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Accounting for U.S. economic growth 1954–2017[☆]

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ABSTRACT

We perform a growth accounting exercise using the whole neoclassical growth model for the U.S. economy during 1954–2017. Our growth accounting exercise reveals that the U.S. extraordinary economic growth in the 1960s has been mainly driven by the increase of the labor efficiency, whereas the growth slowdowns in the 1970s and the first decade of 21st century were mainly driven by the decline in the capital efficiency. However, the reduction of the distortions on the labor supply driven the subsequent recoveries in the 1980s and after the Great Recession.

1. Introduction

According to the evolution of output per capita and hours worked per capita, U.S. economic growth after World War II (WWII) can be categorized into five periods (see Fig. 1): (1) the *Long Boom* between 1954 and 1969, which was a period of high growth in output per capita with hours worked per capita remaining roughly stable; (2) the *First Growth Slowdown* in 1969–1982, which was a period of low economic growth and a decline in hours worked per capita; (3) the *Great Moderation* in 1982–1999, a period during which the growth rate of output per capita was near its average but hours worked per capita experienced a strong increase; (4) the *Second Growth Slowdown* in 1999–2010, which started with the dot-com bubble burst and ended with the Great Recession. It was a period of low growth in output per capita coupled with a strong decline in hours worked per capita; (5) the *Great Recession Recovery* after 2010, which was a period wherein hours worked per capita experienced strong recovery but growth in output per capita was close to its average during 1954–2017.

The available data raise some questions. Why did the U.S. economy experience a long-lasting period of high economic growth after the end of WWII? Why did the rate of growth decline after the beginning of the 1970s and after the beginning of 21st century? Why did hours worked per capita experience a strong increase during the 1980s and 1990s? What did the Great Recession cause?

From at least the 1950s, economists have performed growth accounting exercises by using a neoclassical growth model to guide economic theory in answering such questions. Solow (1957) presented his famous residual formula and concluded that to understand sustained economic growth, studies had to go beyond the accumulation of productive inputs and analyze the determinants of productive efficiency. Kydland and Prescott (1982) argued that shocks to the efficiency of productive inputs were the primary mechanisms influencing economic

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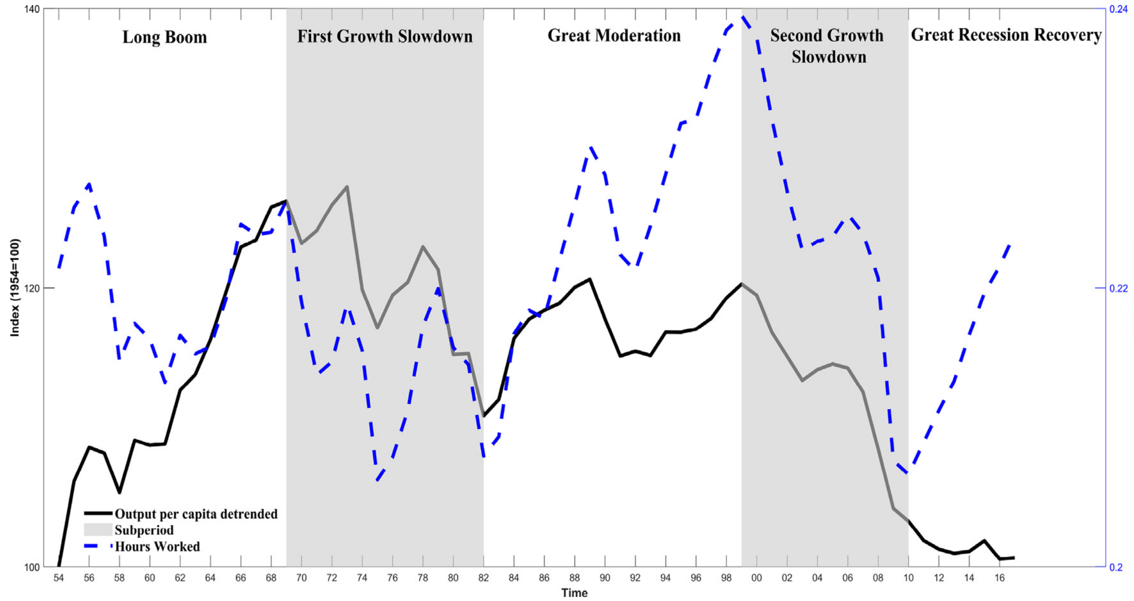


Fig. 1. U.S. Economic growth.

cycles.[1] Prescott (1998) concluded that to understand the enormous differences in per capita income across countries, we must understand why the efficiency of productive inputs varies considerably across countries. However, these authors confined their focus to the production function. More recently, Cole and Ohanian (2002), Chari et al. (2002, 2007), Ohanian and Raffo (2012), and Brinca et al. (2016) have performed accounting exercises by using the complete neoclassical growth model. They concluded that to account for post-WWII recessions in the United States, we must understand the reasons behind the worsening of some economic distortions, which are expressed as wedges in the equilibrium conditions of the standard neoclassical growth model and not merely the changes in the productive efficiency of inputs. In particular, understanding the changes in the labor wedge (i.e., in the relationship between the marginal productivity of labor and marginal rate of substitution between consumption and leisure) is needed.

Our objective is to identify the primary forces driving U.S. economic growth after WWII. To this end, following the idea proposed and developed in a stochastic general equilibrium model by Chari et al. (2002, 2007), we use the complete neoclassical growth model to calculate the wedges under equilibrium conditions for matching the model and data. However, unlike the aforementioned authors, we used the deterministic neoclassical growth model with perfect foresight to compute the wedges and perform the growth accounting exercise because we focus on complete macroeconomic performance after WWII.[2]

The accounting growth method has two steps. First, using data with the equilibrium conditions of the neoclassical growth model, it measures the wedges representing the overall distortions to the relevant equilibrium conditions of the model. Second, the measured wedge values are fed back into the neoclassical growth model one at a time to assess the amount of the observed movements in output, labor, investment, and factor shares during 1954–2017 can be attributed to each wedge. Simulating the model for each wedge, we calculate the wedge-alone component of each variable caused by each wedge, which reflects the contribution of each wedge to variable evolution during 1954–2017. This growth accounting method reveals the mechanisms through which fundamental processes affect economic performance. Therefore, it is used to determine the most promising theories regarding the primary characteristics of U.S. postwar economic growth.

All previous works have specified a Cobb–Douglas (CD) production function to compute the wedges. Under perfect competition and the CD assumption, factor shares are constant. However, the U.S. labor share was far from constant during 1954–2017 (see Fig. 2). The U.S. labor share has particularly undergone a pronounced decline after the beginning of 21st century; it further underwent a significant decline during the 1970s. Fig. 2 shows that in both periods, the decreasing labor share was accompanied by a slowdown in output growth and a downsizing of hours worked. Under the CD production function, movements in factor shares must be driven by market frictions or noncompetitive forces, thereby implying that rental prices move away from their marginal productivities because output elasticities for factors are constant. However, Karabarbounis (2014) argued that explanations of the labor wedge based on departures of the representative firm's marginal productivity of labor from the real wage are rejected by data because the labor share of income is not strongly procyclical. Therefore, the labor wedge must primarily reflect distortions in the labor supply, which is the implicit assumption in our model. Computing the labor and investment wedges and assessing their impact on output, investment and labor crucially depends on if changes in the labor share are either driven by competitive forces modifying output elasticities for factors or by market-frictions or non-competitive forces implying that rental prices depart from their marginal productivities.

Production functions with variable output elasticities for factors allow for the competitive adjustment of the labor share. We compute the wedges and simulate the model by using a (CD) production function and a variable elasticity of substitution (VES) production function. Both functions belong to the family of production functions proposed by Kadiyala (1972), which also includes the constant elasticity of substitution (CES) production function. The VES production function allows for the consideration of the post-WWII evolution of the U.S. labor share because output elasticities for factors are not constant. Under the VES

[1] The real business cycle theory follows the approach of Frisch (1933) and Slutzky (1937), who emphasized exogenous productivity shocks as the impulse mechanism of economic fluctuations.

[2] To use the stochastic or deterministic dynamic general equilibrium model is a methodological choice. Each model has pros and cons. To use the stochastic model requires imposing a certain structure (typically autoregressive) on the wedges, which does not require a deterministic model, but it does so at the expense of assuming perfect foresight. The autoregressive hypothesis may be plausible to analyze high-frequency fluctuations, but it is more debatable for analyzing long-time periods in which low and medium frequencies might be implied.

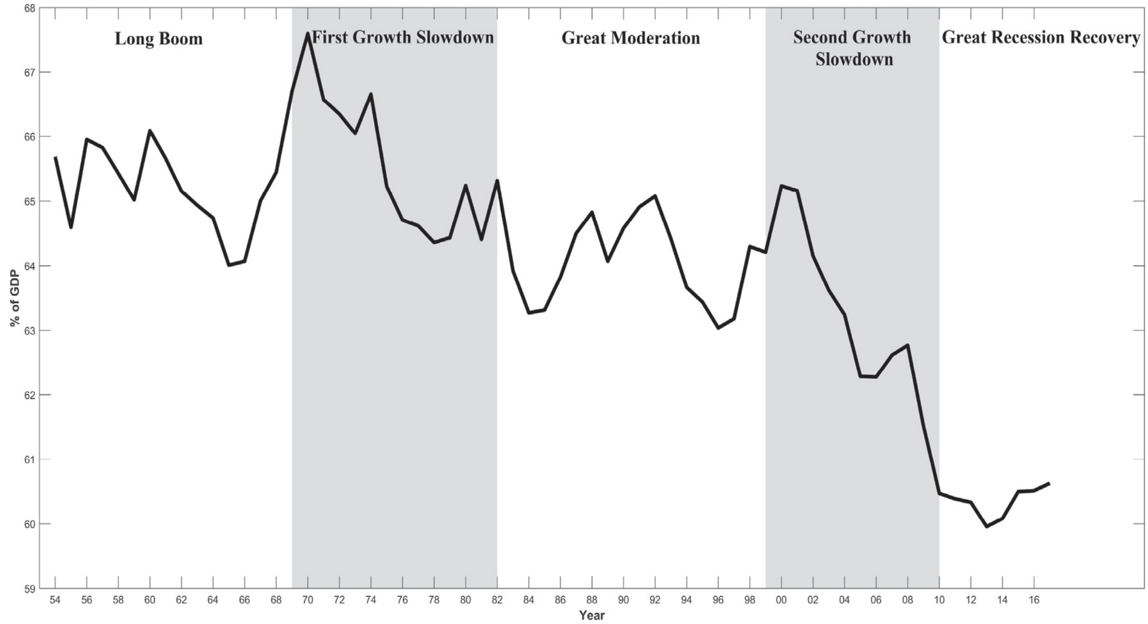


Fig. 2. U.S. Labor share.

specification of the production function, the five wedges are as follows: capital efficiency, labor efficiency, investment, labor, and resource constraint wedges. The capital and labor efficiency wedges are the differences between the capital and hours engaged in production and between the optimal capital and labor needed to reach a certain level of output for a given factor income distribution. The labor wedge reflects the difference in the marginal rate of substitution between consumption and leisure and the marginal product of labor. The investment wedge reflects the difference between the intertemporal marginal rate of substitution and the return on capital. The resource constraint wedge reflects the difference between output and its allocation to consumption and investment. Under a CD specification of the production function, the output elasticity for production factors is constant, and thus, we can compute only four wedges. In particular, the labor and capital efficiency wedges are undetermined, and only an efficiency wedge reflecting total factor productivity (TFP) can be calculated, which is a geometric average of the labor and capital efficiency wedges.

Departing from the CD hypothesis, in addition to allowing to account for the evolution of U.S. factor income shares, it has significant consequences for calculating wedges. If we assume a CD production function, changes in the labor share are imputed to the labor and investment wedges. In particular, a reduction in the labor share will be computed as a decline in the labor wedge and an increase in the investment wedge. Moreover, departing from the CD assumption allows us to calculate an efficiency wedge for each productive factor, whereas using a CD specification of the production function, only an efficiency wedge reflecting TFP can be computed. The rate of change in TFP equals the weighted sum of the rates of change in the efficiency wedges of the production factors, where de weights are the respective output elasticities for each factor. Therefore, if capital and labor efficiency wedges are moving in opposite directions, a small rate of change for TFP may be computed despite both efficiency wedges undergoing substantial changes. Moreover, under the CD assumption, the TFP is calculated assuming that the output elasticities for both factors are constants; however, under the VES assumption, the efficiency wedges are computed with output elasticity for labor considered equal to the labor share. Therefore, if capital intensity is increasing, a decline in the labor share reduces the computed TFP growth under the VES assumption compared with that under the CD assumption. This observation implies that if the labor share is declining because the output elasticity for labor is declining (which should be the case if the marginal returns of productive factors equal their rental prices), a CD specification of the production function would overestimate the decline in the labor wedge and underestimate the reduction in the investment and efficiency wedges.[3] This phenomenon should be considered because of the strong decline in the U.S. labor share from the beginning of the 21st century, particularly during the Great Recession.

Here, similar to the approaches of Cole and Ohanian (2002) and Ohanian and Rafo (2012), we use the deterministic version of the neoclassical growth model for the accounting exercise. However, in contrast to this approach, we compute the complete path of each of the aforementioned five wedges. Chari et al. (2002, 2007) used the stochastic version of the neoclassical growth model to compute the paths of the wedges and perform accounting for the business cycle.[4] Using the neoclassical growth model in its deterministic version implies the perfect foresight assumption; however, more interestingly, it allows the use of the nonlinear version of the first-order conditions to compute the wedges and simulate the model, whereas Chari et al. (2002, 2007) used log-linearized versions of these conditions.[5] This distinction is crucial because our estimations suggest that the U.S. economy was transitioning between two different balanced growth paths (BGPs) during the analysis period, and transitional dynamics may be relevant to the quantitative results. Moreover, using the deterministic version of the neoclassical growth model instead of the stochastic model enables us to use a different method of Chari et al. (2007) to compute the wedges. This different method is relevant in computing the investment wedge. In particular, with our method, we compute the complete path of each wedge consistent with the equilibrium path converging to the BGP.

[3] The estimated wedges for both labor and investment do not depend on the specified production function if output elasticities for factors are variable and factor shares thus adjust competitively. However, the efficiency wedges depend on the particular production function specified.

[4] Other authors have followed in their steps: Cavalcanti (2007), Chakraborty and Otsu (2013), Chakraborty (2006), Cho and Doblas-Madrid (2013), Kersting (2008), Kobayashi and Inaba (2006), Otsu (2010), Sustek (2011), Brinca (2013, 2014), Brinca et al. (2016) and Fehrle and Huber (2020). None of the previously cited works use a VES production function; they all use CD production functions.

