EUI Working Papers

MWP 2010/27
MAX WEBER PROGRAMME

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EUI Working Paper **MWP** 2010/27

ISSN 1830-7728

Printed in Italy
European University Institute
Badia Fiesolana
I – 50014 San Domenico di Fiesole (FI)
Italy
www.eui.eu
cadmus.eui.eu

Abstract
In the usual version of the neoclassical growth model used to identify neutral (N-Shock) and investment shocks (I-Shock), a linear transformation frontier between consumption and investment goods is assumed. This paper extends the original framework, allowing for curvature in the transformation frontier, and studies how this affects the relative price of investment goods and hence the identification of investment shocks. A concave frontier allows a substantial improvement in the prediction of the saving rate. Furthermore, a concave frontier induces short-run aggregate effects of relative demand shifts, thereby fostering the propagation of the shocks under consideration, which overall account for 86% of the aggregate fluctuations. When I identify shocks with curvature, the N-shock appears to be stationary while the I-shock is a unit root. This leads the N-shock to play a major role: 91% of the fluctuations explained are due to the N- shock.

Keywords
Business Cycle, relative price, investment specific technology shocks, transformation frontier sectorial reallocation

JEL Classification Codes: E13, E22, E23, E32

I thank Xavier Mateos-Planas, Martin Gervais, Salvador Ortigueira and Yang Lu for helpful comments. I also thank Maxym Kryshko for giving me the relative price time series. Any errors are mine.
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1 Introduction

Recent work in the field of measuring the importance of technology shocks for the business cycle is based on the neoclassical growth framework. Greenwood et al. (1988) showed that shocks to the productivity of investment goods (I-shock) are an important source of fluctuations, together with *neutral* productivity shocks that hit all sectors of the economy (N-shock). This recognition engendered several studies of this mechanism, including Greenwood et al. (2000), Cummins and Violante (2002) and Fisher (2006).

To identify the I-shock, these papers use the fact that, in the framework considered, the relative price of investment goods only moves with I-shocks. More precisely, I-shocks (V) are identified from the relative price equation between consumption and investment goods, which, under the assumptions of this model - linear transformation frontier between consumption and investments - is simply $p = 1/V$. This is a key identification assumption because, without identifying investment shocks from the price equation, Justiniano et al. (2008) find that the I-shock should be 4 times more volatile in order to match business cycle fluctuations. The sharp contrast that comes from this price equation calls for further investigation of its specification.

This paper investigates whether this oversimplified specification may bias the measuring and the propagation of the shocks. Two signs of a potential misspecification further motivate this investigation: i) the original model fails to replicate the saving rate and ii) the two shocks identified through that framework are negatively correlated. It will be argued that these two observations suggest that the transformation frontier should be concave.

The first sign of misspecification (fact i) is that, with the preferences commonly used, the model's prediction of the saving rate is very poor:[1] the fit of the predicted saving rate on the actual time series, given the shocks identified, gives a very low R^2. This suggests a possible way to pin down the curvature in the transformation frontier: one that maximizes the fit of the saving rate. To motivate this choice, it is important to notice that curvature in the transformation frontier makes the relative price sensitive to any changes in the relative demand of the two types of goods, which

[1] To increase co-movement Greenwood et al. (1988) have to rely on very low short-run wealth effects in the labor supply, as recently emphasized by Jaimovich and Rebelo (2009)

are summarized by changes in the saving rate. Then, a better fit between the saving rate and the relative price should imply a better price equation. Under a linear transformation frontier, the effect of relative demand changes in the relative price is neglected and this may have important quantitative implications.

Of course, how well the model fits the saving rate would be an ideal way to test this model. However, the fact that the moment is used to pin down the parameters does not allow it to be used to test the model. Fortunately, fact ii leads to an alternative way to pin down the degree of curvature. Furthermore, fact ii - that the two shocks identified assuming a linear frontier are negatively correlated - is a direct sign of concavity in the transformation frontier for the following reason: a concave frontier implies a positive relation between the price and the N-shock. This is because an increase (decrease) in the N-shock, will increase (decrease) the saving rate (i.e. the relative demand between investments and consumption) because of households' desire to smooth consumption; firms, due to the concave transformation frontier, will be induced to meet demand through an increase (decrease) in the relative price.

Neglecting this channel, one would have to wrongly attribute the increase in the relative price that comes after a positive N-shock to a decrease in the I-shock: every time p increases as a consequence of a positive N-shock the researcher armed with the simplified price equation would impute the increase in p to a decrease in V. This would make the two shocks appear negatively correlated. Indeed, identifying the shocks in the usual way leads to negatively correlated shocks: after removing unit roots from the shocks, I find a significant correlation between the two shocks of -19%. According to the reasoning above, this negative correlation is the sign of a concave transformation frontier. It follows that one possible way to estimate the curvature is to pick the curvature that makes the two shocks appear independent, in order to avoid capturing as an I-shock the increase in the price due to the N-shock.

Strikingly, the curvature under the two strategies is very close and leads to the same implications. In particular, the fit of the saving rate under the second moment condition is very close to the one obtained under the first strategy, where the parameters were picked to maximize the fit of the predicted saving rate to that of the data.

The model is enhanced with curvature in the transformation frontier by adding only one parameter to the original framework. This is convenient in that it allows the one-sector characterization of the original framework to be preserved, and aggregate data to be used to fully calibrate the model. Importantly, this specification does not affect the balanced growth path predictions of the original framework. This is a virtue of this specification because the original framework is capable of reconciling the downward trend observed in the relative price and the increase in the relative production of investments goods, and make these two facts consistent with a Balanced Growth Path, as shown by Greenwood et al. (1997).[2]

To focus on the role of curvature, the model is kept as simple as possible. The real frictions usually included by the recent literature, although important to improve the fit to the data, are not considered in this paper. Indeed, adding capital adjustment costs and capital utilization would not change the message of the paper as long as they do not affect the relative price equation.[3] This is indeed the case for the usual way in which these frictions are modeled, for example Schmitt-Grohe and Uribe (2008), Justiniano et al. (2008) and Justiniano et al. (2009) consider medium-scale models with several frictions that do not affect the investment price equation. In fact, abandoning a linear frontier is a necessary condition for affecting the price equation. Hence, while allowing for inter-temporal adjustment costs permits improving the saving rate prediction of the model, it does not affect the identification of the I-shock, which this paper argues has been mis-measured.

