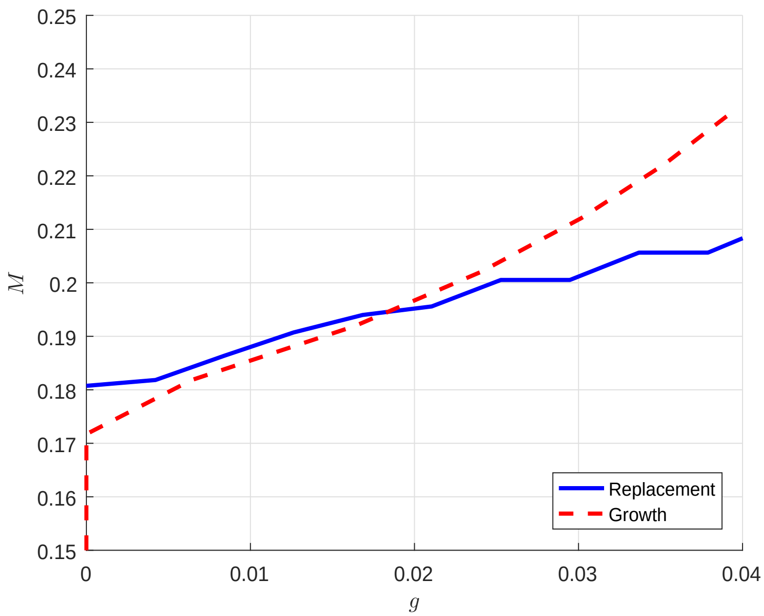
Notes: The table reports the parameter values used in the preliminary quantitative analysis.

depreciation of old capital—i.e. the sum of physical depreciation δ and obsolescence due to quality improvements—becomes more rapid, inducing more firms to replace. Therefore, the demand for new capital is upward sloping in g.

The red dashed line represents the supply of new capital quality—i.e., the growth rate g as a function of the mass of replacing firms M. As more firms decide to replace their capital, total profits for innovators increase due to a standard market size effect. Hence, R&D intensity, innovation, and capital quality growth increase, as represented by the upward sloping curve in the figure. Moreover, the model features an inaction region where no R&D and growth occur if the mass of replacing firms is small enough. At the calibrated parameter values of Table 1 the model features an equilibrium quality growth of approximately 1.8% per year and a share of replacing firms around 0.19.

Next, we illustrate the feedback effects between capital replacement decisions and endogenous quality growth. We do so by performing a comparative statics analysis of the balanced growth path equilibrium as the rate of physical depreciation δ varies. To highlight the role of the endogenous quality growth channel, we compare our model with a counterfactual economy where the growth rate of quality of new capital vintages is exogenous and fixed. Figure 4 shows the results. In all panels, the solid blue (dashed red) lines refer to the endogenous (exogenous) growth model.

Figure 3: Capital Replacement and Innovation on the Balanced Growth Path



Notes: The figure provides a graphical representation of the two equilibrium conditions that determine the balanced growth path of the economy. The blue solid line represents the demand for new capital—i.e., the mass M of firms that replace their capital stock as a function of the growth rate g of new capital quality. The red dashed line represents the supply of capital quality—i.e., the growth rate g as a function of M. The balanced growth path equilibrium is identified by the pair (g, M) that simultaneously satisfies both equations.

The top left panel of the figure illustrates that, in both economies, the higher the rate of physical depreciation of capital, the greater the mass of replacing firms in equilibrium. Firms choose to pay the replacement cost when the quality-adjusted level of their existing capital stock is sufficiently far from the new vintage. Two factors decrease the relative quality of existing and new capital. The first is physical depreciation and the second is obsolescence due to quality growth over time. With a faster physical depreciation, the relative quality of old capital declines more rapidly and the mass of replacing firms increases.

Furthermore, in our model faster capital replacement leads to faster growth, as the top-right panel shows. In turn, fast capital-quality growth increases the endogenous degree of capital obsolescence, creating a further incentive for final-good firms to replace their capital. Accordingly, we find that the optimal frequency of replacement M in the top-left panel is steeper in our model than in the comparison model with exogenous quality growth.