[5] To compute the wedges, we use annual data instead of quarter data, which are more suitable for the deterministic model and the implicit assumption of perfect foresight.

Brinca et al. (2016) developed the stochastic model and compare it with the deterministic model; however, they use a different method than that proposed in this study. In particular, they set the initial value of the investment wedge as 1; however, we set its final value (its value in the BGP) and then compute the path converging to the BGP. Lu (2012) and Cheremukhin et al. (2015, 2017) also use deterministic growth models with wedges to perform some growth accounting exercises; however, they consider a capital wedge (i.e., a wedge between marginal productivity of capital and its rental price) instead of an investment wedge. This difference is relevant because the investment wedge is intertemporally involved in the equilibrium conditions, and thus, it is determined using a forward-looking structure; the complete model must be solved to obtain a path for the investment wedge. However, this is not the case for the capital wedge.

Our results show that efficiency wedges accurately account for the evolution of productivity and labor shares of the U.S. economy during the 1954–2017 period.[6] Therefore, on the one hand, our accounting exercise does not question the validity of the usual focus of the growth literature on understanding and explaining the efficiency of productive inputs as the engines of productivity growth, and on the other hand, our results suggest that investment-specific technological change may have played a primary role in the evolution of U.S. productivity and U.S. factor income distribution over the 1954–2017 period. Moreover, Chari et al. (2007) and Brinca et al. (2016) found that the primary force driving U.S. postwar economic fluctuations was the efficiency wedge. Our results confirmed this finding but point to the capital efficiency wedge, and not the labor efficiency wedge, as the main force driving the evolution of output, investment, and hours worked over the 1954–2017 period. Lu (2012) found that the rising capital wedge was responsible for most of the rapid growth in the earlier stages of development for the Asian tigers, whereas the efficiency wedge tended to be dominant in the later stages.[7]

If a VES production function is specified, we find that the primary force driving the growth slowdown and the fall in hours worked during the 1970s and the first decade of 21st century was the decline in the capital efficiency wedge. However, if a CD production function is specified, the primary force driving the growth slowdown and the decline in hours worked in the first decade of 21st century was the labor wedge, whereas the efficiency wedge was the primary force driving the growth slowdown and the decline in hours worked during the 1970s. From a strictly accounting perspective, the behavior of the U.S. economy in both periods of the growth slowdown is more homogeneous when a VES production function is used (and consequently when frictions are assumed to be manifested exclusively in labor supply distortions) than when a CD production function is used. If the *First Growth Slowdown* in the 1970s is compared with the *Second Growth Slowdown* in 21st century, we observe the same fact: the VES specification of the production function tends to reduce the negative impact of the labor wedge and to increase (reduce) the negative (positive) impact of the investment wedge on the evolution of output, labor, and investment. This phenomenon is attributed to the labor share experiencing a significant decrease in both periods. Using a CD production function, Chari et al. (2007) found that the efficiency and labor wedges play primary roles in accounting for the evolution of output, labor, and investment in the 1982 recession, and the investment wedge has essentially no role. Ohanian and Rafo (2012) found that the labor wedge accounts for almost all of the decline in the U.S. output per capita during the Great Recession, whereas the efficiency wedge explains only approximately 20% of the decrease and almost none of the reduction in hours. Brinca et al. (2016) found a similar result; in the Great Recession in the U.S., the labor wedge had a predominant role, whereas the investment wedge had a crucial but secondary role. However, the efficiency wedge is not important. As noted above, under the VES assumption, the role played by the labor wedge is reduced with regard to the CD case in both the first and second growth slowdowns, and in both periods, the worsening of the capital efficiency wedge was the primary force driving the growth slowdown of output and investment as well as the decline in hours worked per capita. Therefore, our results suggest that leaving the CD assumption may contribute to homogenizing the role of the wedges in both recessions; however, our conjecture must be checked with a specific analysis of these recessions in a stochastic framework to compare results.

We also find that under both specifications of the production function, the labor wedge was the primary force driving the economic recovery in the 1980s and the boom in hours worked during the 1990s as well as the economic recovery from the Great Recession. Along these lines, Kersting (2008) found that improvement in the labor wedge contributed to the recovery of the UK economy starting in 1984. U.S. hours worked per capita did not display any significant long-run trend during 1954–2017, which can be explained by two forces working in the opposite directions. On the one hand, the decline in the resource constraint wedge reduced hours worked per capita. On the other hand, the increase in the labor wedge increased hours worked per capita. Moreover, our results show that the rapid economic growth of the 1950s and 1960s was driven by increases in the efficiency wedge (particularly, the labor efficiency wedge if a VES production function is specified). Finally, we find that the investment wedge played a secondary role in accounting for the evolution in the magnitude of the primary U.S. macroeconomic factors over the 1954–2017 period. Notably, the increase in the investment wedge contributed to mitigate the economic crisis of the 1970s; however, its decline also contributed to slowing of the subsequent recovery in the 1980s.

According to our results, understanding the *Long Boom* requires analyzing the economic forces that provoked the strong increase in the labor efficiency wedge in the 1950s and 1960s. According to Gordon (1999, 2000), the unusual productivity growth during the *Long Boom* was due to the diffusion of four clusters of inventions engendered in the late 19th century and early 20th century: electricity, internal-combustion engines, rearranging molecules, and communications/entertainment. Gordon (1999, 2000) argued that the “big four” were considerably more profound creators of productivity growth than anything that has happened recently. The *Long Boom* period together with The Roaring Twenties was a period of high economic growth in the U.S. during the 20th century. We find that the worsening of the labor wedge contributed to slow growth in the *Long Boom* and Hansen et al. (2020) reported the same finding in The Roaring Twenties. As recognized by Hansen et al. (2020), this observation in the 1920s has no obvious interpretation. However, the worsening of the labor wedge in the 1950s and 1960s might have been caused by the increase in income tax rates, whereas the improvement of the labor wedge in the 1980s and after the Great Recession might have been due to lowering income tax rates. Following WWII, income taxes increased. In particular, top marginal individual tax rates stayed near or higher than 90% with an effective tax rate of 70% for the highest incomes until the top marginal tax rate was reduced to 70% in 1964.[8]

Our results suggest that to understand the long periods of growth slowdown and decrease in the use of the labor factor in the 1970s and in the first decade of 21st century, we must focus on the circumstances influencing the capital efficiency wedge, whereas understanding the periods of economic recovery requires focusing on the circumstances influencing the increase in the labor wedge. The decline in the capital

[6] del Rio and Lores (2019), using a VES production function, show that the evolution of capital efficiency can accurately account for the evolution of the U.S. labor share after WWII.

[7] Cheremukhin et al. (2015, 2017) use the neoclassical growth model to compute market distortions and assess their importance for structural changes in the Russian and Chinese economies.

[8] Krugman (2012) called to the 1950s and 1960s The Twinkie Era.

efficiency wedge during the *Second Growth Slowdown* might have been caused by facts surrounding the bursting of the dot-com and housing bubbles. The dramatic increase in energy prices during the 1970s might have caused a large decline in the capital efficiency of most energy-intensive sectors. In particular, Nordhaus (2004) found that the productivity slowdown in the 1970s was primarily centered in that were most energy-intensive sectors, such as pipelines, auto repair, and oil and gas extraction industries. The primary candidates improving the labor wedge in the 1980s and after the Great Recession are tax reforms. In the 1980s, The Economic Recovery Tax Act of 1981 and The Tax Reform Act of 1986 established some income tax cuts in the U.S..[9] In particular, the top marginal tax rate was lowered to 50% in 1982 and eventually to 28% in 1988. Romer and Romer (2010) reported that the 1980s was a period particularly intensive in exogenous tax cuts in the U.S.. Following the Great Recession, the Economic Stimulus Act of 2008 established some individual income tax rebates that lowered federal taxes by approximately 5% in 2008, thereby reducing the estimated average effective federal tax rate from 19.6% to 18.6%. The American Recovery and Reinvestment Act of 2009 reduced federal taxes by an estimated $287 billion over 10 years. More than 80% of the tax cuts, $232 billion, were for individuals. The Tax Relief Unemployment Insurance Reauthorization and Job Creation Act of 2010 extended many of the previous tax cuts and reduced the Social Security tax rate on employees to 4.2% for 2011 and the self-employment tax rate by 2% for 2011.[10]

The remainder of this paper is organized as follows. Section 2 describes the model. In Section 3, we illustrate the mapping between a two-sector economy and the prototype economy. The relationship between the wedges and investment-specific technical progress is also discussed in Section 3. Section 4 describes the building of data. We compute the wedges and discuss the implications of the specification of the production function in measuring the wedges in Section 5. In Section 6, the model is simulated to assess the contribution of each wedge to the evolution of output, hours worked, and investment in the U.S. in the 1954–2017 period. Finally, Section 7 concludes.

2. The model

A perfectly competitive representative firm produces output, Y_t, according to a VES production function and using capital, K_t, and labor as production factors, $H_t = h_t L_t$, where h_t is worked time per worker and L_t the number of workers (which equals population),

$$Y_t = \left(\alpha(q_t K_t)^{\omega\psi}\left(z_t(1+\gamma)^t H_t\right)^{(1-\omega)\psi} + (1-\alpha)\left(z_t(1+\gamma)^t H_t\right)^{\psi}\right)^{\frac{1}{\psi}},$$

where $\psi \leq 1$, $0<\alpha < 1$, $0<\omega < 1$, $\gamma \geq 0$ is the rate of labor-augmenting technological progress, q_t is the *capital-efficiency wedge* and z_t is the *labor-efficiency wedge*.[11]

The proposed VES production function follows from a CES production function with variable capital utilization that depends on the ratio of labor to capital. Consider the following production function:

$$Y_t = \left(\alpha(e_t K_t)^{\psi} + (1-\alpha)\left(z_t(1+\gamma)^t H_t\right)^{\psi}\right)^{\frac{1}{\psi}}, \tag{1}$$

where $e_t = q_{0,t} u_t$ is capital efficiency, being $q_{0,t}$ is an exogenous variable of efficiency and

$$u_t = \left(\frac{H_t}{K_t} z_t^{\rho}\right)^{(1-\omega)}$$

is the utilization rate of capital, which is a function of the ratio of labor to capital and the labor efficiency as $0<\omega < 1$ and $\rho \geq 0$. Note that if $\rho = 0$, capital utilization depends on the ratio of unadjusted labor to capital, whereas if $\rho = 1$, capital utilization depends on the ratio of efficient labor to capital. Therefore, production function (1) gives rise to the VES production function with

$$q_t = \left(q_{0,t} z_t^{(\rho-1)}\right)^{(1-\omega)}. \tag{2}$$

Under this interpretation of the VES production function, the capital efficiency wedge is inversely related to the labor efficiency wedge if $\rho < 1$.

Therefore, detrended output per worker, $y_t = \frac{Y_t}{(1+\gamma)^t L_t}$, is given as follows:

$$y_t = \left[\alpha(q_t k_t)^{\omega\psi}(z_t h_t)^{(1-\omega)\psi} + (1-\alpha)(z_t h_t)^{\psi}\right]^{\frac{1}{\psi}}, \tag{3}$$

where $k_t = \frac{K_t}{(1+\gamma)^t L_t}$ is detrended capital per capita. The representative firm hires capital and labor to equalize its marginal productivities to their rental prices (r_t and W_t),

$$s_t = r_t \frac{k_t}{y_t} \equiv s_{k,t} \tag{4}$$

and

$$1 - s_t = w_t \frac{h_t}{y_t} \equiv s_{h,t}, \tag{5}$$

where $w_t = \frac{W_t}{(1+\gamma)^t}$ is detrended wage per worked hour,

$$s_t = \alpha\omega\left(q_t \frac{k_t}{y_t}\right)^{\omega\psi}\left(z_t \frac{h}{y_t}\right)^{(1-\omega)\psi} \tag{6}$$

is output elasticity for capital and $1 - s_t$ is output elasticity for labor. According to the first order conditions (4) and (5), the capital share, $s_{k,t}$, equals output elasticity for capital and the labor share, $s_{h,t}$, equals the output elasticity for labor. Moreover, both factor shares add to 1.

The resource constraint is $Y_t(1-g_t) = C_t + X_t$, where C_t is household consumption, X_t is investment, and g_t is the *resource constraint wedge*, which is the fraction of output not allocated to investment or consumption. The resource constraint can be rewritten in terms of the detrended variables per capita as follows:

$$c_t + x_t = (1-g_t) y_t, \tag{7}$$

where $c_t = \frac{C_t}{(1+\gamma)^t L_t}$ is detrended consumption per capita and $x_t = \frac{X_t}{(1+\gamma)^t L_t}$ is detrended investment per capita.

Capital evolves according to the following move law, which includes quadratic investment adjustment costs,

$$K_{t+1} = X_t + (1-\delta_t) K_t - \frac{\phi}{2}\left(\frac{X_t}{K_t} - \kappa\right)^2 K_t,$$

where $\phi > 0$, $\kappa > 0$ and $0<\delta_t < 1$ is the economic depreciation rate of capital at time t. The move law of capital can be rewritten in terms of the detrended variables per capita as follows:

$$(1+\eta_{t+1})(1+\gamma) k_{t+1} = x_t + (1-\delta_t) k_t - \frac{\phi}{2}\left(\frac{x_t}{k_t} - \kappa\right)^2 k_t \tag{8}$$

where η_{t+1} is the population growth rate between t and $t+1$, $\frac{L_{t+1}}{L_t} = 1 + \eta_{t+1}$.

The representative household at time t is composed of L_t members. Each member of the representative household is endowed with one unit of time that can be shared between leisure and labor in return for a wage, W_t. Therefore, at equilibrium, $H_t = L_t h_t$, where $1<h_t < 0$ is time offered in the labor market by a member of the representative household. The intertemporal utility function of the representative household is as follows:

$$U_t = \sum_{t=0}^{\infty} L_t \beta^t \left[\log C_{L,t} + \mu \log(1-h_t)\right]$$

[9] See Laffer (2004).

[10] See Urban-Brookings Tax Policy Center (2009, 2020).

[11] We discuss the choice of a VES production function in del Río and Lores (2019).

where $1-h_t$ is leisure per capita, $0<\beta<1$ is the discount factor, $C_{L,t}=\frac{C_t}{L_t}$ is consumption per capita and $\mu>0$ is the value of leisure relative to consumption. The household budget constraint is as follows:

$$L_tC_{L,t}+\pi_{x,t}X_t=\pi_{h,t}W_th_tL_t+r_tK_t+B_t$$

where B_t are lump-sum transfers, $\pi_{h,t}$ is the *labor wedge* and $\pi_{x,t}^{-1}$ is the *investment wedge*.