One finding of this paper is that the N-shock identified appears to be stationary, while the investment shock is a unit root. In most of the previous studies the two shocks were either considered both stationary, as in Greenwood et al. (2000), or both unit roots as in Fisher (2006). This difference has important implications for the relative importance of the two shocks. When the N-shock is stationary and the I-shock a unit root, the first plays a major role in explaining aggregate fluctuations.

[2] Another advantage of the proposed specification is that, although making the price equation function of both the shocks, it allows the shocks to be backed out analytically, given the parameters. This permits them to be backed out without the use of a filter or by using a simulated method, thereby increasing precision and saving on computing time.

[3] These frictions introduce *inter-temporal* adjustment costs. Instead, concavity in the transformation frontier is a concept that is closer to the *intra-temporal* adjustment costs considered by Huffman and Wynne 1999. See Guerrieri et al. (2009) for an interpretation of I-shocks in a fully-fledged multi-sector model.

This overthrows previous findings, where the I-shock played the main role.[4] There is a simple intuition for this result: when there is a permanent shock, productivity grows but so does expected wealth. Therefore, the expected marginal utility of consumption decreases, lowering the boost in the saving rate and in the labour supply. This implies that the households' reactions to a permanent shock are weaker than the reactions to a transitory shock. This explains why transitory shocks play a stronger role in accounting for the business cycle.

Whether the Business Cycle is about stationary fluctuations around a deterministic trend, or is due to a stochastic trend has been debated since the paper by Nelson and Plosser (1982). The present finding may reconcile the two views in that both things happen; this paper suggests that there is a stochastic trend due to the I-shock and stationary fluctuations around it through the N-shock.

With these slight changes to the original framework, this simple model accounts for 86% of the Business Cycle - substantially more than what is predicted by the usual framework. For a comparison, the point estimation is above the 95% confidence interval extremum considered by Fisher (2006).

The paper is organized as follows, the next section identifies and discusses the misspecification, Section 3 modifies the framework in order to allow for curvature in the transformation frontier, Section 4 reports the calibration, Section 5 reports the findings and section 6 concludes.

2 Identifying the Misspecification

Below follows a description of the standard growth model with investment-specific technological change like, for instance, the one adopted in Fisher (2006).
The representative household solves the following problem, taking prices as given:

$$\max_{\{ct, k_{t+1}, n_t\}} E_0 \left[\sum_{t=0}^{\infty} \beta^t \left(\log(c_t) - \chi \frac{n^{t^{1+1/\nu}}}{1+1/\nu} \right) \right]$$

$$s.t. \quad c_t + p_t k_{t+1} = w_t n_t + p_t k_t (1 + r_t - \delta).$$

[4]This result is in line with the findings of Schmitt-Grohe and Uribe (2008), where investment shocks play little role in aggregate fluctuations.

These preferences are adopted for instance by Fuentes-Albero et al. (2009), as they point out ν is the Frisch elasticity of labour. Capital evolves according to the law of motion

$$k_{t+1} - k_t(1-\delta) = V_t A_t k_t^{\theta} n_t^{1-\theta}(1-s_t),$$

while non-durable consumption is

$$c_t = s_t A_t k_t^{\theta} n_t^{1-\theta} \tag{1}$$

where s_t is the fraction of physical production allocated to consumption. V_t is the investment shock, which only hits the production devoted to increasing the capital stock. It follows the following process:

$$\begin{aligned} V_t &= V_0 \gamma_v^t \exp(u_{vt}) && (2) \\ u_{vt} &= \rho_v u_{vt-1} + \varepsilon_{vt}. && (3) \end{aligned}$$

A_t is a neutral shock that hits both sectors in the same way and evolves according to the following process:

$$\begin{aligned} A_t &= A_0 \gamma_a^t \exp(u_{at}) && (4) \\ u_{at} &= \rho_a u_{at-1} + \varepsilon_{at}. && (5) \end{aligned}$$

Firms are competitive: given prices they solve the following static problem:

$$\max_{k_t, n_t, s_t} y_t - w_t n_t - p_t k_t r_t$$
$$s.t.$$

$$y_t = s_t A_t k_t^{\theta} n_t^{1-\theta} + p_t V_t (1-s_t) A_t k_t^{\theta} n_t^{1-\theta}. \tag{6}$$

The first order conditions for the firm are as below:

$$\begin{aligned} \theta A_t k_t^{\theta-1} n_t^{1-\theta}(s_t + p_t V_t(1-s_t)) &= p_t r_t \\ (1-\theta) A_t k_t^{\theta} n_t^{-\theta}(s_t + p_t V_t(1-s_t)) &= w_t \end{aligned}$$

and

$$p_t = 1/V_t. \tag{7}$$

The price equation (7) reflects the fact that a firm can choose where to allocate its

inputs with no costs. Hence, it will be indifferent between producing consumption or investment goods if and only if (7) holds. This strong implication of the model is what is disputed in the present paper. This assumption is innocuous for the growth analysis of the model as in Greenwood et al. (1997) [5] for which the model was originally built, but it matters for the business cycle analysis.
From (1), (7) and (6) $s_t = \frac{c_t}{y_t}$ holds. Therefore aggregate production is

$$y_t = A_t k_t^{\theta} n_t^{1-\theta}.$$

From this and (7), time series for A and V are identified as follows

$$A_t = \frac{y_t}{k_t^a n_t^{1-a}} \tag{8}$$

$$V_t = 1/p_t. \tag{9}$$

2.1 Correlation Between Shocks

To identify the neutral shock A, α is assumed equal to 1/3 and the results of this section are robust to changes in this parameter. Data on the relative price of investment goods are those constructed by Fisher (2006), who extended the analysis by Gordon (1990), and successively by Cummins and Violante (2002). These data are available from 1947 IV to 2006 IV. [6], [7] In the first years of the sample, however, the shocks seem to exhibit properties opposite to what the data shows later on. In the early years, the two variables appear to be positively correlated, although the economy does not yet seem to be on a balanced growth path: as Figure 1 shows, the capital output ratio exhibits an increasing trend before stabilizing when the period considered starts. A positive correlation of the shocks never occurs later in the sample. That initial period is therefore omitted from the analysis, because it presumably

[5] The modification introduced in section 3 leaves the balanced growth path unchanged and therefore it maintains the same growth implications of the original framework as shown in Appendix 2, section A.2.

[6] I thank Maxym Kryshko for giving me the relative price time series. The rest of the time series comes from the Bureau of Economic Analysis (c, I) and from the Bureau of Labor Statistics (n, pop).