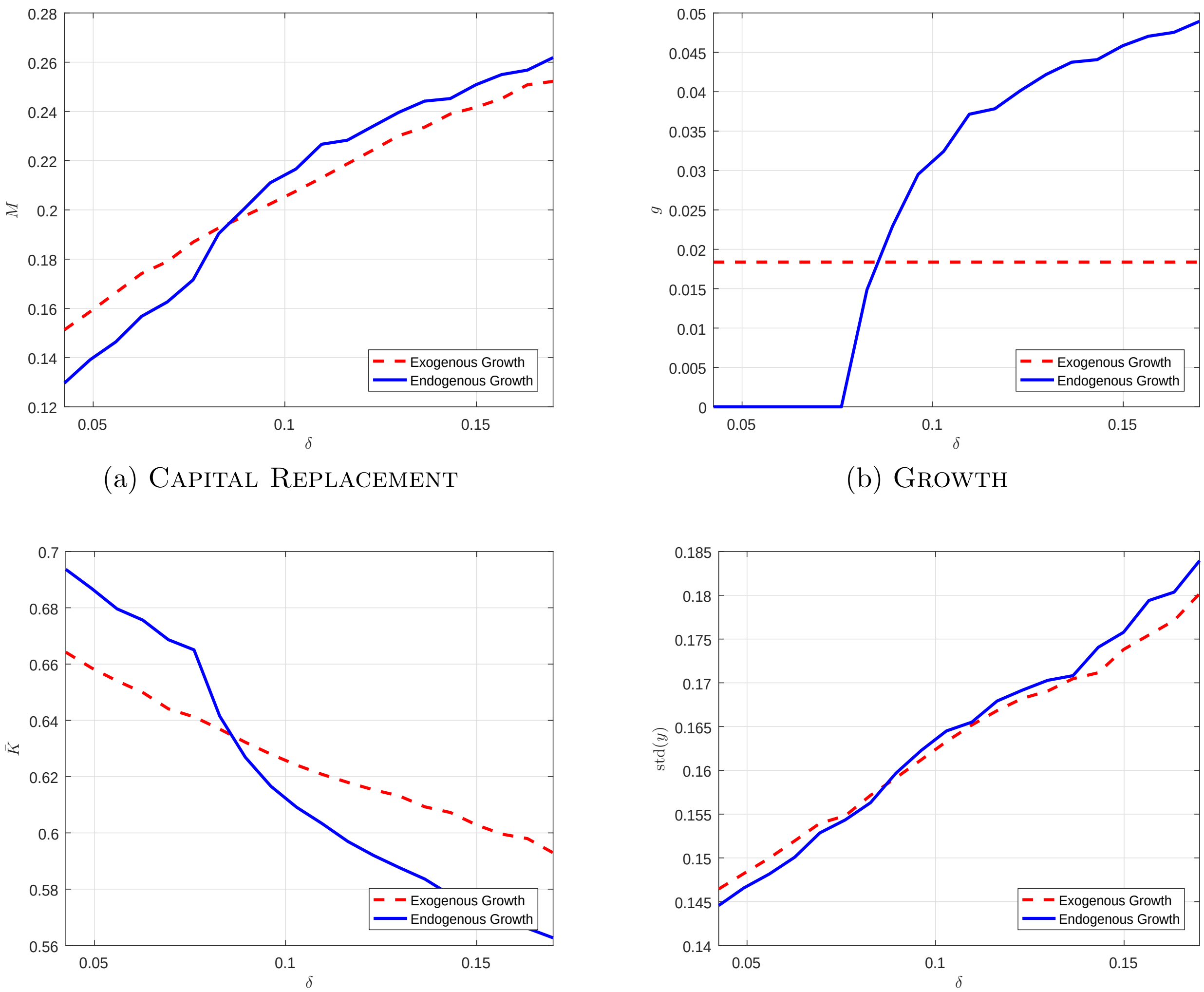
The bottom left panel shows that aggregate quality-adjusted capital declines with δ because a higher frequency of replacement is not sufficient to offset the direct decline in the capital stock of firms that do not replace, due to depreciation.

The bottom-right panel shows that output dispersion across final-good producers increases with the depreciation rate δ. With higher depreciation, more firms replace their capital, but the decline in capital quality for those that do not replace is faster, thus widening the support of the distribution of capital quality across firms and resulting in greater dispersion of final output. When quality growth is endogenous, the effects of depreciation on output dispersion are magnified, because as depreciation increases, so does endogenous obsolescence, and thus there is a larger difference in quality across capital vintages. Overall, our model provides rich implications for the relation between dispersion in production at the micro level and aggregate output dynamics.

6 Conclusion

To be added.

Figure 4: Interaction of Capital Replacement and Innovation: Varying Depreciation δ



(a) Capital Replacement

(b) Growth

(c) Quality-adjusted Capital Stock

(d) Output Dispersion

Notes: The top-left panel plots the mass of replacing firms M on the balanced-growth path equilibrium as a function of the physical depreciation parameter δ. The top-right panel plots the quality growth rate g in the balanced-growth path equilibrium as a function of the physical depreciation parameter δ. The bottom-left panel plots the quality-adjusted capital stock on the balanced-growth path equilibrium as a function of the physical depreciation parameter δ. The bottom-right panel plots the dispersion of final output in the balanced growth path equilibrium as a function of the physical depreciation parameter δ. In all the panels, the blue solid lines refer to our model with endogenous growth in capital quality and the red dashed lines refer to a counterfactual model where capital quality growth is exogenous and constant.

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