The first-order conditions characterizing a maximum of the household problem are as follows

$$\frac{1}{\beta}(1+\gamma)\frac{c_{t+1}}{c_t}=1+i_{t+1} \tag{9}$$

$$r_{t+1}=\frac{\pi_{x,t}(1+i_{t+1})}{1-\phi\left(\frac{x_t}{k_t}-\kappa\right)}+\frac{\pi_{x,t+1}}{1-\phi\left(\frac{x_{t+1}}{k_{t+1}}-\kappa\right)}\cdot$$
$$\cdot\left[\frac{\phi}{2}\left(\frac{x_{t+1}}{k_{t+1}}-\kappa\right)^2-\phi\left(\frac{x_{t+1}}{k_{t+1}}-\kappa\right)\frac{x_{t+1}}{k_{t+1}}-(1-\delta_{t+1})\right] \tag{10}$$

$$\mu\frac{c_t}{1-h_t}=\pi_{h,t}w_t \tag{11}$$

Here i_{t+1} is the interest rate at time $t+1$,

$$i_{t+1}=\frac{p_t}{p_{t+1}}-1, \tag{12}$$

where p is the Arrow-Debreu price of the composite commodity. Equation (9) is the Euler equation, according to which the marginal rate of intertemporal substitution equals the gross interest rate. Equation (10) establishes that the rental price of capital equals its user cost, which in addition to the interest rate and the economic depreciation rate, includes the investment wedge and investment adjustment costs. Equation (11) states that the marginal rate of substitution between consumption and leisure equals the wage adjusted by the labor wedge.

Given the seven exogenous variables $\{q_t, z_t, g_t, \pi_{x,t}, \pi_{h,t}, \delta_t, \eta_{t+1}\}_{t=0}^{\infty}$, equation system (3)-(11) with the transversality condition and an initial condition for the detrended capital per capita, k_0, characterize the dynamic behavior of the economy.

3. Two sectors, investment-specific technological change and wedges

Now, we illustrate the mapping between a two sector economy and the prototype economy. Let an economy be composed of firms using capital, K, and labor, L, to produce goods. The economy has a sector C producing consumption goods and a sector I producing investment goods as follows:

$$C_t=A_{C,t}F(K_{C,t},L_{C,t})=A_{C,t}f(k_{C,t})L_{C,t}$$

and

$$I_t=A_{I,t}F(K_{I,t},L_{I,t})=A_{I,t}f(k_{I,t})L_{I,t},$$

where $f(k_i)=F(k_i,1)$, $k_i=K_i/L_i$ is capital intensity in sector i, and $A_{i,t}$ is TFP in sector i at time t. Capital accumulation takes place in accordance with the following equation

$$K_{t+1}=B_{I,t}I_t+(1-\delta)K_t,$$

where $0<\delta<1$ is the depreciation rate of capital and $B_{I,t}$ is efficiency of investment, which is often is called quality of investment goods. The constraints on the sectorial allocation of capital and labor are $K_t=K_{C,t}+K_{I,t}$ and $L_t=L_{C,t}+L_{I,t}$, whereas aggregate output is as follows:

$$Y_t=C_t+E_t,$$

where $E_t=p_{I,t}I_t$ are expenditures in investment goods, $p_{I,t}$ is the relative price of investment goods; because the relative price of consumption is normalized to one, $p_{C,t}=1$; and C_t are expenditures in consumption goods. The frictionless and perfectly competitive firms of both sectors equal the rental prices of factors (R and W) to the values of their marginal productivities as follows:

$$p_{i,t}A_{i,t}f'(k_{i,t})=R_t$$

and

$$p_{i,t}A_{i,t}(f(k_{i,t})-k_{i,t}f'(k_{i,t}))=W_t.$$

Therefore

$$f'(k_{i,t})/(f(k_{i,t})-k_{i,t}f'(k_{i,t}))=R_t/W_t$$

and

$$p_{I,t}(A_{I,t}f'(k_{I,t}))/(A_{C,t}f'(k_{C,t}))=1.$$

Therefore, the ratio of capital to labour is equal in both sectors, $k_{i,t}=k_t=K_t/L_t$, and the relative price of investment reflects the TFP gap between sectors, $p_{I,t}=A_{C,t}/A_{I,t}$, whereas the so-called quality-adjusted relative price of investment is $p_{I,t}^A=p_{I,t}/B_{I,t}$.

(1) Deflating investment expenditures by the quality-adjusted relative price of investment, $p_{I,t}^A$, the resource constraint can be rewritten as follows:

$$Y_t=C_t+\pi_{x,t}X_t=A_{C,t}F(K_t,L_t),$$

where $X_t=B_{I,t}I_t$ is efficient investment (or quality-adjusted investment), and the accumulation of capital is as follows:

$$K_{t+1}=X_t+(1-\delta)K_t.$$

Here, the investment wedge,

$$\pi_{x,t}^{-1}=\frac{1}{p_{I,t}^A}=B_{I,t}\frac{A_{I,t}}{A_{C,t}},$$

reflects the inverse of the quality-adjusted relative price of investment. In this case, both the labor and the capital efficiency wedge equal TFP in the consumption sector $q_t=z_t=A_{C,t}$. Therefore, investment-specific technical progress is reflected in changes of the investment wedge.

(2) If investment expenditures are deflated by the unadjusted relative price of investment, $p_{I,t}$ the resource constraint can be rewritten as follows:

$$Y_t=C_t+\pi_{x,t}I_t=F(q_tK_{1,t},z_tL_t)$$

where the measured capital services are $K_{1,t}=K_t/B_{I,t-1}$ and evolve as follows:

$$K_{1,t+1}=I_t+(1-\delta_1)K_{1,t}$$

where $\delta_1=1-(1-\delta)B_{I,t-1}/B_{I,t}$. In this case, the capital efficiency wedge reflects both investment efficiency and TFP in the consumption sector, $q_t=B_{I,t-1}A_{C,t}$, the labor efficiency wedge reflects TFP in the consumption sector, $z_t=A_{C,t}$, and the investment wedge reflects the inverse of the relative price of investment,

$$\pi_{x,t}^{-1}=\frac{1}{p_{I,t}}=\frac{A_{I,t}}{A_{C,t}}.$$

Therefore, investment-specific technical progress reflected in the decline of the relative price of investment is expressed in the investment wedge; however, the investment-specific technical progress or any circumstance influencing the efficiency (or quality) of investment that is not reflected in the relative price of investment is expressed in the capital efficiency wedge.

Gordon (2007) discusses the importance of the technical progress embodied in new durable goods, and particularly, in new investment goods, as well as the need to adjust the prices of these goods for the changes in their quality. The available empirical evidence suggests that the National Income and Product Accounts (NIPA) prices of the investment goods are very poorly adjusted for changes in their quality.

(3) If investment expenditures are deflated by the price of consumption, then the resource constraint can be rewritten as follows:

$$Y_t = C_t + E_t = F\left(q_t K_{2,t}, z_t L_t\right),$$

where the measured capital services are $K_{2,t} = K_t p_{I,t-1}$ and evolve as follows:

$$K_{2,t+1} = E_t + (1-\delta_2) K_{2,t}$$

where $\delta_2 = 1-(1-\delta) B_{I,t-1}/B_{I,t} p_{I,t}/p_{I,t-1}$. In this case, the capital efficiency wedge reflects both TFP in the consumption sector and the inverse of the quality-adjusted relative price of investment:

$$q_t = \frac{1}{p^A_{I,t-1}} A_{C,t} = B_{I,t-1} A_{I,t-1} \frac{A_{C,t}}{A_{C,t-1}},$$

the labor efficiency wedge reflects TFP in the consumption sector, $z_t = A_{C,t}$, and the investment wedge is one. Therefore, in this case, investment-specific technical progress is reflected in the changes of the capital efficiency wedge.

Here, to deflate nominal variables, we use the implicit deflator of consumption, and consequently, changes in both the relative price of investment and the efficiency (or quality) of investment are reflected in the capital efficiency wedge. However, in the Business Cycle Accounting literature, investment expenditures are generally deflated using the implicit deflator of gross domestic product (GDP), and therefore, changes in the relative price of investment are partially reflected in the investment wedge and in the efficiency wedge.

4. Building the data

Depreciation The economic depreciation rate of capital is calculated as $\delta = D_N/K_N$ where D_N is NIPA current-cost depreciation of fixed assets and durable consumer goods and K_N is the NIPA current-cost net stock of fixed assets and durable consumer goods.

Nominal output Nominal output, Y_N, is nominal NIPA GDP, GDP_N, minus NIPA taxes on production and imports plus subsidies, T_N, plus the flow of services of durable consumer goods, S^d_N: $Y_N = GDP_N - T_N + S^d_N$.[12] The flow of services of durable consumer goods is $S^d_N = iK^d_N + D^d_N$ where K^d_N is NIPA current-cost net stock of durable consumer goods, $i = 0.04$ is the interest rate and D^d_N is NIPA current-cost depreciation of durable consumer goods. We adjust output for the services of durable consumer goods following Brinca et al. (2016).

Taxes Following Prescott (2004), we compute net direct taxes on personal expenditures in consumption, T^p_N, as a fraction of NIPA taxes on production and imports plus subsidies $T^p_N = \mu T_N$ where $\mu = \left(\frac{2}{3} + \frac{1}{3} G^c_N / \left(G^c_N + G^x_N\right)\right)$ is the fraction proposed by Prescott (2004), G^c_N are nominal NIPA personal expenditures in consumption and G^x_N is nominal NIPA gross private domestic investment. Durable consumer goods are excluded from consumption and included in investment, and thus, taxes on consumption, T^c_N, are $T^c_N = T^p_N \left(G^{nd}_N + G^s_N\right)/G^c_N$, where G^{nd}_N are nominal NIPA personal expenditures in nondurable consumer goods and G^s_N are nominal NIPA personal expenditures in services. Net direct taxes on investment equals the NIPA taxes on production and imports plus subsidies minus taxes on consumption: $T^x_N = T_N - T^c_N$.

Components of output Nominal consumption, C_N, is $C_N = G^{nd}_N + G^s_N - T^c_N + S^d_N$. From the expenditures in nondurables and services, we subtract taxes and, following Brinca et al. (2016), we add the flow of services of durable consumer goods. Nominal Investment, X_N, is $X_N = G^x_N + G^{gx}_N - T^x_N + G^d_N$, where G^{gx} is nominal NIPA government gross investment and G^d_N are nominal NIPA personal expenditures in durable consumer goods. Following Brinca et al. (2016), we add personal expenditures in durable consumer goods to investment (which includes both private and government investment) and we take away taxes.[13]

Population and labor We follow Prescott (2004) and measure population, L, as civilian noninstitutional population aged 16 − 65 years (data are taken from the database of the Federal Reserve Bank of St. Louis) and military personnel on active duty (data are from the Defense Manpower Data Center, Office of the Secretary of Defense, U.S. Department of Defense). Per capita hours worked, H, are worked hours by persons engaged in production, which are calculated as $H = H_w E_p/E_f$, where H_w are NIPA hours worked by full-time and part-time employees, E_f are NIPA full-time equivalent employees and E_p are NIPA persons engaged in production. Therefore, hours worked per capita are $\frac{H}{L}$ and the fraction of time devoted to work, h, equals the hours worked per capita divided by the available hours per person ($\frac{2}{3}$ of the total hours, 8760 h per year, $H_A = 5840$), $h = H/(LH_A)$.

Real Output Nominal output is deflated by the consumption price index before taxes, $P_C = P^a_C/(1+\tau_c)$, where τ_c is the consumption tax rate, $\tau_c = T^c_N/C_N$, and P^a_C is a weighted arithmetic average of the NIPA chain-price index of personal consumption expenditures in nondurable consumption goods, P_{nd}, and the NIPA chain-price index of personal consumption expenditures in services, P_s: $P^a_C = \upsilon P_{nd} + (1-\upsilon) P_s$, where $\upsilon = G^{nd}_N / \left(G^{nd}_N + G^s_N + S^d_N\right)$.[14] Real output, real consumption and real investment are computed deflating the corresponding nominal magnitudes by the consumption price index before taxes: $Y = Y_N/P_C$, $C = C_N/P_C$ and $X = X_N/P_C$.

Labor and capital shares The U.S. gross labor share, s_h, from the whole U.S. economy from 1954 to 2017 was calculated using data on compensation of employees (CE) by industry ($i = 1, 2, \ldots M$) provided by NIPA. The compensation of all workers (employees (E) and self-employees (SE)) by industry was calculated assigning to the self-employees in each industry the average compensation of employees in the industry. The aggregate compensation of all workers in all industries was divided by Y_N. In particular,$s_h Y_N = \sum_{i=1}^{M} \left[CE_i + \frac{CE_i}{E_i} SE_i\right]$. The capital share is $s_k = 1 - s_h$.

5. Calibrating the balanced growth path (BGP)

Along a BGP, both the population growth rate and economic depreciation rate are constants, $\eta_t = \eta$ and $\delta_t = \delta$, and there are not adjustment costs, $\frac{x_t}{k_t} = \kappa$. Moreover, along a BGP, the resource constraint wedge, g_t, the investment wedge, $\pi_{x,t}$, the labor wedge, $\pi_{h,t}$, the capital efficiency wedge, q_t, and the labor efficiency wedge, z_t, remain constant along with c_t, x_t, k_t, h_t, w_t, y_t and i_t.[15] Given q, z, π_x, π_h, and g, the following equations characterize a BGP:

$$\frac{1+\gamma}{\beta} = 1 + i \tag{13}$$

$$(1+\eta)(1+\gamma) - (1-\delta) = \frac{x}{k} \tag{14}$$

$$sy = \pi_x (i+\delta) k \tag{15}$$

$$(1-s) y = wh \tag{16}$$

[12] Before 1959, NIPA included the current surplus of government enterprises together with the subsidies.

[13] Under our definitions of consumption and investment, the resource constraint wedge, g, equals the ratio of government consumption plus net exports to output.

[14] We are implicitly imputing the price of the personal consumption services to the flow of services of durable consumer goods.