[7] Given the emphasis on technological shocks, the fact that the data do not include the last years may not be considered a disadvantage in that the last recession may be due to sources not considered in this framework, thereby increasing the misspecification of the model and hence biasing the findings.

captures mis-measurement due to the transition to the BGP, where the model, calibrated trough the BGP properties of the data, fails to properly measure the shocks. The transition and structural breaks after the Korean war mean that much of the macro analysis starts after the Korea war.

The analysis is therefore restricted to the sample that goes from 1957 IV to 2006 IV [8]. ADF and Phillips-Perron tests accept the hypothesis of a unit root for $\ln(A)$ and for $\ln(V)$. I therefore estimate the regression

$$d\ln(A_t) = \underset{.06}{.0025} - \underset{.045}{.32} d\ln(V_t) + \varepsilon_t \tag{10}$$

$$corr[d\ln(A), d\ln(V)] = -.19. \tag{11}$$

The two time series in the sample that goes from 1956 to 2006 seem to be strongly negatively correlated.

Considering sub-samples of this sample gives the same result. Extending the sample a little more, considering years before 1956 does not change the results. For example, starting from 1952 one still gets a significant negative correlation of the relative change of the shocks of -15%. This however does not hold in the first years of the sample, where the two time series appear to be highly positively correlated. This is in such a sharp contrast with what happens in the rest of the sample (and in sub-samples of it), that it casts doubts on the reliability of the model to measure the shocks over that early period of time[9].

I conclude that the two time series for the shocks identified through the usual framework appear to be negatively correlated.

2.2 Saving Rate

The other dimension where the misspecification is notable is that the model predicts counter-factual savings rates. With a conventional calibration (that of section 4, but with the parameter that governs curvature in the transformation frontier $\rho = 0$, which implies a linear frontier), and the shocks identified from the data, let $\widehat{s}$ be the time series of s predicted by the model, and s the time series realized. At least with the

[8] 1956 is when the capital output ratio reached a level from which continued over time on a trend-less path.

[9] Fisher (2006) argues that the quality bias in the NIPA data is stronger in the earlier part of the sample.

utility function considered, the two time series are so different from one another, that the $R^2 = 1 - var(\widehat{s} - s)/var(s)$ is even negative. This implies that the saving rate predicted by the model is countercyclical with respect to the actual one, and therefore even the simple mean performs better, leaving a smaller residual variance.

The two facts above - he tnegative correlation between the shocks and the counterfactual saving rate - suggest that there is a misspecification in the model. Section 3 describes a modification of the framework where a different specification for the two sectors is modelled. Before that, an attempt is made to interpret the negative correlation in (11) and the bad fit in the saving rate as being suggestive of curvature in the transformation frontier.

2.3 The Case for Curvature in the Transformation Frontier

Since the model can be expressed in recursive form with state variables A, V, K, assume that the true price equation is of the form

$$p = f(A, V, K) \tag{12}$$

and let the total production measured in consumption units be

$$y = y(A, V, K). \tag{13}$$

Considering instead the price equation (7) and the aggregate resource constraint (6) would wrongly impute all the increase(decrease) in the relative price to a decrease (increase) in V, and all the variation in production not explained by k to A. If instead $\frac{\partial p}{\partial A} > 0$, increases in p may be due to increases in A, and when this happens, also y increases through A. With the misspecified policy functions, the increase in the price would be attributed to a decrease in V, while instead only an increase in A occurred. This leads to the negative correlation between A and V, which is not a pure negative correlation between the two shocks, but is due to the misspecification of the model.

The misspecification also leads to counter-factual saving rates: when there is an increase in A, according to the true policy function (12) p grows. When this happens, the original model identifies a decrease in V. Because the productivity of investments decreased, the saving rate predicted by the model decreases. If, on the

contrary, no I-Shock occurred, the increase in A would imply an increase in the saving rate. Therefore, the counter-factual saving rate predicted by the original model is a consequence of the misspecified price equation.
It follows from these considerations that a model used to measure these shocks for the business cycle should be specified in a way such that the time series for the shocks that it predicts, appear to be independent and match as closely as possible the saving rate time series. These are the two facts that will be targeted in the calibration of the model presented in the next section.

3 The Modified Framework

Consider the following modification to the model: a generic firm produces

$$y_t = A_t k_t^a n_t^{1-a} s_t^{1-\rho} + p_t V_t A_t k_t^a n_t^{1-a} (1-s_t)^{1-\rho}, \tag{14}$$

where $\rho \ \epsilon \ [0,1)$. s_t measures the share of inputs allocated to the production of consumption goods.
Therefore,

$$\begin{aligned} c_t &= A_t k_t^a n_t^{1-a} s_t^{1-\rho} \\ k_{t+1} - k_t(1-\delta) &= V_t A_t k_t^a n_t^{1-a} (1-s_t)^{1-\rho}. \end{aligned}$$

The firm can produce for both sectors, but the marginal productivity of producing for one sector is decreasing. This makes the firm willing to produce for both the sectors, even if $p_t V_t \neq 1$.
The firm's problem is

$$\max_{k,n,s} A_t k_t^a n_t^{1-a} s_t^{1-\rho} + p_t V_t A_t k_t^a n_t^{1-a} (1-s_t)^{1-\rho} - wn - rpk. \tag{15}$$

When $\rho > 0$ the marginal productivity of consumption and of investment goods is decreasing[10], and therefore the firm will always choose to produce both types of goods. This technology has constant returns to scale, and therefore the Euler theorem holds, so the problem is consistent with perfect competition where the size and number of

[10] In this sense, ρ can be interpreted as an intra-temporal adjustment cost as in Huffman and Wynne (1999)

firms does not matter and firms take prices as given.

The equilibrium conditions are reported in appendix A.2 and are essentially unchanged with respect to the usual framework, except for the resource constraints above and for the price equation, which comes from the optimal choice of s_t:

$$p_t V_t = \frac{(s_t)^{-\rho}}{(1-s_t)^{-\rho}}. \tag{16}$$

It can be noticed how when $\rho = 0$ the price equation (and the whole model) boils down to the usual framework. This price equation shows that the change in the relative price is not only due to a change in V_t, but it also depends on the change in s_t, i.e. on the change in the relative demand for the two goods. This in turns depends on both the shocks and on capital. The relative importance of one shock with respect to the other depends on the parameter ρ. How the two shocks affect p is what in the preceding section was indicated to be crucial for the two shocks to be uncorrelated. Since this depends on ρ, this parameter will be pinned down to make the two shocks uncorrelated, and to improve the fit of the saving rate.

4 Calibration

The parameters of the model are $\beta, \alpha, \delta, A_0, \gamma_a, V_0, \gamma_v, \sigma\varepsilon_a, \sigma\varepsilon_v, \rho, \chi, \nu, \rho_a, \rho_v$.

The crucial parameter choice is ρ. As mentioned in the introduction, two strategies are employed. The first is to pick ρ such that the shocks identified are uncorrelated. In this model the shocks can be identified from the price equation (16) and (14) as

$$V = \left(\frac{s}{1-s}\right)^{-\rho} \frac{1}{p} \tag{17}$$

$$A = \frac{Y}{k_t^{\alpha} n_t^{1-\alpha} \left[s^{1-\rho} + pV(1-s)^{1-\rho}\right]}. \tag{18}$$

As becomes clear from observing the two equations above, to identify the shocks, it is first necessary to identify s. From (16) and from the fact that

$$\frac{s^{1-\rho}}{pV(1-s)^{1-\rho}} = \frac{c}{y-c}, \tag{19}$$

which comes from the two resource constraints, one gets the convenient fact that

$$\frac{s}{1-s} = \frac{c}{y-c}. \tag{20}$$

This highlights the close relation of s with the consumption rate and it is used to identify s from the data.
The strategy to calibrate ρ is the following: a guess for ρ very close to zero (as in the usual framework) is made. V and A are identified through the above equations. The relevant correlation between the two shocks is estimated as follows: [11], if it is other than zero, ρ is increased, otherwise ρ has been found. In order to implement this procedure, a value for α has to be fixed in order to back out A. In this model $1-\alpha$ is equal to the labour share and hence α is calibrated equal to $1/3$.

This procedure leads to $\rho = .028$. This means that the marginal productivity of the two goods is decreasing and this makes the price equation 17 deviate from the one used in the main framework. As already noted, if $\rho = 0$, the price equation and the whole model boils down to the original one.
Given these shocks, $A_0, \gamma_a, V_0, \gamma_v, \sigma\varepsilon_a, \sigma\varepsilon_v, \rho_a, \rho_v$ are picked by running an OLS regression on the log of the shocks as identified above. The parameter values are $A_0 = 5.46$, $V_0 = 1$, $\gamma_v = 1.\underset{.00}{00}74$, $\sigma\varepsilon_A = .00918$, $\sigma\varepsilon_V = .00498$.
γ_a is not significantly different from 1, which means zero growth in the neutral shock. Therefore it is set equal to 1. This implies a growth rate of the I-shock of 0.74 %.
δ is picked to match the average investment capital ratio, as inferred from the law of motion for capital: assuming that the economy fluctuates around a balanced growth path

$$\delta = \frac{pI}{pK} - (\gamma_a \gamma_v)^{\frac{1}{1-\theta}} - 1 \tag{21}$$

this gives a value of $\delta = .0177$.
From the Euler Equation for consumption, on a BGP one gets [12]

$$\beta = E\left(\frac{\frac{c_{t+1}}{c_t}\frac{p_t}{p_{t+1}}}{1+\theta y/(pK)-\delta}\right) = 0.98. \tag{22}$$

It remains to calibrate the parameters of the supply of labour: the critical one is ν, which represents the Frisch elasticity. As Prescott mentioned during his Nobel Prize Lecture, how much of the business cycle can be explained by technology shocks

[11] 'relevant' meaning that if the shocks are unit roots, the correlation of the first differences is run; if they are stationary, the correlation of the levels is run; if one is stationary and the otherone is non-stationary, only the non-stationary one is differentiated.

[12] (22) implies $\beta = \frac{(\gamma_a \gamma v)^{\frac{1}{1-\theta}} \gamma_V}{1+\theta E(y/(pK))-\delta}$ if γ_a is not restricted to be 1 and therefore $E(\frac{c_{t+1}}{c_t}) = (\gamma_a \gamma v)^{\frac{1}{1-\theta}}$.

depends crucially on this parameter. The problem is that there is not a clear way to calibrate it; micro studies suggest $\nu = .2$ but they may understate adjustments to the extensive margin. The quasi-linear preferences of Hansen, where all the adjustment is on the extensive margin, imply $\nu = \infty$. Fuentes-Albero et al. (2009) estimate with Bayesian methods $\nu = .3$ with 95% confidence interval $[0.05 \;\; 0.53]$[13]. The same choice is made here, and given the importance of this parameter and the weak arguments to motivate a particular choice, some sensitivity analysis will be carried out in the next section. Finally, χ is chosen to match the observed average labour supply $n = .3$.

The second strategy to pin down ρ is to maximize R^2 of the saving rate predicted by the model given the shocks identified. This is done by setting a greed on ρ, and for each value of ρ, doing the following: 1. given the other parameters, back out the two shocks time series through 17 and 18; 2. Estimate the parameters of the shocks' processes. 3. Solve the model. 4. Simulate given the shocks identified, and compute the R^2.

The value of ρ that gives the highest R^2 is 0.024. Strikingly, this value is very close to that obtained with the other procedure. R^2 of 0.37 is a substantial increase in the portion of variance of the saving rate explained by this model compared to the original framework[14]. Figure 2 reports the actual and predicted saving rate time series. With this value of ρ, the parameters of the shock process are essentially unchanged. The following tables summarize the parameter values.

Table 1: Curvature Parameter ρ

1^{st} strategy	0.28
2^{nd} strategy	0.24

[13] The modification made to the original framework does not have remarkable effects on the labour reaction to the shocks. This makes their estimation valid even for the present framework.

[14] In the original framework the variance explained is essentially zero.

Table 2: Other Parameter Values

β	α	δ	γ_A	γ_V	$\sigma\varepsilon_A$	$\sigma\varepsilon_V$	ρ_a	ρ_v	ν	χ
.98	.33	.018	1	1.0074	.00918	.00498	.95	1	.3	180

5 Results

This section describes the properties of the shocks identified. The main finding is that the N-Shock is trend stationary, while the I-Shock is trend stochastic. The quality of the shocks identified is tested by seeing how well the policy function for the relative price can predict the actual time series of the relative price when the shocks identified are used as inputs in the policy function. The model, if misspecified, could provide a wrong prediction, given that the shocks have not been identified through that policy function. Successively, a qualitative analysis of the propagation mechanism is carried out. In the last subsection the model is confronted with the main business cycle facts, and compared with the performance of the baseline framework. Under the preferred calibration, the model can predict 86% of the aggregate fluctuations. 91% of the fluctuations explained are due to the N-shock.