[15] Of course, if q_t is constant, the production function displays purely labor-augmenting labor technical progress, which is a necessary condition for the existence of a BGP (see Uzawa (1961) and Jones and Scrimgeour (2008)).

$$\mu \frac{c}{1-h} = \pi_h w \tag{17}$$

$$s = \alpha\omega \left(q\frac{k}{y}\right)^{\omega\psi} \left(z\frac{h}{y}\right)^{(1-\omega)\psi} \tag{18}$$

$$y = \left[\alpha (qk)^{\omega\psi} (zh)^{(1-\omega)\psi} + (1-\alpha)(zh)^{\psi}\right]^{\frac{1}{\psi}} \tag{19}$$

$$c + x = (1-g)y \tag{20}$$

Equation (13) is the Euler equation. equation (14) establishes that the accumulation of capital is such that the ratio of investment to capital is constant. equations (15) and (16) are the profit-maximizing conditions of the representative firm that equalize the marginal productivities of capital and labor to their rental prices. Equation (17) establishes that the marginal relation of substitution between leisure and consumption equals the wedge-adjusted wage rate. equation (18) offers the output elasticity for capital. Equation (19) is the production function. Equation (20) is the resource constraint.

According to our strategy, we restrict the values of the parameters of the model such that they are compatible with observations from the U.S. economy. (1) We set $x/y = 0.28$, which is approximately the average value of the U.S. ratio in the period 1954–2017 and $c/y = 0.62$, which is around the U.S. average ratio in the last years of the sample.[16] (2) According to NIPA data in 2017, the ratio of the current-cost depreciation of NIPA fixed assets to the current-cost net stock of NIPA fixed assets was approximately 6.4%. Therefore, we set $\delta = 0.064$. (3) We set $\gamma = 0.0163$ and $\eta = 0.0118$, which are the annual average growth rates of output per worker and population in the United States in the 1954 − 2017 period respectively. (4) According to our calculations using NIPA data, the U.S. average annual gross labor share in the period 1954–2017 was approximately 64%. Thus, we set $\frac{wh}{y} = 0.64$. (5) According to our calculations, the U.S. average annual hours worked in the 1954–2017 period represented 22% of annual available time for U.S. non-institutional population between 16 and 64 years; we then set $h = 0.22$. (6) We set the same annual interest rate as Brinca et al. (2016), $i = 0.04$. (7) We set $\psi = -1.9$ and $\omega = 0.5$, which are values near the estimated values by del Río and Lores (2019). In particular, del Río and Lores (2019) estimate $\psi = -1.9$ and $\omega = 0.36$. We consider a value of ω higher than the estimated value by del Río and Lores (2019) because for a well-defined series for z_t and q_t, $\omega > s_{k,t}$ for all t as according to the proposed VES production function, ω is an upper bound on the capital share, $s_{k,t}$. (8) The relative value of leisure is normalized to 1, $\mu = 1$, and detrended output per capita is also normalized to 1, $y = 1$. (9) We set $\alpha\omega = 0.36$, and thus, the VES production function converges to a CD production with output elasticity for capital 0.36. Therefore, $\alpha = 0.72$. (10) Along a BGP, the investment-capital ratio is given by (14), and hence, $\kappa = (1+\eta)(1+\gamma) - (1-\delta) = 0.092$. The function of adjustment costs is quadratic, which is typical in macroeconomic literature, and it also used in Brinca et al. (2016). To perform the quantitative analyses, we follow Brinca et al. (2016) and set $\phi = 0.25/\kappa = 2.7174$ to obtain elasticity of the price of capital with respect to the investment-capital ratio of 0.25. Calibrated parameters, variables, and wedges are calculated by solving the equation system (13)-(20) and are displayed in Table 1.

To compare our results with others in the literature, we compare the results obtained from the simulations by using our VES production function with the results obtained from the simulations by using the CD production function arising as a limit case of the VES production function when ψ goes to 0. In particular, the production function $Ak^{\alpha\omega}h^{1-\alpha\omega}$, where $A = q^{\alpha\omega}z^{1-\alpha\omega}$ is TFP or the efficiency wedge. Solving the equation system (13)-(20) with the CD production function, the same variables, parameters, and wedges are calibrated as those in the VES case, except that $A = 1.7674$. The CD specification of the production function does not allow the identification of q and z but only that of (TFP), A. In the VES case, TFP is $A = q^s z^{1-s}$, where s is output elasticity for capital. Under our assumptions, $s = s_k$, and in the VES case, we calculate TFP, as $A = q^{s_k} z^{1-s_k}$.

[16] For $\frac{c}{y}$, we do take the average of the period, because this ratio has undergone a significant increases between the mid-1950s and 2017.

Table 1
Model parameters and BGP variables..

Parameter	Description	Value
Model parameters obtained exogenously or estimated.		
η	Population Growth Rate	0.0118
γ	Growth Rate of Output per Worker	0.0163
δ	Depreciation Rate of Capital	0.0640
ψ	Production Function Parameter	−1.900
ω	Production Function Parameter	0.5000
α	Production Function Parameter	0.7200
μ	Relative Value of Leisure	1.0000
Model parameters obtained solving the model.		
β	Discount Factor	0.9772
BGP variables		
q	Capital Efficiency Wedge	0.3296
z	Labor Efficiency Wedge	4.5454
π_x	Investment Wedge	1.1409
π_h	Labor Wedge	0.2732
g	Resource Constraint Wedge	0.10
k	Capital-Output Ratio	3.0338
y	Output per Capita	1.0000
h	Worked Hours per Capita	0.2200
x	Investment Rate	0.2800
c	Consumption to Output Ratio	0.6200
s	Capital-Output Elasticity	0.3600
i	Interest Rate	0.0400

6. The wedges

In this section, we compute the wedges that allow us to match the model and the U.S. data for the 1954–2017 period. Our strategy is (1) to compute the paths of the wedges and of detrended capital per capita consistent with the U.S. observations on hours worked per capita, labor share, consumption per capita, investment per capita, and output per capita in the 1954–2017 period assuming that the economy is converging to the previously calibrated BGP. Our strategy yields wedges not only for the observed period but also for the future. The results are not very sensitive to the calibrated final BGP given the property of the rapid convergence of the neoclassical growth model.

6.1. Computing the wedges

The wedges are computed in both VES and CD cases. In the CD case, only the path of the efficiency wedge (i.e. TFP), A_t, can be identified but not the paths of the efficiency wedges of each factor, q_t and z_t; furthermore, there are four wedges. In the VES case, the path of the TFP is calculated as $A_t = q_t^{s_{k,t}} z_t^{1-s_{k,t}}$. To compute the wedges with the aforementioned calibrated parameters, we solve the equilibrium equation system given by equations 21–26 for k_{t+1}, $\pi_{x,t}$, $\pi_{h,t}$, g_t, q_t, and z_t, given the observed paths of η_{t+1}, y_t, c_t, x_t, $s_{k,t}$, δ_t and h_t in the 1954 − 2017 period, and an initial condition for capital k_0

$$c_t + x_t = (1-g_t)y_t \tag{21}$$

$$(1+\eta_{t+1})(1+\gamma)k_{t+1} = x_t + (1-\delta_t)k_t - \frac{\phi}{2}\left(\frac{x_t}{k_t} - \kappa\right)^2 k_t \tag{22}$$

$$\alpha(q_t k_t)^{\omega\psi}(z_t h_t)^{(1-\omega)\psi} + (1-\alpha)(z_t h_t)^{\psi} = y_t^{\psi} \tag{23}$$

$$s_{k,t} = \alpha\omega\left(q_t\frac{k_t}{y_t}\right)^{\omega\psi}\left(z_t\frac{h_t}{y_t}\right)^{(1-\omega)\psi} \tag{24}$$

$$\frac{\pi_{x,t}}{1-\phi\left(\frac{x_t}{k_t}-\kappa\right)}\frac{1+\gamma}{\beta}\frac{c_{t+1}}{c_t} = s_{k,t+1}\frac{y_{t+1}}{k_{t+1}} - \frac{\pi_{x,t+1}}{1-\phi\left(\frac{x_{t+1}}{k_{t+1}}-\kappa\right)}\cdot$$
$$\cdot\left[\frac{\phi}{2}\left(\frac{x_{t+1}}{k_{t+1}}-\kappa\right)^2 - \phi\left(\frac{x_{t+1}}{k_{t+1}}-\kappa\right)\frac{x_{t+1}}{k_{t+1}} - \left(1-\delta_{t+1}\right)\right] \tag{25}$$

$$\mu c_t\frac{h_t}{1-h_t} = \pi_{h,t}\left(1-s_{k,t}\right)y_t \tag{26}$$

Equation (21) is the resource constraint. Equation (22) is the capital accumulation law. Equation (23) is the production function. Equation (24) is the first-order condition for the capital of the representative firm. Equation (25) is the Euler condition. Finally, equation (26) is the household condition for the optimal allocation of time.

We set $k_0 = x_0\left[(1+\eta)(1+\gamma)-(1-\delta_0)\right]^{-1}$, where γ and η are the calibrated values, $\delta_0 = 0.06$, which is around the economic depreciation rate of NIPA fixed assets and durable consumer goods in the 1950s, and x_0 equals the U.S. investment rate in year 1954, $x_0/y_0 = 0.2786$, times detrended output per capita in year 1954, $y_0 = 0.87453$. Here, the detrended output per capita at year t, y_t, is expressed relatively to the average detrended output per capita in the 1954–2017 period (e.g., $y_0 = 0.87453$ means that in year 1954, the detrended output per capita was 87.45% of the average detrended output per capita in the 1954 − 2017 period), and after calibrating the BGP, we have normalized $y = 1$; therefore, implicitly, we are assuming that the stationary level of detrended output per capita is the average value of this variable in the 1954 − 2017 period. After 2017, we assume that variables η_{t+1}, c_t, x_t, y_t, $s_{k,t}$, δ_t and h_t follow the following process:

$$j_t = j_T e^{-\lambda(t-T)} + j\left(1-e^{-\lambda(t-T)}\right)$$

where j_t is η_{t+1}, c_t, x_t, y_t, $s_{k,t}$, δ_t or h_t at period $t \geq T$, $T = 2017$ and j is the constant calibrated value above. We set $\lambda = 0.03$, which is around the speed of convergence estimated in most studies (see Barro and Sala-i-Martin, 1995). Our method allows us to compute converging paths of wedges from the initial period until infinity. In practice, we have computed 1000 periods. The time-varying wedges together are presented in Fig. 3. The primary features of the evolution of wedges are as follows: (1) from the beginning of 21st century until 2009, the capital efficiency wedge underwent a sharp decline. The decline in the capital efficiency wedge in 21st century was similar to its large decline in the 1970s. As a consequence of these two large declines, the capital efficiency wedge has declined by approximately 35% from the middle of the 1950s until 2017. (2) The labor efficiency wedge experienced a significant increase from the mid-1950s until the min-1960s and during the first decade of 21st century; however, it declined from the mid-1980s to the end of the 1990s and after the Great Recession (after 2010). (3) TFP increased from the mid-1950s to the early 1970s; however, it underwent a strong decline both in the 1970s and early years of 21st century; the decline is stronger in VES than in the CD. (4) The labor wedge slightly decreased until the mid-1970s, subsequently experienced an increase until the early 1980s, and remained roughly stable from the early 1980s, which then strongly increase until the end of the 1990s. It also increased after the Great Recession (after 2010); however, it decreased from the end of the 1990s, and in particular, during the Great Recession (2007–2010). The decline in this period is stronger in CD than in VES. (5) The investment wedge remained roughly stable until the 1970s, increased in the 1970s, and decreased in the 1980s. Its decline in the 1980s is higher in VES than in CD, and in VES, it continued to decrease until the Great Recession, whereas in CD, it remained roughly stable. (5) The resource constraint wedge remained roughly stable until the mid-1970s and experienced a sustained decline from the middle of the 1970s until the Great Recession, during which it increased significantly.

Remark. Average levels of the resource constraint wedge, labor wedge, and capital efficiency wedge have undergone a significant change from the beginning of the analyzed period and its end (see Fig. 3), which suggests that the BGP of the U.S. economy changed during the analyzed period. Therefore, it may be crucial to solve the nonlinear equilibrium conditions. The economic depreciation rate of capital also experienced a significant increase during the analyzed period; however, its evolution is not presented in a figure nor is the evolution of the population growth rate. Changes in the depreciation rate and population growth rate provoke changes in the endogenous variables in the same way that changes in the wedges do; hereafter, we ignore them because their impact on the endogenous variables was negligible.