5.1 The Shocks Identified

A relevant result is that while the investment shock is a unit root, the neutral one is trend stationary. Under all the calibrations, ADF and Philip Perron tests, with various lags, reject the hypothesis of a unit root for the neutral shock, with p-values that range between 1% and 9%. Under the preferred calibration ($\nu = .3$ and $\rho = .024$) the autoregressive parameter is $\rho_a = .95$. As with the baseline framework, the process for the N-Shock does not show a significant trend: all the growth is captured by the I-Shock.

This overthrows the previous findings, that the I-shock plays the main role in accounting for the Business Cycle. Here the N-shock accounts for 91% of the total fluctuation explained. As explained in the introduction, agents react more strongly to a transitory shock than to a permanent one. Intuitively, agents realize that they have plenty of time to benefit from a permanent shock, while they have to extract the potential benefits that arises from a positive transitory shock more quickly. This explains why transitory shocks play a stronger role in accounting for the business cycle, and having the N-shock being transitory and the I-shock permanent makes the N-Shock the most important one, overthrowing the results found in the previous literature. It turns out that considering both the shocks, the model accounts for 86% of the Business Cycle, much more than generally predicted in previous studies: in Greenwood, Hercowitz, and Krusell (2000) the variance explained is around 70%; in Fisher (2006) it is between 40% and 60%. To the overall higher output variance found here, it contributes the new propagation mechanism implied by the presence of curvature in the transformation frontier, which makes shifts in the relative demand for goods cause a change in aggregate production. The mechanism is explained in the next subsection.

The stationarity of the N-shock is quite a relevant result for that branch of the quantitative literature that uses long-run restriction based on the unit root assumption to identify the shocks in a VAR model, such as Fisher (2006). According to the present model, only the investment shock can be identified through its long run properties, since the neutral shock is trend stationary. Whether the business cycle is about stationary fluctuations around a deterministic trend or stochastic changes in the trend has been debated since the influential paper by Nelson and Plosser (1982). The fact that one shock is trend stochastic and the other one is trend stationary may reconcile the two views: there is a stochastic trend, and also stationary fluctuations around that trend. Appendix A.3 derives the equivalent stationary conditions when there is a trend stochastic shock and a stationary one. The transformed stationary model proves the existence of a Balanced Growth Path and allows for a recursive formulation. In A.2, the model is also detrended under the assumption that both the shocks are trend stationary. From this it becomes clear that the model has the same long-run implications as the original framework: the expected growth rates of all the variables are unchanged.

A problem with the method, that uses fully specified theoretical models to identify the shocks, is that there is no proof that the shocks are close to the "true" ones. It is argued in this paper that the fit of the saving rate to the actual saving rate time series is a good measure of the quality of the specification, and allowing for curvature in the transformation frontier induces a clear improvement over this dimension. Another specification check can be made by exploiting the fact that the identification of V has not been done through the policy function for the relative price. Therefore, this policy function can reproduce prices that differ from the real ones when filled with the shock time series identified. Comparing the prediction with the actual price series is a robustness check that has been carried out as follows. The shocks identified are plugged into the computed policy function $p = p(k, A, V)$ and the predicted $\hat{p}$ is compared with the actual time series. If the model predicts a policy function for the relative price that is incorrect, then this fitting exercise will suggest that the model is misspecified. A good fit may be reassuring that the model is well-suited for the question at hand: to quantify the two technology shocks.

In the usual framework, this checking exercise cannot be performed because the investment shock is identified using the policy function for p. However, by tending ρ to zero this model boils down to the original framework and the policy function would become $p = 1/V$ and therefore the fit would be total. Given that ρ is quite close to zero, a good fit should not surprise. A good result therefore cannot be used to claim success. However a bad fit would be a clear sign of a wrong policy function. It is interesting to compute the R^2 on the deflated variables and for the ones in levels. The model performs surprisingly well: the predicted prices in levels are so close to the actual ones that $\mathrm{R}^2 = .9997$ Some of the good fit depends on the trend; removing it, the fit remains substantially high: $\mathrm{R}^2 = .79$. Figures 3 and 4 show the predicted and actual time series in levels and in growth rates. From figure 3 it is evident how most of the variance of the price time series is due to the trend. That is why the R^2 in levels is so high and therefore less informative than the one in growth rates.

5.2 Qualitative Results

The main differences of this model compared to the usual framework are due to the fact that the price also depends on the neutral shock. This is at the heart of the identification of different time series for the shocks and it has three important implications.

1. Perhaps surprisingly, the presence of curvature in the transformation frontier increases the effects of the shocks.

   This is explained as follows: after a neutral or I- shock, the consumption share s decreases because agents find it optimal to increase investments. The decrease in s implies that the marginal productivity of consumption goods $(1-\rho)A_t k_t^{\theta} n_t^{1-\theta} s_t^{-\rho}$ increases. The marginal productivity of investments, measured in consumption goods $p_t V_t (1-\rho)A_t k_t^{\theta} n_t^{1-\theta}(1-s_t)^{-\rho}$ also has to increase, since the two marginal productivities must be equal in equilibrium. This calls for an increase in $p * V$. Compared with the original framework, the price reacts less to a change in the investment shock, making the product $p * V$ procycliclal. Unlike what happens in the original framework, the fact that $p*V$ increases even after an investment shock, makes aggregate productivity increase. Therefore, the proposed mechanism increases the propagation of the shocks, increasing the proportion of the business cycle explained by productivity shocks.

2. After a positive neutral shock A, households want to increase the investment rate; because of the curvature in the transformation frontier. Firms, however, are reluctant and the price has to increase to induce them to adjust supply and meet demand.

   This highlights the fact that the change in the relative price of goods is not all due to the I-shock and how it could be misleading to identify the investment shock in the usual way.

   The fact that p increases after an N-shock implies that consumption is more volatile to a change in A with respect to the framework without curvature in the transformation frontier; the increase in the relative price induces agents to increase consumption with respect to what they would do in the usual framework, where the investment price does not depend on the N-shock. This is a feature typical of two-goods models with imperfect input reallocation, which turned out to imply a high equity premium as has been shown by Boldrin et al. (2001).

3. Unlike in the usual framework, here consumption increases after an I-shock. This is because, due to the smaller (compared to the usual framework) decrease in the price that follows the investment shock, pV increases, increasing GDP

measured in consumption goods. Given this increase in GDP, households, although increasing the saving rate, can also increase consumption a little. This helps the matching of the positive correlation of consumption and total production, which is hard to match in the usual framework.

5.3 Accounting for the Business Cycle and Labour Supply Elasiticity

This section studies quantitatively the business cycle implications of this model. Since results may depend on the labour supply elasticity, the exercise is carried out for $\rho = .28$ but for two different values of ν. [15]

5.3.1 The model with $\nu = 0.3$

With this parametrization, the model accounts for 86% of aggregate fluctuations. Labour fluctuations in the model account for 17% of the actual labour fluctuations. Investment fluctuations are substantially what they are in the actual data: the variance is 96% of the data. These two facts imply that part of the aggregate fluctuations are due to the change in the relative price and the saving rate as explained in paragraph 5.2: the original propagation mechanism implies oscillations not accounted for by changes in labour, capital and TFP. What remains unexplained of the Business Cycle should be due to the low volatility of hours. Consumption fluctuates 1.9 times more than in the data . To this, it may contribute the low relative risk aversion parameter used. This choice was necessary to have a balanced growth path with the adopted utility function.

The model matches the usual correlations observed to confront the model with the data reasonably well: the correlation of consumption and GDP is .99 in the data and .98 in the model. The correlation of Investments and GDP is .93 in the data and .95 in the model. The model under-predicts the correlation of labour: .45 in the data and .25 in the model.

The following two tables summarize these results:

[15] Putting $\rho = .24$ essentially does not affect the results.

Table 3: Standard Deviation Explained by the Model

Output	Consumption	Investments	Hours
86%	190%	96%	17%

Notes: Numbers are espressed in percentage terms of the actual data.

Table 4: Correlations with Output

	Output	Consumption	Investments	Hours
Data	1	.99	.93	.45
Model	1	.98	.95	.25

Although usually not considered, the correlations of the growth rates are reported; they highlight dimensions in which this model (and the original one) performs poorly. This may be useful for future research in that it addresses weaknesses of the framework.

The fact that consumption fluctuates too much and investments fluctuate essentially what they should, implies a lower correlation of consumption and investment goods. This becomes evident when one observes the growth rates'correlation. -0.763, compared to the observed one 0.25. This is a problem that this model shares with the usual framework. The decreasing marginal productivity of the two goods should help mitigate the problem with respect to the usual framework, but in practice, given the very small curvature in the transformation frontier, the improvement with respect to the usual framework is very weak. In principle, the decreasing marginal productivities in the production of the two goods induce the sectors to covary to a certain extent -in order to maintain the consumption share, and therefore the ratio of the two goods, as smooth as possible. However, the small curvature of the transformation frontier implied by $\rho = .28$ is not enough for this purpose. Nevertheless, it helps to increase the correlation between GDP and output, which is .48 in this model, .66 in the data

and -.36 in the usual framework.
The fact that labour fluctuations are small suggests that increasing the Frisch elasticity may improve the results. This is done in the next section, where a very elastic labour supply is considered. As in Hansen (1985), this calibration captures the case of adjustments on the extensive margin.

5.3.2 The model with $\nu = 100$

With such an elastic labour supply, the model predicts a variance of GDP 4 times higher than the actual one. This is due to the labour volatility, which now varies 16 times more than in the actual data. Also, the price prediction with the policy function is not as good as before: the R^2 of the detrended data is .3. The only good news with this parametrization is that now the correlation between consumption and investments is around 0, an improvement with respect to before, especially if one compares this with the usual framework, where the correlation is around -.9.
The last experiment suggests that labour supply cannot be so elastic. Considering a value of ν somewhere in between the two values considered and a higher curvature in the transformation frontier, $\rho > .28$ may help match the data. However, this would reduce the fit that the model has in predicting the relative price, which is quite an important dimension for the purpose of the paper: measuring technology shocks and their importance for the Business Cycle. Nonetheless, this parametrization highlights the fact that other sources of fluctuations and propagation mechanisms may also be relevant in explaining the Business Cycle. The choice of a parametrization that shows the strengths and weaknesses of this model characterizes the calibration method with respect to other estimation techniques.

6 Conclusions

Counter-factual saving rates and the presence of a negative correlation between the Neutral and Investment-Specific Technology Shocks identified through the neoclassical Growth model as implemented at first by Greenwood et al. (1988), and recently by several authors, casts doubts on the specification of that model for the question at hand - to measure the N-shock and the I-shock and to quantify their importance for the Business Cycle.

It is claimed that the absence of curvature in the transformation frontier between consumption and investment goods is the cause of the two observed facts. The model is enhanced with the above feature in a way that is convenient, in that it allows us to use aggregate data, to fully calibrate a two-sector model, and not to alter the balanced growth path prediction of the original framework, which is able to reconcile the decline in the relative price of investments with the relative increase in the production of investment goods.

The distinctive prediction of this model is that the relative price is now a function of both the shocks, and not only of the investment one as in the original framework. This depends on the curvature of the transformation frontier, which makes the relative price depend on the relative demand for the two goods, i.e. the saving rate, which in turn depends on both the shocks. The degree of curvature in the transformation frontier is accounted for by only one parameter, which is calibrated in two different ways. The first strategy is to maximize the fit of the predicted time series of the saving rate with the observed one. Given that in the present model the price depends on the relative demand for the two goods, i.e. the saving rate, it is judged to be important to have a good prediction of the saving rate. The second calibration strategy is to pick the parameter that generates uncorrelated time series for the two shocks. The two strategies deliver very close parameters and business cycle predictions, suggesting that the model is well-specified for the question at hand.

While the model shares the growth implications of the original framework, it has different predictions of Business Cycle frequencies. It is relevant that, when identifying the shocks through this framework, the neutral shock is stationary, and the investment one has a stochastic trend. This fact implies that the N-shock plays the most important role in accounting for aggregate fluctuations. This is due to the fact that a transitory shock induces a stronger and more sudden reaction than a permanent one would.

A good feature of the proposed identification technique for the investment shock is that the prediction can be tested using the policy function for the relative price to predict a relative price time series, given the identified shocks, that then can be compared to the actual price time series. Unlike in the original framework, the predicted prices can be wrong[16], since the shocks have not been identified through that equation. A good fit like the one obtained ($R^2 = .99$ for the price in levels and .79 in growth rates) is comforting as evidence of a well-specified price equation.

In this model technology shocks together account for a higher share of aggregate fluctuations than predicted by the original framework: in the preferred calibration, 86% of aggregate fluctuations are explained by the two shocks considered. The presence of curvature in the transformation frontier makes any shift in the relative demand of goods cause a change in aggregate production and in the relative price. This further propagation mechanism, not present in the usual framework, is responsible for the larger portion of fluctuations explained by the aggregate shocks. The fact that not all price variations are captured by I-shocks, contributes to making this shock less important for the Business Cycle.[17].