6.2. Specification of the production function and the wedges

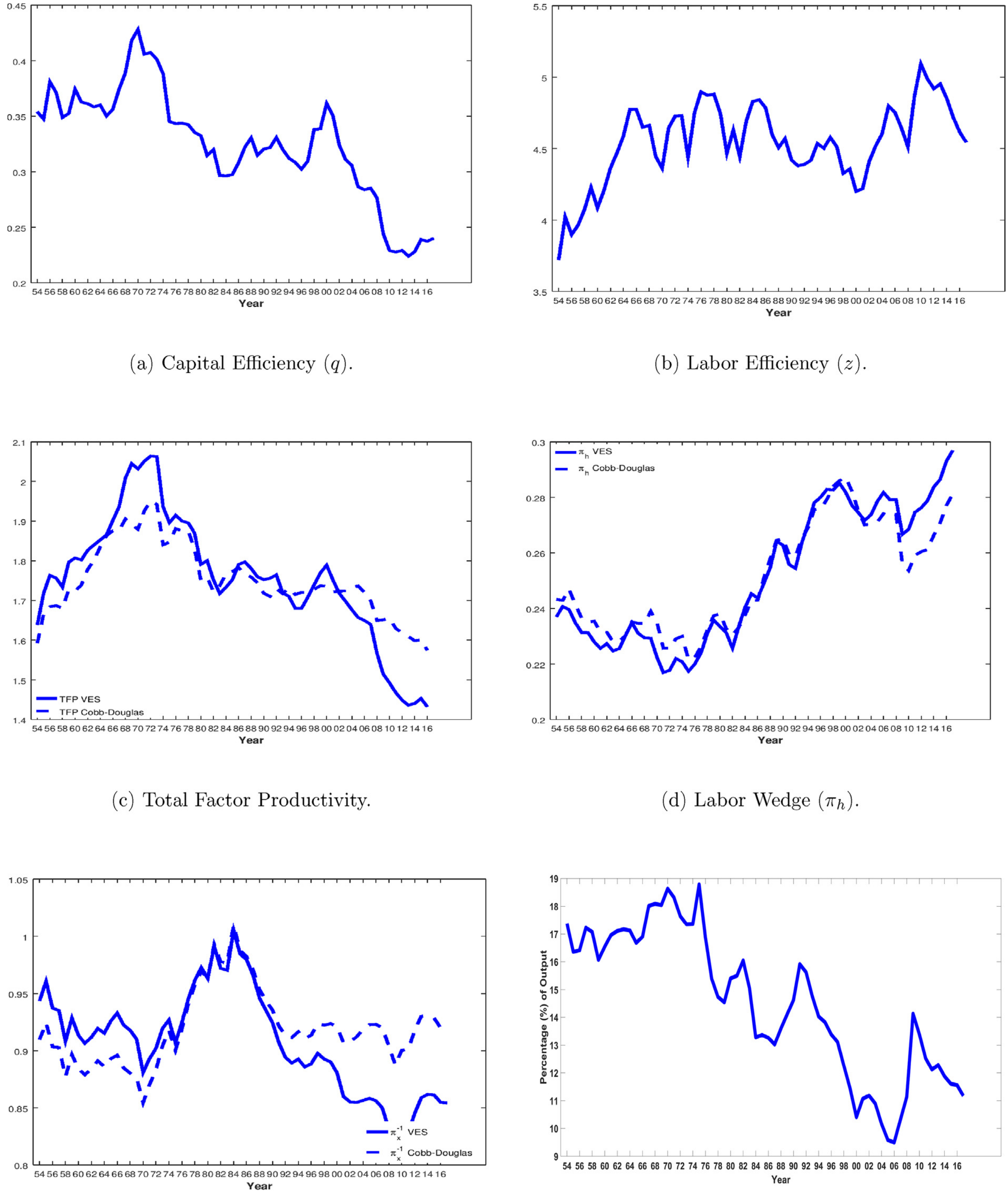
We have computed the labor and investment wedges under the production function with variable output elasticities for factors, (π_h, and π_x^{-1}), assuming that the output elasticities for labor and capital equal their observed income shares, and under the CD production function, assuming that output elasticities for capital and labor are constant, ($s_t = s$ and $1 - s_t = 1 - s$). It follows from the first order conditions (25) and (26) for labor and capital that the labor and investment wedges ($\widetilde{\pi}_h$ and $\widetilde{\pi}_x^{-1}$) computed under the CD assumption are $\widetilde{\pi}_{h,t} = \pi_{h,t}\frac{s_{h,t}}{1-s}$ and $\widetilde{\pi}_{x,t}^{-1} \simeq \pi_{x,t}^{-1}\frac{1-s_{h,t+1}}{s}$.[17] Therefore, if $s_{h,t}$ decreases, then $\widetilde{\pi}_h$ decreases relative to π_h whereas $\widetilde{\pi}_x^{-1}$ increases relative to π_x^{-1}.

After the end of the 1990s, and in particular, during the Great Recession (between 2007 and 2010), the U.S. labor share experienced a strong decline.[18] Therefore, around this time, the investment and labor wedges calculated with a VES production function and with a CD production function significantly begin to differ [see Fig. 3, panel (c) and panel (d)]. In particular, the sharp drop in the labor share is reflected in that the computed decline in the labor (investment) wedge under a CD specification is higher (lower) than its computed decline under a VES specification.

If there are constant returns to scale, the growth rate of TFP is $g_{A,t} \equiv s_t g_{q,t} + (1-s_t)g_{z,t} = g_{Y,t} - s_t g_{K,t} - (1-s_t)g_{H,t}$, which can be computed assuming the output elasticities for labor and capital are constants ($s_t = s$ and $\widetilde{g}_{A,t} = g_{Y,t} - s g_{K,t} - (1-s)g_{H,t}$) or assuming that the output elasticity for labor equals its observed income share ($1 - s_t = s_{h,t}$ and $\overline{g}_{A,t} = g_{Y,t} - \left(1-s_{h,t}\right)g_{K,t} - s_{h,t}g_{H,t}$). First, note that if g_q and g_z are moving in opposite directions, it might compute a low value for g_A, even if g_q, and g_z are experiencing large variations. According to our VES production function, this happened during the *Second Growth Slowdown* in which both efficiency wedges largely moved in opposite directions [see Fig. 3, panel (a) and panel (b)]. Therefore, to calculate $g_{A,t}$ ignoring $g_{q,t}$ and $g_{z,t}$ might lead to the wrong conclusion that changes in the efficiency wedges of the factors are not important in accounting for movements in output and labor. Second, if the labor share, s_h, goes down and the ratio of capital to worked hours is increasing, $g_{K,t} - g_{H,t}$, then $\overline{g}_{A,t}$ decreases relative to $\widetilde{g}_{A,t}$. As noted above, after the end of the 1990s, and particularly during the Great Recession (2007–2010), the U.S. labor wedge experienced a strong decline. Therefore, the efficiency wedge computed using a CD production function and the efficiency wedge implied by our VES specification differ significantly from the end of the 1990s. In particular, the decline in the efficiency wedge computed using a CD production function is lower than the decline in

[17] The relationship between $\widetilde{\pi}_x^{-1}$ and π_x^{-1} is not a very good approach if the labor share s_h is changing too much.

[18] The labor share also decreased in the 1970s, but its decline was not so sharp.



(a) Capital Efficiency (q). (b) Labor Efficiency (z).

(c) Total Factor Productivity. (d) Labor Wedge (π_h).

(e) Investment Wedge. (π_x^{-1}) (f) Resources Constraint Wedge.

Fig. 3. Wedges paths.

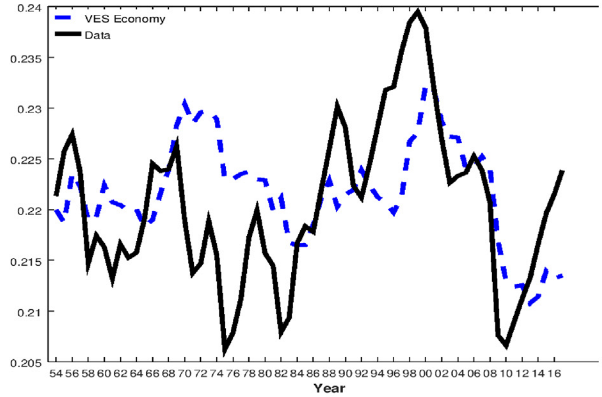
the efficiency wedge computed using a VES production function (see Fig. 3).[19]

Therefore, the large fall in the U.S. labor share after the end of the 1990s explains that after this time, the investment wedge, labor wedge, and the efficiency wedge (i.e., $q^{1-s_h}z^{1-s_h}$) computed using a VES specification of the production function, significantly differ from those computed using a CD production function.

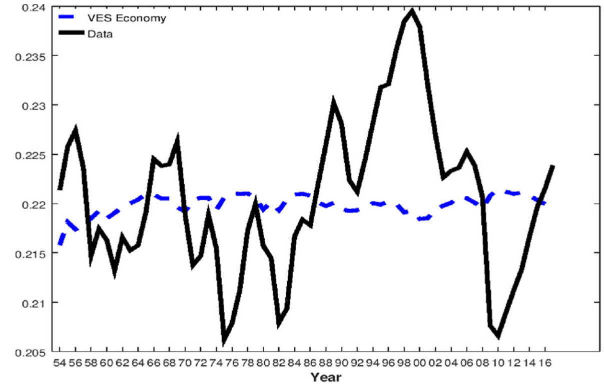
7. The U.S. economic growth 1954–2017

We simulate the model to assess the extent to which the evolution of the wedges can account for the evolution of output per capita, hours

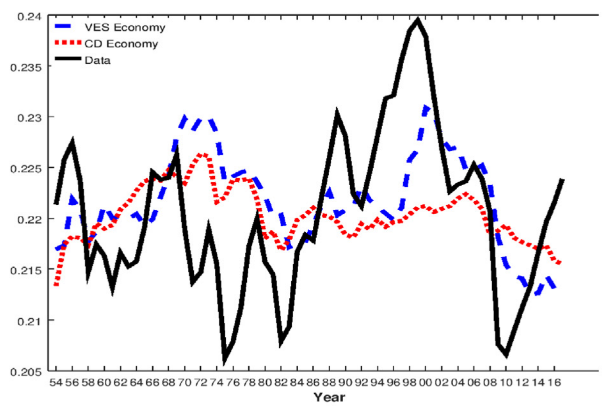
[19] They also significantly differ in the late 1960s and early 1970s, because in this period, the labor share experienced a strong swing.



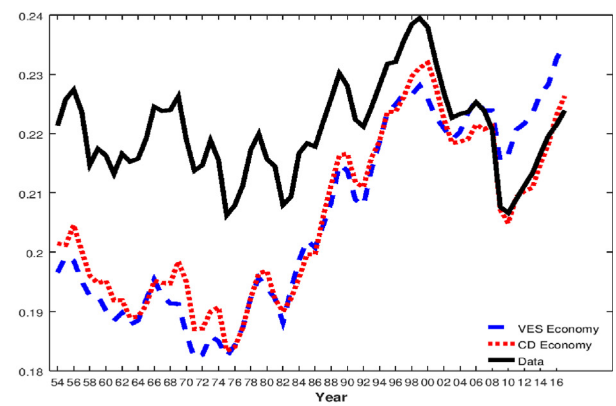
(a) q.



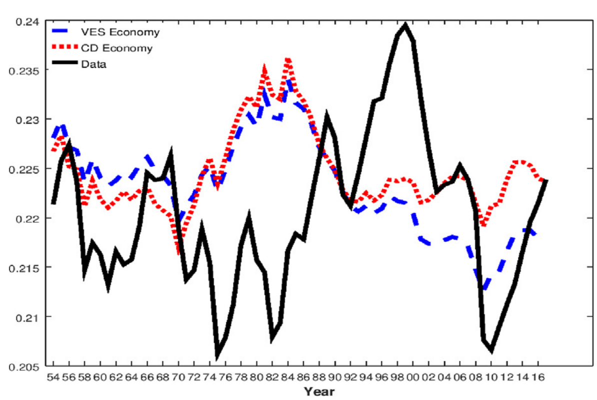
(b) z.



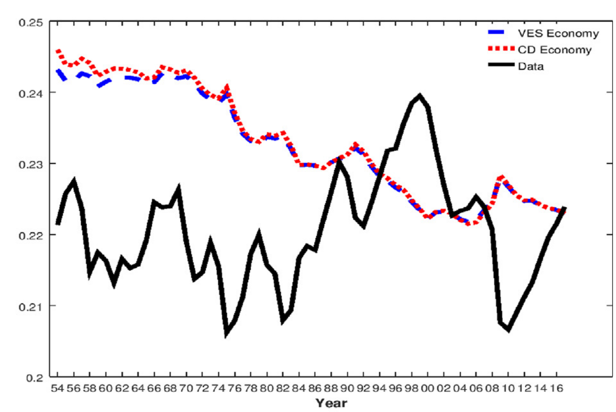
(c) q and z.



(d) π_h.



(e) π_x.

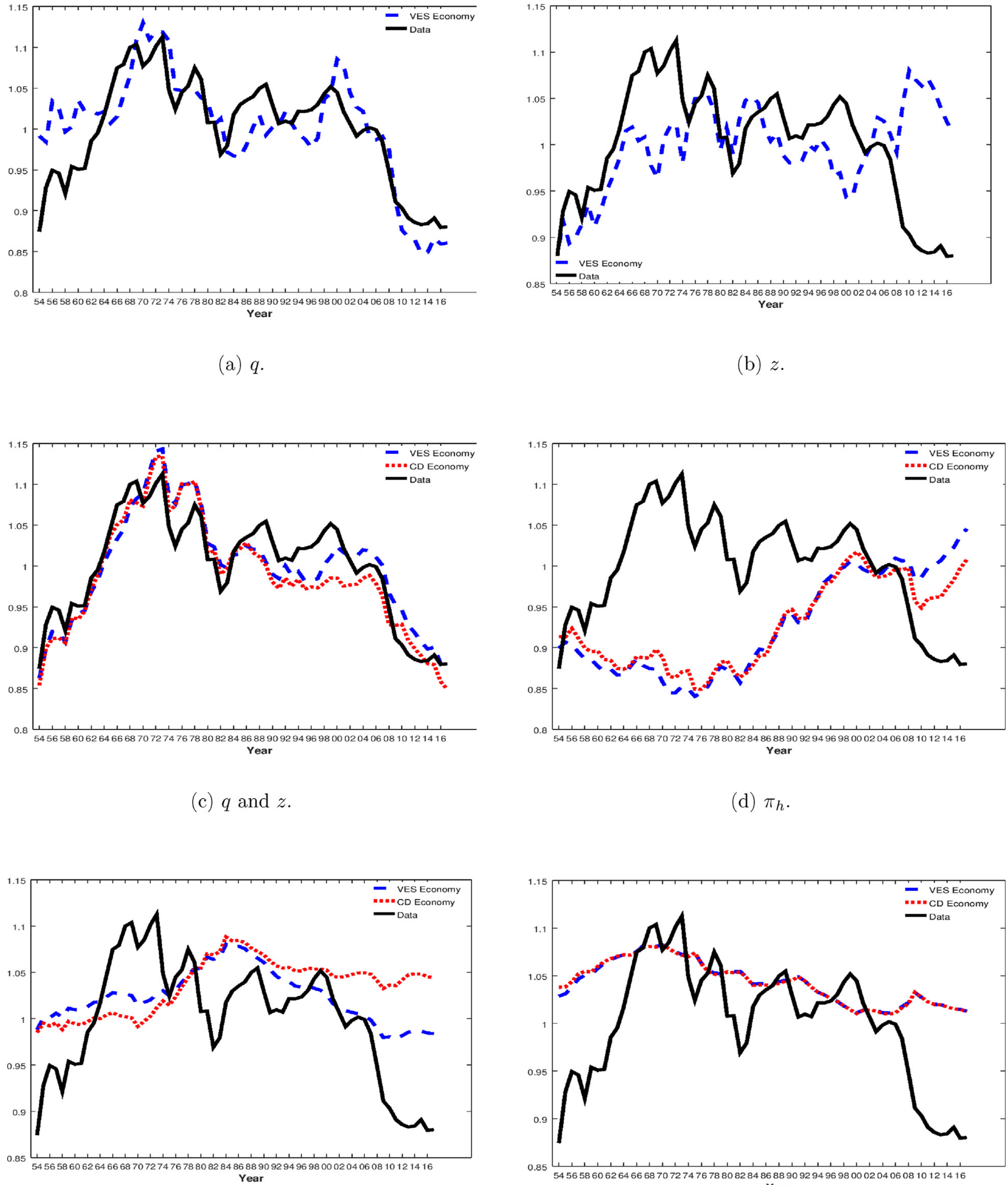


(f) g.