The presence of curvature in the production frontier allows an improvement in the prediction of the correlation between the growth rates of consumption and aggregate production, a dimension where the original framework performs poorly. However, due to the small degree of curvature, this correlation is still too low compared with the actual data. This is also highlighted by the counter-factual negative correlation of the growth rates of investment and consumption, where, due to the chosen parametrization, the improvement with respect to the original framework is very small. A higher curvature would improve over this dimension, but the aim of identifying uncorrelated shocks and a good prediction of the saving rate, imposes discipline on the calibration, and the good fit of the price equation suggests that the proposed parametrization is well suited to the question at hand, to measure technology shocks. The good and bad features highlighted by the calibration chosen, suggest that future research should be carried out aiming to improve the present mechanism in a way that would allow for a greater curvature in the production frontier, which would allow consumption and investments to co-vary, while at the same time predicting the right saving rate time series and essentially uncorrelated technology shocks. On this dimension, the introduction of other frictions, such as inter-temporal adjustment costs, may be found to be complementary to the present one and improve the fit of the model with the data.

[16] As they are, for instance, when the model is calibrated with an excessively elastic labor supply.

[17] The mechanism is explained in more detail in section 5.2

A Appendix

A.1 Data

The relative price time series is as in Fisher (2006).
Non-farm hours of work and population come from The Bureau of Labor Statistics.
Non-durable consumption, investments, capital stock comes from the Bureau of Economic Analysis.

A.2 Balanced Growth Path with trend-stationary shocks

The equilibrium conditions are

$$\frac{c_{t+1}}{c_t} = \beta E \left\{ \left[1 + \theta A_{t+1} k_{t+1}^{\theta-1} n_{t+1}^{1-\theta} \left[s_{t+1}^{1-\rho} + p_{t+1} V_{t+1} (1-s_{t+1})^{1-\rho} \right] / p_{t+1} - \delta \right] \frac{p_{t+1}}{p_t} \right\} \tag{23}$$

$$\frac{(1-\theta) A_t k_t^{\theta} n_t^{-\theta} \left[s_t^{1-\rho} + p_t V_t (1-s_t)^{1-\rho} \right]}{c_t} = \xi n_t^{\nu} \tag{24}$$

$$A_t k_t^{\theta} n_t^{1-\theta} s_t^{1-\rho} = c_t \tag{25}$$

$$V_t A_t k_t^{\theta} n_t^{1-\theta} (1-s_t)^{1-\rho} = k_{t+1} - k_t (1-\delta) \tag{26}$$

$$p_t V_t = \frac{(s_t)^{-\rho}}{(1+s_t)^{-\rho}} \tag{27}$$

$$V_t = V_0 \gamma_v^t \exp(u_{vt}) \tag{28}$$

$$u_{vt} = \rho_v u_{vt-1} + \varepsilon_{vt} \tag{29}$$

$$A_t = A_0 \gamma_a^t \exp(u_{at}) \tag{30}$$

$$u_{at} = \rho_a u_{at-1} + \varepsilon_{at} \tag{31}$$

In a stationary environment ($\rho_v < 1$, $\rho_a < 1$) the model oscillates around the deterministic growth path. In this case Equation 23 is consistent with a B.G.P if

$$(1+\mu_a)(1+\mu_k)^{\theta-1} = (1+\mu_p) \tag{32}$$

$$\mu_s = 0, \quad (1+\mu_v)(1+\mu_p) = 1. \tag{33}$$

Equation 24 is consistent with a B.G.P if

$$(1+\mu_a)(1+\mu_k)^{\theta} = (1+\mu_c) \tag{34}$$
$$\mu_s = 0, \quad (1+\mu_v)(1+\mu_p) = 1. \tag{35}$$

Conditions $(1+\mu_a)(1+\mu_k)^{\theta-1} = (1+\mu_p)$ $\&(1+\mu_a)(1+\mu_k)^{\theta} = (1+\mu_c)$ imply

$$(1+\mu_k) = \frac{(1+\mu_c)}{(1+\mu_p)}. \tag{36}$$

Equation 26 is consistent with a B.G.P if

$$(1+\mu_v)(1+\mu_a)(1+\mu_k)^{\theta-1} = 1. \tag{37}$$

This condition is already implied by $(1+\mu_a)(1+\mu_k)^{\theta-1} = (1+\mu_p)$ & $(1+\mu_v)(1+\mu_p) = 1$.
Equation 25 is consistent with a B.G.P if 34 holds.
Finally, from 27 if $(1+\mu_v)(1+\mu_p) = 1$ then $\mu_s = 0$, consistently with the Euler equation for consumption.
The above conditions summarize to

$$\mu_s = 0, \quad (1+\mu_p) = 1/(1+\mu_v), \tag{38}$$
$$(1+\mu_k) = [(1+\mu_a)(1+\mu_v)]^{\frac{1}{1-\theta}}, \tag{39}$$
$$(1+\mu_c) = (1+\mu_a)^{\frac{1}{1-\theta}}(1+\mu_v)^{\frac{\theta}{1-\theta}} \tag{40}$$
$$1+\mu_a = \gamma_a, \; 1+\mu_v = \gamma_v \; . \tag{41}$$

Define the variable $\hat{x}_t = \frac{x_t}{(1+\mu_x)^t}$ with $x = \{A, V, k, c, p\}$ and rewriting the model with these variables one gets a model with a globally stable steady state, which corresponds to the balanced growth path for the original economy. The model has the same implication for growth as the usual framework.
Detrending the variables in the way mentioned, the model is equivalent to the following:

$$\frac{\hat{c}'}{\hat{c}} = \hat{\beta}\left\{1 + \theta \hat{A}' \hat{k}'^{\theta-1} n'^{1-\theta}\left[s'^{1-\rho} + \hat{p}'\hat{V}'(1-s')^{1-\rho}\right]/\hat{p}' - \delta\right\}\frac{\hat{p}'}{\hat{p}} \tag{42}$$

$$\frac{(1-\theta)\hat{A}\hat{k}^{\theta} n^{-\theta}\left[s^{1-\rho} + \hat{p}\hat{V}(1-s)^{1-\rho}\right]}{\hat{c}} = \xi n^{\nu} \tag{43}$$

$$\hat{A}\hat{k}^{\theta} n^{1-\theta} s^{1-\rho} = \hat{c} \tag{44}$$

$$\hat{V}\hat{A}\hat{k}^{\theta} n^{1-\theta}(1-s)^{1-\rho} = \hat{k}' \gamma_v \gamma_a - \hat{k}(1-\delta) \tag{45}$$