Fig. 4. Contribution of wedges to hours worked.

worked, and investment in the United States during 1954–2017. Ceteris paribus, the simulations of the model together with the corresponding observed variables (output, labor, and investment) are displayed in each panel of Figs. 4–6. Additionally, the evolution of detrended output per worked hour and the labor share together with their wedge-alone component due to the efficiency wedge in both the CD and VES cases is displayed in Fig. 7.

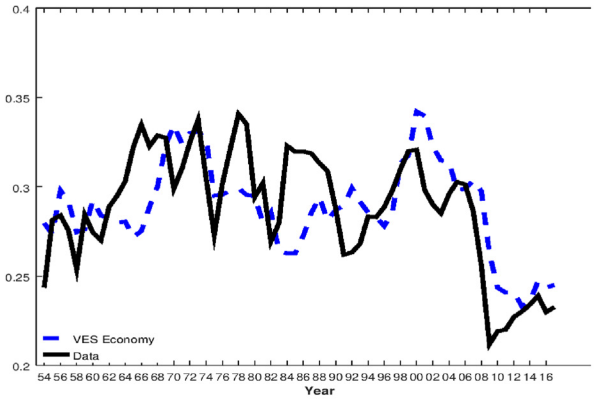
The model is simulated for both the calibrated VES and CD production functions. The observed variable is displayed with a solid line and its simulated paths are displayed with dashed-solid lines (VES) and pointed solid lines (CD). For example, in panel (d) of Fig. 4, the simulated paths of hours worked per capita (under both the VES and CD specification) are the result of simulating, given k_0, the equilibrium equation



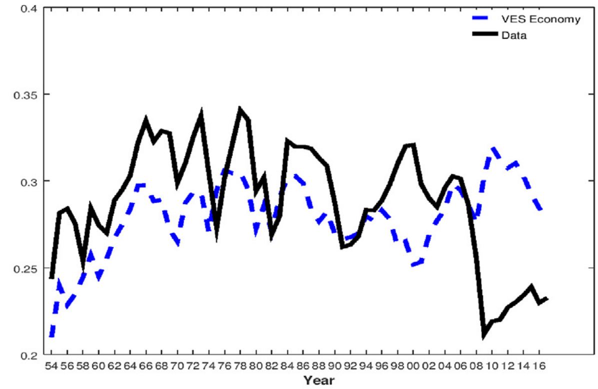
(a) q. (b) z. (c) q and z. (d) π_h. (e) π_x. (f) g.

Fig. 5. Contribution of wedges to output (detrended).

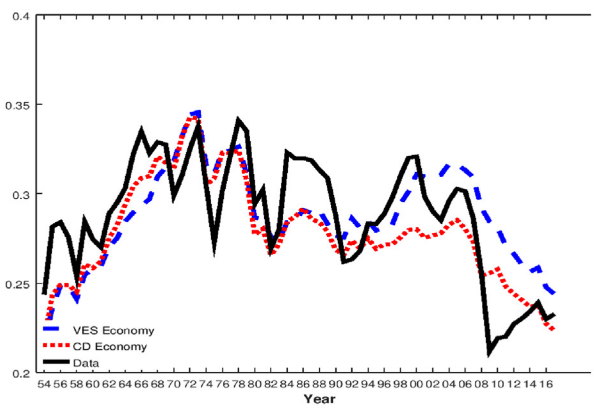
system (21)-(26), assuming that π_h follows the computed path above [displayed in Fig. 3, panel (d)], and the remaining wedges and both the depreciation and population growth rate remain in their steady values with $q_t = q$, $z_t = z$, $g_t = g$, $\pi_{x,t} = \pi_x$, $\eta_t = \eta$ and $\delta_t = \delta$. Thus, we can isolate the effect of each wedge on each variable. In particular, in the example, the effect of the labor wedge on the evolution of U.S. hours worked per capita in the 1954–2017 period. We term the variables simulated in this way the wedge-alone components of the observed variables. For the sake of accuracy, it must be pointed out that in each wedge-alone component is included a transitional component, because $k_0 \neq k$, but quantitatively it is not very significant. We will discuss this below. The growth rates of the wedge-alone components of variables



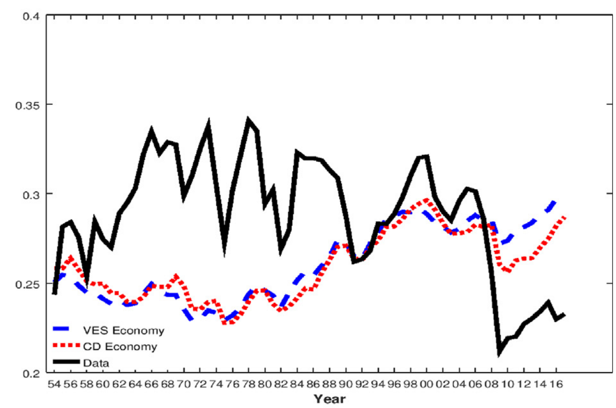
(a) q.



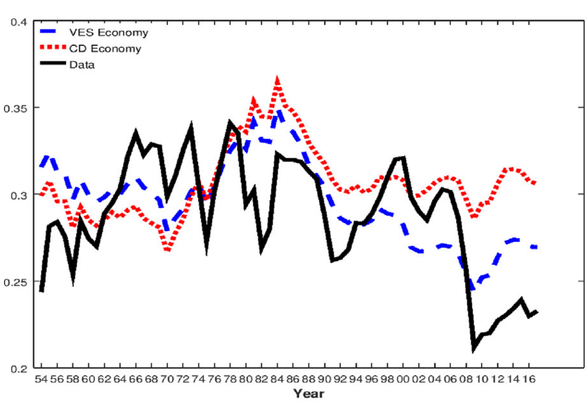
(b) z.



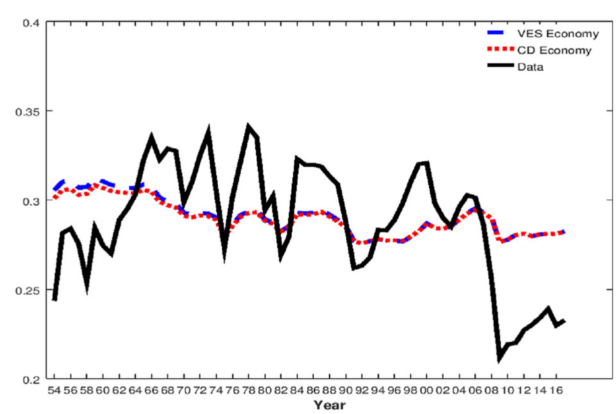
(c) q and z.



(d) π_h.



(e) π_x.



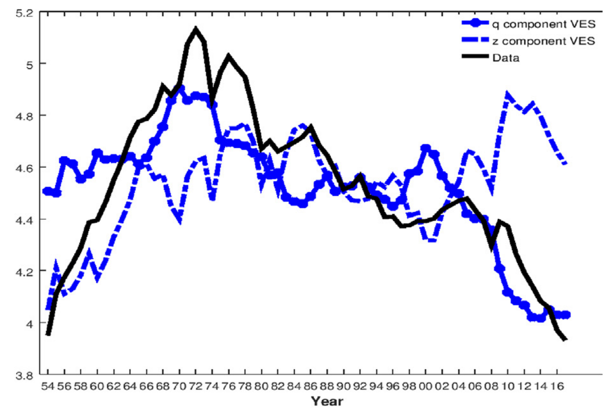
(f) g.

Fig. 6. Contribution of wedges to investment.

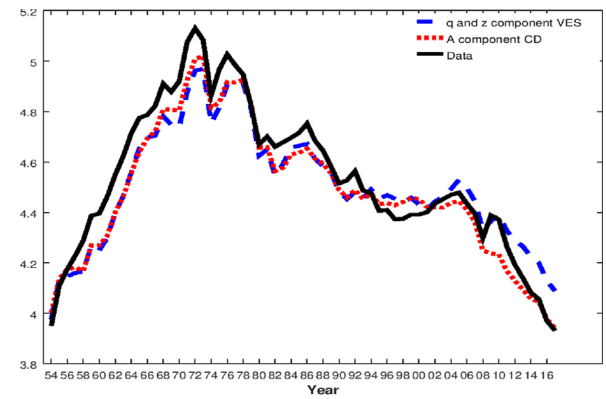
for the five subperiods in which we have divided the U.S. post-WWII growth are displayed in Table 2. In the VES case, we simulate the model jointly changing the capital and labor efficiency wedges to compare the results with the results obtained in the CD case.

To summarize the results, we define the σ-statistic, which captures how closely a particular component tracks the changes in the underlying variable. The σ-statistic for detrended output per capita of wedge i is as follows

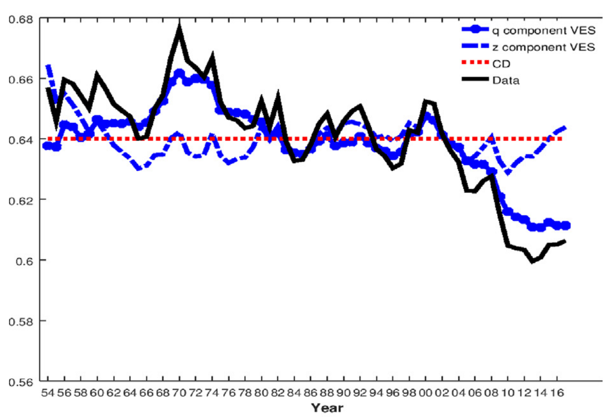
$$\sigma_i^y = \frac{1/Var_i(y_t - y_{i,t})}{\sum_j (1/Var_j(y_t - y_{j,t}))}$$



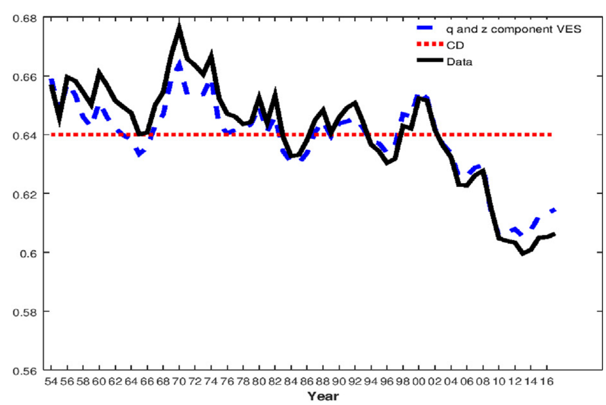
(a) Output per hour worked (Detrended).



(b) Output per hour worked (Detrended).



(c) Labor share.



(d) Labor share.

Fig. 7. Contribution of efficiency wedges.

Table 2
Wedge-alone components, growth rate (%).

	Data	VES						CD			
		q	z	q and z	π_x	π_h	g	A	π_x	π_h	g
						Long Boom					
h	2.21	3.79	1.76	5.09	−2.10	−2.70	−0.49	5.01	−2.90	−1.49	−1.31
y	26.21	11.85	11.85	25.44	3.71	−2.85	5.09	26.12	1.59	−1.71	4.06
x	34.38	15.62	29.52	45.75	−6.10	−2.85	−2.51	45.43	−6.11	−1.89	−1.72
						First Growth Slowdown					
h	−8.10	−3.14	−0.14	−3.36	3.09	−1.64	−3.40	−3.23	5.58	−4.26	−3.48
y	−12.19	−8.67	1.28	−7.48	3.81	−1.89	−2.45	−8.13	6.79	−3.79	−2.40
x	−17.73	−11.60	−0.47	−12.34	11.64	−2.77	−5.10	−16.24	22.76	−7.56	−4.53
						Great Moderation					
h	15.16	2.91	−0.03	2.92	−3.78	21.24	−4.41	1.95	−3.66	21.64	−4.55
y	8.51	3.03	−2.04	0.93	−3.13	17.33	−3.78	−0.44	−1.41	17.04	−3.76
x	18.82	11.13	−2.06	9.23	−13.05	23.37	−0.18	5.28	−10.14	25.55	−0.01
						Second Growth Slowdown					
h	−13.72	−6.45	1.01	−5.01	−3.25	−5.10	1.47	−0.79	−1.23	−11.35	1.51
y	−14.12	−16.00	11.39	−6.43	−4.89	−1.95	1.27	−5.77	−1.67	−6.16	1.30
x	−31.51	−23.32	20.53	−6.64	−12.42	−6.21	−1.56	−7.86	−4.92	−12.94	−1.61
						Great Recession Recovery					
h	7.21	0.14	−0.68	−1.05	1.70	7.47	−1.45	−1.58	1.27	8.91	−1.51
y	−2.63	−1.96	−5.15	−6.97	0.42	5.09	−1.24	−7.56	0.87	5.10	−1.26
x	4.85	0.07	−11.05	−11.91	7.06	8.50	1.15	−11.81	4.38	10.08	1.13

Table 3
σ-statistics.

Variable	VES									CD			
	q	z	π_x	π_h	g	q and z	π_x	π_h	g	A	π_x	π_h	g
Entire Sample													
h	0.33	0.26	0.20	0.10	0.12	0.43	0.27	0.13	0.17	0.35	0.27	0.24	0.15
y	0.38	0.11	0.25	0.05	0.21	0.62	0.18	0.04	0.16	0.67	0.11	0.06	0.16
y/h	0.36	0.14	0.18	0.17	0.15	0.76	0.08	0.08	0.07	0.89	0.03	0.04	0.04
x	0.29	0.14	0.26	0.10	0.21	0.35	0.30	0.11	0.24	0.52	0.16	0.11	0.21
1-s_k	0.60	0.11	0.09	0.12	0.08	0.80	0.07	0.08	0.05	-	-	-	-
Long Boom													
h	0.19	0.13	0.21	0.33	0.15	0.20	0.24	0.38	0.18	0.16	0.24	0.39	0.21
y	0.17	0.45	0.14	0.08	0.16	0.93	0.03	0.02	0.03	0.93	0.02	0.02	0.03
y/h	0.15	0.43	0.16	0.09	0.16	0.84	0.06	0.03	0.06	0.82	0.06	0.04	0.07
x	0.13	0.54	0.10	0.11	0.11	0.73	0.09	0.09	0.09	0.76	0.08	0.07	0.08
1-s_k	0.26	0.17	0.16	0.26	0.15	0.59	0.12	0.19	0.11	-	-	-	-
First Growth Slowdown													
h	0.27	0.19	0.12	0.23	0.19	0.32	0.16	0.29	0.23	0.19	0.07	0.57	0.16
y	0.42	0.12	0.09	0.14	0.22	0.62	0.08	0.12	0.19	0.57	0.06	0.17	0.20
y/h	0.30	0.15	0.15	0.25	0.14	0.69	0.09	0.14	0.08	0.76	0.06	0.12	0.06
x	0.18	0.22	0.11	0.21	0.28	0.33	0.12	0.24	0.31	0.32	0.08	0.27	0.33
1-s_k	0.44	0.14	0.13	0.18	0.11	0.72	0.09	0.12	0.07	-	-	-	-
Great Moderation													
h	0.16	0.10	0.05	0.61	0.07	0.17	0.06	0.69	0.08	0.17	0.08	0.66	0.10
y	0.25	0.17	0.22	0.14	0.22	0.41	0.23	0.14	0.22	0.30	0.32	0.14	0.23
y/h	0.13	0.37	0.12	0.23	0.15	0.56	0.11	0.20	0.13	0.60	0.07	0.21	0.12
x	0.12	0.26	0.18	0.13	0.31	0.32	0.19	0.15	0.34	0.38	0.21	0.12	0.30
1-s_k	0.27	0.27	0.16	0.17	0.13	0.51	0.17	0.18	0.14	-	-	-	-
Second Growth Slowdown													
h	0.38	0.10	0.19	0.24	0.09	0.36	0.24	0.29	0.11	0.06	0.06	0.85	0.04
y	0.41	0.04	0.29	0.16	0.10	0.48	0.28	0.15	0.10	0.40	0.17	0.33	0.10
y/h	0.03	0.03	0.33	0.20	0.41	0.58	0.15	0.09	0.18	0.21	0.29	0.10	0.40
x	0.42	0.05	0.24	0.15	0.13	0.29	0.33	0.20	0.18	0.28	0.23	0.30	0.18
1-s_k	0.56	0.20	0.10	0.06	0.08	0.97	0.01	0.01	0.01	-	-	-	-
Great Recession Recovery													
h	0.02	0.02	0.03	0.91	0.02	0.02	0.03	0.93	0.02	0.05	0.09	0.82	0.05
y	0.30	0.03	0.12	0.02	0.53	0.05	0.17	0.02	0.75	0.04	0.13	0.02	0.80
y/h	0.16	0.43	0.14	0.18	0.10	0.68	0.11	0.14	0.07	0.63	0.08	0.22	0.07
x	0.10	0.02	0.56	0.15	0.17	0.02	0.62	0.17	0.19	0.03	0.63	0.12	0.22
1-s_k	0.26	0.06	0.26	0.12	0.29	0.24	0.29	0.13	0.33	-	-	-	-

where $y_{i,t}$ is the wedge-alone component of output due to wedge i and $Var_i\left(y_t - y_{i,t}\right)$ is the variance of the error (i.e., the variance of the difference between the variable and the wedge-alone component). The σ-statistic measures how each wedge-alone component accurately fits the fluctuations of each variable around its average. The σ-statistic does not consider differences in levels between components and variables.[20] The statistic lies in $[0, 1]$, sums to one across the five wedges (four under the CD assumption) and reaches its maximum value of 1 when a particular output component tracks output perfectly.

We compute similar statistics for hours worked per capita, detrended output per capita, and detrended investment per capita. We compute the σ-statistics for the 1954–2017 period under the VES and CD assumptions and for the five subperiods described in the introductory section. The σ -statistics are displayed in Table 3. In the VES case, we compute the σ-statistics in the following two ways: 1. computing the wedge-alone components due to each wedge and then computing the σ -statistics of each efficiency wedge and the other wedges and 2. computing the wedge-alone components due to both efficiency wedges together and then computing the σ-statistics of both efficiency wedges together and the other wedges. We do so to compare them with the CD case.

Hours worked per capita did not display any significant increasing or decreasing trend between 1954 and 2017 (see Fig. 4). In both the VES and CD cases, two forces worked in opposite directions. On the one hand, the fall in the resource constraint wedge pushed hours worked per capita down. On the other hand, the increase in the labor wedge pushed hours worked per capita up [see Fig. 4, panels (d) and (f)].

In both the VES and CD cases, the efficiency wedges are the main forces driving changes in hours worked, output, and investment between 1954 and 2017. As Table 3 shows, in the VES (resp. CD) case, the σ-statistics for hours worked, output, and investment of both efficiency wedges are 0.43, 0.62, and 0.35 (resp. 0.35, 0.67, and 0.52). However, to accurately adjust the data, we need the other wedges, especially in accounting for the evolution of hours worked per capita and detrended investment per capita. Moreover, the role played by the wedges differs along the periods in which we have divided the entire sample.

In both the CD and VES cases, the increase in the efficiency wedges (especially, the labor efficiency wedge in the VES case) accurately accounts for the increase in detrended output per capita and detrended investment per capita in the *Long Boom* during 1954–1969 [see Figs. 5

[20] The σ-statistic is different from the ϕ statistic proposed by Brinca et al. (2020) because whereas Brinca et al. (2020) use the sum of the quadratic errors to build their statistic, we use the variance of the errors. Therefore, ϕ-statistic takes into account the level differences between the observed variables and the wedge-alone components. Both statistics yield the same results if the averages of the variable and its wedge-alone component are equal. Brinca et al. (2016) normalize the simulated and observed variables so that the results yielded by our σ-statistic must not be very different from their ϕ-statistic.

and 6, panels (a), (b) and (c)]. As Table 3 shows, the σ-statistic for output (resp. investment) of the efficiency wedge in the CD case is 0.93 (resp. 0.76), and the σ-statistic for output (resp. investment) of the efficiency wedge in the CD case is 0.93 (resp. 0.76) and the σ-statistic for output (resp. investment) of both efficiency wedges in the VES case is 0.93 (resp. 0.73). In the VES case, the wedge-alone component of output (resp. investment) due to the labor efficiency wedge performs a better adjustment of the changes in detrended output (resp. investment) per capita during the *Long Boom* (σ-statistic 0.45 for output and 0.54 for investment) than the wedge-alone component of output (resp. investment) due to the capital efficiency wedge (σ-statistic 0.17 for output and 0.13 for investment). As Table 2 shows, during 1954–1969, the detrended output (resp. investment) per capita grew by 26.21% (resp. 34.38%), and the wedge-alone component of output (resp. investment) due to both efficiency wedges increased by 25.44% (resp. 45.75%) in the VES case (26.12% and 45.43% in the CD case).

Both investment and labor wedges worsen during the *Long Boom* in 1954–1969 (see Fig. 3, panels 8d) and 8e)) and contribute to moderate the economic expansion of this period. As Table 2 shows, in the VES, the wedge-alone component of hours worked due to the labor (investment) wedge decreased by 2.70% (2.10%), the wedge-alone component of investment due to the labor (investment) wedge decreased by 2.85% (6.10%), and the wedge-alone component of output due to the labor (investment) wedge decreased by 2.85% (−3.71%). The results in the CD case are similar.

In both the VES and CD cases, the primarily responsibility of the subsequent growth slowdown in 1969–1982 lies with the decline in efficiency wedges (in particular, of the capital efficiency wedge in the VES case) [see Figs. 4–6, panels (a), (b), and (c)]. As Table 2 shows, under the VES assumption, in the *First Growth Slowdown* (between 1969 and 1982), the wedge-alone component of output due to the capital efficiency wedge decreased by 8.67% (its σ -statistic is 0.42, see Table 3, and the σ-statistic of both efficiency wedges is 0.62), and under the CD assumption, the wedge-alone component of output due to the efficiency wedge decreased by 8.13% (as Table 3 shows, its σ-statistic is 0.57). In the *First Growth Slowdown*, detrended output per capita decreased by 12.19%. Detrended investment per capita experiences a significant decrease in 1969–1982 (it decreased by 17.73%) but with significant oscillations (see Fig. 6). In both the VES and CD cases, the drop in detrended investment per capita was mostly driven by the decrease in the efficiency wedges (capital efficiency wedge in the VES case). As Table 2 shows, in the VES case, the wedge-alone component of investment due to the capital efficiency wedge decreased by 11.60% and the wedge-alone component of investment due to the labor efficiency wedge decreased by 0.47%, while in the CD case, the wedge-alone component of investment due to the efficiency wedge decreased by 16.24%. In the VES case, the wedge-alone component of investment due to the labor efficiency wedge accounts for a good part of the oscillations of detrended investment per capita during the *First Growth Slowdown*, which is reflected in the value of the σ-statistic for investment of the labor efficiency wedge, at 0.22, whereas the σ-statistic for investment of the capital efficiency wedge is 0.18. In the VES case, the σ-statistic for investment of both efficiency wedges is higher at 0.33, whereas in the CD case, the σ-statistic for the investment of the efficiency wedge is 0.32 (see Table 3).

In the VES case the evolution of hours worked per capita during the *First Growth Slowdown* was mostly influenced by the capital efficiency wedge, whereas in the CD case, the evolution of hours worked per capita was mostly driven by the labor wedge even if the efficiency wedge also played a significant role. As Table 2 shows, in the VES case, the decrease in the wedge-alone component of hours worked due to the capital efficiency wedge between 1969 and 1982 was higher than the decrease in the wedge-alone component due to the labor wedge (3.14% and 1.64%, respectively). However, in the CD case, the decrease in the wedge-alone components of hours worked due to the efficiency wedge and due to the labor wedge was more similar (3.23% and 4.26%, respectively). In this period, hours worked per capita dropped by 8.1%. In the VES case, the σ-statistic for hours worked of the capital efficiency wedge is 0.27, that of the labor efficiency wedge is 0.19, and of both efficiency wedges is 0.32, whereas that of the labor wedge is 0.29 (see Table 3). However, in the CD case, the σ-statistic for hours worked of the efficiency wedge is 0.19 and that of the labor wedge is higher, at 0.57. The high value of the σ-statistic in the CD case reveals that in this case, the labor wedge played a significant role in accounting for the evolution of the hours worked per capita during the *First Growth Slowdown*.

In both the VES and CD cases, the increase in the investment wedge in the 1970s contributed to reduce the growth slowdown and the downsizing of hours worked per capita [see Figs. 4–6, panel (e) and Table 2]. As Table 2 shows, in the VES case (CD case) the wedge-alone components of hours worked, output, and investment due to the investment wedge increased by 3.09%, 3.81%, and 11.64% (5.58%, 6.79%, and 22.76%) during 1969–1982.

In the VES case, the decline in hours worked per capita and the growth slowdown from the end of the past century until 2010 were mainly driven by the fall in the capital efficiency wedge, whereas the labor wedge played a significant but secondary role [see Figs. 4–6, panels (a) and (d)]. In the VES case, the σ-statistics for hours worked, output, and investment of the capital efficiency wedge are 0.38, 0.41, and 0.42, whereas the same σ-statistics of the labor wedge are 0.24, 0.16, and 0.15 (see Table 3). As Table 2 shows, the wedge-alone components of hours worked, output and investment due to the capital efficiency wedge decreased by 6.45%, 16%, and 23.32% during 1999–2010, whereas the hours worked per capita, detrended output per capita, and detrended investment per capita fell by 13.72%, 14.12%, and 31.51%.

However, in the CD case, in the *Second Growth Slowdown* (during 1999–2010), the main role corresponded to the labor wedge even if the efficiency wedge also played a prominent role, especially in accounting for the evolution of detrended output per capita and detrended investment per capita [see Figs. 4–6, panels (c) and (d)]. In the CD case, the σ-statistics for hours worked, output, and investment of the labor wedge are 0.85, 0.33, and 0.30, respectively, whereas the same σ-statistics of the efficiency wedge are 0.06, 0.40, and 0.28, respectively (see Table 3). As Table 2 shows, the wedge-alone components of hours worked, output, and investment due to the labor (resp. efficiency) wedge decreased by 11.35%, 6.16%, and 12.94%, respectively, (resp. 0.79%, 5.77%, and 7.86%) during 1999–2010.

During the *Second Growth Slowdown* and particularly in the VES case, the investment wedge strengthened the fall of hours worked per capita, detrended output per capita, and detrended investment per capita [see Figs. 4–6, panel (e), as well as Table 2]. As Table 2 shows, in the VES case (resp. CD case), the wedge-alone components of hours worked, output, and investment due to the investment wedge decreased by 3.25%, 4.89%, and 12.42%, respectively, (resp. 1.23%, 1.67%, and 4.92%) during 1999–2010. However, in the VES case, the labor efficiency wedge contributed to reduce the growth slowdown and the fall in hours worked per capita during the *Second Growth Slowdown*, whereas its impact on the decrease in output and investment growth and hours worked was negligible during the *First Growth Slowdown*. As Table 2 shows, in the VES case, the wedge-alone components of hours worked, output, and investment due to the labor efficiency wedge increased by −0.14%, 1.28%, and −0.47%, respectively, during 1969–1982, and by 1.01%, 11.39%, and 20.53%, respectively, during 1999–2010.

In both the VES and CD cases, the labor wedge was the main force driving the recovery of growth and hours worked per capita in the 1980s and 1990s and after the Great Recession [see Figs. 4–6, panel (d)]. As Table 2 shows, in the VES case (CD case) the wedge-alone components of hours worked, output, and investment due to the labor wedge increased by 21.24%, 17.33%, and 23.37% (resp. 21.64%, 17.04%, and 25.55%), respectively, during 1982–1999 and by 7.47%, 5.09%, and 8.50% (resp. 8.91%, 5.10%, and 10.08%), respectively, during 2010–2017. Hours worked per capita, detrended output per capita, and detrended investment per capita increased by 15.16%, 8.51%, and

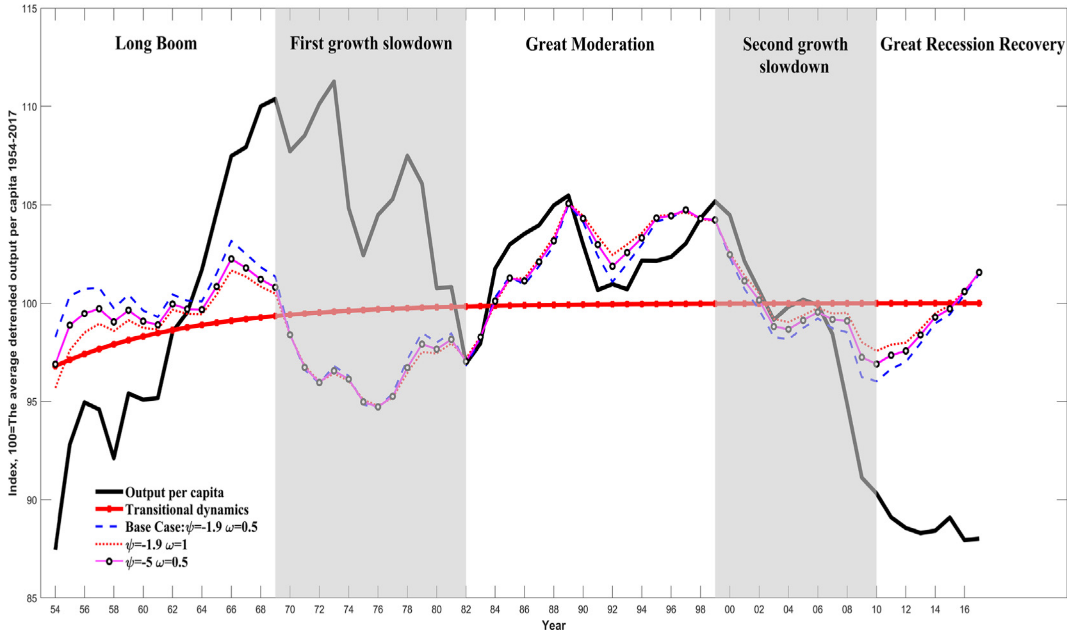


Fig. 8. Trajectory from the model with all wedges except efficiency for different values of ψ and ω.

18.82%, respectively, during 1982–1999 and by 7.21%, −2.63% and 4.85%, respectively, during 2010–2017.

The investment wedge's fall in the 1980s contributed to reduce the recovery of output per capita, investment, and hours worked in the 1980s and 1990s [see Figs. 4–6, panel (e) and Table 2]. As Table 2 shows, in the VES case (CD case) the wedge-alone components of hours worked, output, and investment due to the investment wedge decreased by 3.78%, 3.13%, and 13.05%, respectively, (resp. 3.66%, 1.41%, and 10.14%) during 1982–1999.

In the VES case, the fall in the labor efficiency wedge also contributed to reduce recovery of output, investment, and labor both after the *First Growth Slowdown* and the *Second Growth Slowdown* [see Figs. 4–6, panel (b) and Table 2]. As Table 2 shows, in the VES case the wedge-alone components of hours worked, output, and investment due to the labor efficiency wedge decreased by 0.03%, 2.04%, and 2.06%, respectively, during 1982–1999 and by 0.68%, 5.15%, and 11.05%, respectively, during 2010–2017. In the CD case, the recovery of output, investment, and labor after the *Second Growth Slowdown* was reduced because of the decline in the efficiency wedge [see Figs. 4–6, panel (b) and Table 2]. As Table 2 shows, in the CD case the wedge-alone components of hours worked, output, and investment due to the efficiency wedge decreased by 1.58%, 7.56%, and 11.81%, respectively, during 2010–2017.

Productivity and labor share The evolution of detrended output per worked hour and the labor share with their wedge-alone components due to the efficiency wedges in both the CD and VES cases is displayed in Fig. 7. For the effects of the wedges on the evolution of these variables, we mention only three points. First, in the VES and CD cases, the efficiency wedges accurately account for the evolution of the U.S. output per worked hour during 1954–2017 [see Fig. 7, panel (b)]. In particular, the σ-statistic for productivity of the efficiency wedge in the CD case is 0.89 and that for the productivity of both efficiency wedges in the VES case is 0.83. Second, in the VES case, the efficiency wedges accurately account for the evolution of the U.S. labor share during 1954–2017 [see Fig. 7, panel (d)]. In particular, the σ -statistic for the labor share of both efficiency wedges is 0.80. Third, in the VES case, the wedge-alone components of productivity and labor share due to the capital efficiency wedge mostly account for the changes in these variables and not the wedge-alone components due to the labor efficiency wedge [see Fig. 7, panel (a) and (c)]. In particular, in the VES case, the σ-statistic for productivity (the labor share) of the capital efficiency wedge is 0.36 (0.60) and that of the labor efficiency wedge is 0.14 (resp. 0.11).

Robustness In Fig. 8, we display both the observed output per worker and the components of output per worker for all wedges jointly, except the efficiency wedges, in three parametric cases. One case is the baseline, another implies a CES production function because $\omega = 1$, and another case implies a high degree of complementarity between the productive factors because $\psi = -5$. The σ-statitics of the wedges in the three cases are displayed in Table 4. As argued previously, the labor wedge and the investment wedge estimated in the three cases are identical; however, both the labor and the capital efficiency wedges are different. As can be seen in Fig. 8 and Table 4, the three cases give very similar results. (1) Recoveries of the 1980s and post-Great Recession are mainly driven by the labor wedge; (2) both the first and second productivity slowdowns are mainly driven by the decline in the capital efficiency wedge even if the labor wedge played a significant but secondary role; and (3) the fast growth of output per capita during the *Long Boom* was mainly driven by the labor efficiency wedge.

Transitional dynamics In Fig. 8, we display the transitional component of output per capita (i.e., the simulated path of output per capita departing from k_0 assuming that all wedges take their BGP values). Its quantitative importance for the results is negligible, except in accounting for a little part of the fast growth during the *Long Boom*.

8. Conclusion

We performed a growth accounting exercise for the U.S. by using the deterministic version of the neoclassical growth model. In this framework, we compute five wedges that reflect distortions in the equilibrium conditions of the model and that allow for the matching of the theory and data. We apply it to measure the wedges in the U.S. economy for the 1954–2017 period. The model is simulated to assess the contribution of the wedges to the U.S. postwar economic growth.

To perform our growth accounting, we make two alternative technology assumptions. On the one hand, we assume the usual CD production function, which displays constant output elasticities for factors. This technological assumption implies that the fluctuations in the labor share reflect frictions distorting the labor demand. These distortions are reflected in the labor wedge. On the other hand, we assume a VES production function that displays variable output elasticities for factors.

Table 4
σ-statistics for different values of ψ and ω.

Variable	Base Case					$\psi = -1.9\ \omega = 1$					$\psi = -5\ \omega = 0.5$				
	q	z	π_x	π_h	g	q	z	π_x	π_h	g	q	z	π_x	π_h	g
								Entire Sample							
h	0.33	0.26	0.20	0.10	0.12	0.27	0.30	0.22	0.09	0.12	0.29	0.29	0.21	0.09	0.12
y	0.38	0.10	0.25	0.05	0.21	0.31	0.30	0.18	0.04	0.17	0.38	0.22	0.18	0.04	0.17
y/h	0.36	0.13	0.18	0.17	0.16	0.11	0.64	0.09	0.08	0.08	0.20	0.41	0.13	0.13	0.12
x	0.29	0.14	0.26	0.10	0.21	0.24	0.29	0.22	0.08	0.17	0.25	0.25	0.23	0.08	0.18
1-s_k	0.61	0.10	0.09	0.12	0.08	0.42	0.10	0.14	0.26	0.09	0.50	0.10	0.12	0.19	0.09
								Long Boom							
h	0.19	0.14	0.20	0.32	0.15	0.22	0.15	0.20	0.30	0.12	0.23	0.15	0.20	0.29	0.14
y	0.15	0.52	0.12	0.07	0.14	0.21	0.46	0.11	0.06	0.16	0.18	0.51	0.11	0.06	0.14
y/h	0.11	0.59	0.12	0.07	0.12	0.03	0.88	0.03	0.02	0.03	0.06	0.79	0.06	0.03	0.06
x	0.13	0.55	0.10	0.11	0.10	0.24	0.42	0.10	0.13	0.10	0.20	0.49	0.10	0.12	0.10
1-s_k	0.22	0.30	0.14	0.22	0.13	0.10	0.21	0.09	0.53	0.07	0.13	0.23	0.13	0.40	0.11
								First Growth Slowdown							
h	0.26	0.19	0.12	0.23	0.19	0.26	0.19	0.14	0.21	0.20	0.27	0.20	0.13	0.22	0.19
y	0.43	0.11	0.09	0.15	0.22	0.68	0.09	0.05	0.06	0.11	0.66	0.09	0.05	0.07	0.12
y/h	0.31	0.14	0.16	0.25	0.15	0.19	0.43	0.11	0.15	0.11	0.26	0.29	0.13	0.19	0.12
x	0.18	0.22	0.11	0.21	0.28	0.40	0.17	0.10	0.13	0.21	0.32	0.20	0.10	0.15	0.23
1-s_k	0.44	0.13	0.14	0.18	0.11	0.22	0.06	0.25	0.36	0.12	0.30	0.07	0.20	0.31	0.12
								Great Moderation							
h	0.16	0.10	0.05	0.61	0.07	0.12	0.07	0.04	0.73	0.04	0.13	0.08	0.05	0.69	0.05
y	0.25	0.17	0.22	0.14	0.22	0.46	0.10	0.19	0.11	0.14	0.41	0.12	0.19	0.11	0.16
y/h	0.13	0.36	0.12	0.23	0.15	0.03	0.87	0.03	0.04	0.03	0.05	0.73	0.06	0.09	0.07
x	0.12	0.26	0.18	0.14	0.31	0.21	0.19	0.20	0.13	0.27	0.18	0.21	0.20	0.13	0.28
1-s_k	0.27	0.27	0.16	0.17	0.13	0.13	0.24	0.22	0.21	0.20	0.17	0.25	0.20	0.22	0.17
								Second Growth Slowdown							
h	0.38	0.10	0.19	0.24	0.09	0.36	0.15	0.21	0.18	0.10	0.34	0.14	0.21	0.21	0.10
y	0.41	0.04	0.29	0.16	0.10	0.60	0.08	0.16	0.09	0.07	0.68	0.05	0.14	0.08	0.05
y/h	0.03	0.03	0.33	0.20	0.41	0.17	0.30	0.19	0.14	0.20	0.12	0.13	0.27	0.17	0.30
x	0.42	0.05	0.24	0.15	0.13	0.34	0.13	0.23	0.15	0.15	0.37	0.10	0.23	0.15	0.15
1-s_k	0.56	0.20	0.10	0.06	0.08	0.49	0.18	0.18	0.05	0.10	0.54	0.18	0.14	0.05	0.09
								Great Recession Recovery							
h	0.02	0.02	0.03	0.91	0.02	0.05	0.09	0.07	0.75	0.04	0.03	0.04	0.04	0.87	0.02
y	0.30	0.03	0.12	0.02	0.53	0.25	0.05	0.17	0.02	0.52	0.32	0.04	0.14	0.02	0.49
y/h	0.16	0.43	0.14	0.18	0.10	0.02	0.89	0.03	0.03	0.02	0.05	0.78	0.06	0.07	0.04
x	0.10	0.02	0.56	0.15	0.17	0.09	0.02	0.60	0.18	0.11	0.10	0.02	0.58	0.17	0.13
1-s_k	0.26	0.06	0.26	0.12	0.29	0.54	0.02	0.11	0.03	0.30	0.49	0.03	0.15	0.05	0.29

Under this technological assumption, changes in the factor shares are driven by changes in output elasticities for factors, and the labor wedge exclusively reflects frictions distorting the labor supply. We argued that the measure of both investment and labor wedges crucially depends on if factor shares equal output elasticities and adjust competitively or not. The reason is that if output elasticities for factors are assumed to be constant, differences between the factor shares and output elasticities for factors are expressed in the wedges. In particular, the computed wedges can significantly differ when labor share differs substantially from assumed output elasticity for labor. We show that this point is empirically relevant especially due to the large fall underwent by the U.S. labor share after the end of the 1990s.

Our main findings are as follows:

(1) Evolution of U.S. productivity is accurately accounted by the efficiency wedges during 1954–2017, and if a VES production is assumed, the evolution of the U.S. labor share during 1954–2017 is also accurately accounted for by the evolution of the efficiency wedges. Moreover, under a VES specification of the production function both the evolution of the U.S. labor share and the U.S. detrended output per hour worked during 1954–2017 are mainly accounted by the evolution of the capital efficiency wedge, and in particular, the fall in the capital efficiency wedge is primarily responsible for the decline in the U.S. labor share in 21st century and during the 1970s.

(2) U.S. hours worked per capita did not display any significant long-run trend during 1954–2017, which according to our model, can be accounted for by two forces working in opposite directions. On the one hand, the fall in the resource constraint wedge pushed hours worked per capita down. On the other hand, the increase in the labor wedge pushed hours worked per capita up.

(3) The outstanding growth in the 1950s and 1960s was mainly driven by the increase in efficiency wedges. In particular, by a the increase in the labor efficiency wedge whether a VES production is assumed. However, both investment and labor wedges worsen during the *Long Boom* 1954–1969 and contribute to moderate the economic expansion of this period.

(4) If a CD production function is assumed, the labor wedge was the main force driving the fall of output, investment, and labor during the *Second Growth Slowdown* in the first decade of 21st century. In this period, the efficiency wedge played a significant but secondary role in accounting for the decrease in output, investment, and labor. However, during the *First Growth Slowdown* in the 1970s, the main force driving the evolution of output and investment was the efficiency wedge, whereas the main force driving the fall of labor was the labor wedge.

(5) If a VES production function is assumed, the decline in output, investment, and labor both during the *First Growth Slowdown* and the *Second Growth Slowdown* was driven by the capital efficiency wedge. In both periods, the labor wedge played a significant but

secondary role in accounting for the evolution of output, investment, and labor.

(6) It follows from (4) and (5) that allowing factor shares to adjust competitively assuming a production function with variable output elasticities for factors helps harmonize both periods of growth slowdown. However, there are two differences between the periods. First, the investment wedge played a significant but secondary role in accounting for the fall of output, investment, and labor in the *Second Growth Slowdown*; however, it contributed to reduce the decrease in output, investment, and labor in the *First Growth Slowdown.* Second, the efficiency labor wedge played a negligible role in accounting for the fall of output, investment, and labor in the *First Growth Slowdown*, but it contributed to reduce the fall of output, investment, and labor in the *Second Growth Slowdown.*

(7) The labor wedge was the main force driving the recovery of growth and hours worked per capita in the 1980s and 1990s and after the Great Recession.

Our analysis has the following implications: (1) to understand the periods of economic rise and recession recovery, we must understand the factors improving the labor wedge. Similarly, (2) to understand the periods of economic decline and recession, we must first understand the factors worsening the capital efficiency wedge. (3) To understand the outstanding growth of the 1950s and 1960s, we must understand the factors improving the labor efficiency wedge. Finally, (4) The focus of the growth literature on understanding and explaining the efficiency of productive inputs as the engines of productivity growth is well oriented.

According to our results, if the labor wedge reflects primarily labor supply distortions, and then, when the labor share decreases, the labor wedge loses importance in explaining periods of growth slowdown, whereas the investment wedge gains it. Therefore, to delve into the causes of economic recessions, it would be interesting to extend our analysis to a stochastic framework and analyze the role played of the different wedges in the economic recessions experienced by the U.S. and other OECD countries to check whether the results of Brinca et al. (2016) experience any significant modification.

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