$$s = \frac{\left(\hat{p}\hat{V}\right)^{-\frac{1}{\rho}}}{1 + \left(\hat{p}\hat{V}\right)^{-\frac{1}{\rho}}} \tag{46}$$

$$\begin{aligned} \hat{V} &= V_0 \exp(u_v) & (47) \\ u_v' &= \rho_v u_v + \varepsilon_v' & (48) \\ \hat{A} &= A_0 \exp(u_a) & (49) \\ u_a' &= \rho_a u_a + \varepsilon_a' & (50) \end{aligned}$$

where

$$\hat{\beta} = \beta \left(\gamma_v \gamma_a\right)^{\frac{1}{1-\theta}}$$

A.3 Balanced Growth Path with a trend-stationary and a trend-stochastic shock

Identifying the shocks through this framework, the neutral shock appears to be stationary ($\rho_a = .95$), while the investment one has a stochastic trend ($\rho_v = 1$). The equivalent stationary model when there is a trend-stochastic shock and a stationary one is derived below.

Consider the variables

$$\begin{aligned} z_t &= A_0^{\frac{1}{1-\theta}} \gamma_a^{\frac{(t)}{1-\theta}} V_t^{\frac{\theta}{1-\theta}},\ \tilde{c}_t = \frac{c_t}{z_t},\ \tilde{k}_t = \frac{k_t}{z_t V_t}, & (51) \\ \tilde{p}_t &= p_t V_t,\ \tilde{A}_t = \frac{A_t}{A_0 \gamma_a^t}. & (52) \end{aligned}$$

Substituting these variables into 23-31 one gets the following:

$$\frac{1}{\tilde{c}_t} = \beta E \frac{1}{\tilde{c}_{t+1}} \left(\gamma_a \gamma_v exp(\varepsilon_{v,t+1})\right)^{\frac{1}{\theta-1}} \left\{ 1 + \theta \tilde{A}_{t+1} \tilde{k}_{t+1}^{\theta-1} n_{t+1}^{1-\theta} \left[s_{t+1}^{1-\rho} + \tilde{p}_{t+1}(1-s_{t+1})^{1-\rho} \right] / \tilde{p}_{t+1} - \delta \right\} \frac{\tilde{p}_{t+1}}{\tilde{p}_t} \tag{53}$$

$$\frac{(1-\theta)\tilde{A}_t \tilde{k}_t^{\theta} n_t^{-\theta}\left[s_t^{1-\rho}+\tilde{p}_t(1-s_t)^{1-\rho}\right]}{\tilde{c}_t}=\xi n_t^{\nu}$$

$$\tilde{A}_t \tilde{k}_t^{\theta} n_t^{1-\theta} s_t^{1-\rho}=\tilde{c}_t$$

$$\tilde{A}_t \tilde{k}_t^{\theta} n_t^{1-\theta}(1-s_t)^{1-\rho}=\tilde{k}_{t+1}\left(\gamma_a \gamma_v exp(\varepsilon_{v,t+1}\right)^{\frac{1}{1-\theta}}-\tilde{k}_t(1-\delta)$$

$$s_t=\frac{\tilde{p}_t^{-\frac{1}{\rho}}}{1+\left(\tilde{p}_t\right)^{-\frac{1}{\rho}}}$$

B Figures

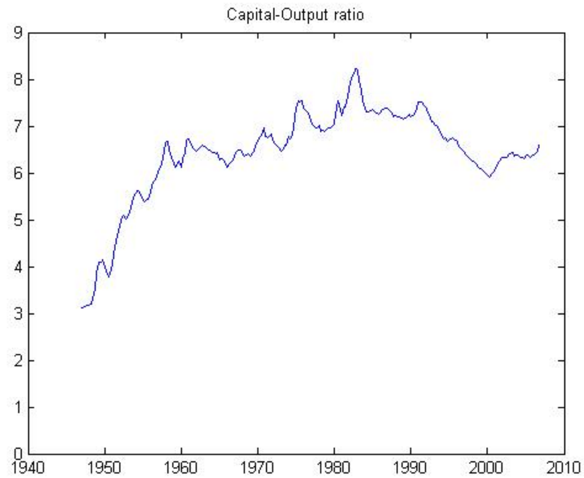

Figure 1: Capital Output Ratio

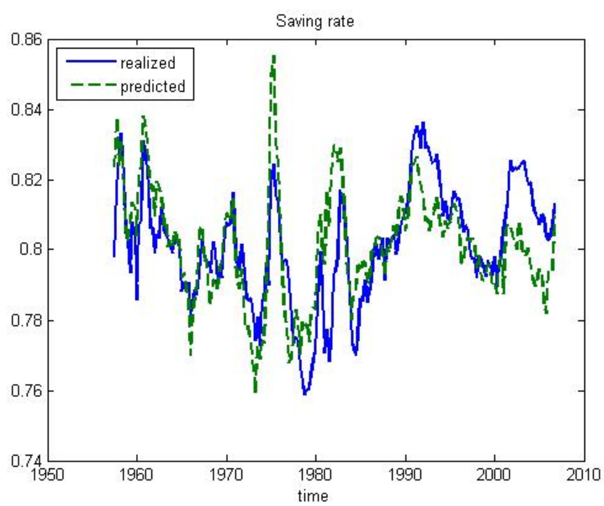

Figure 2: Saving Rate Fit

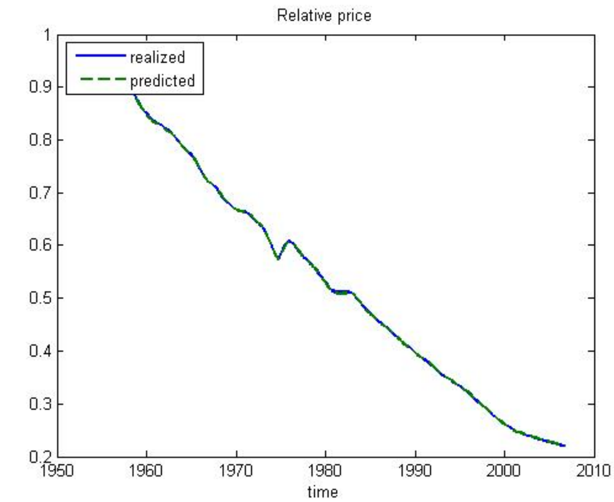

Figure 3: Relative Price Fit

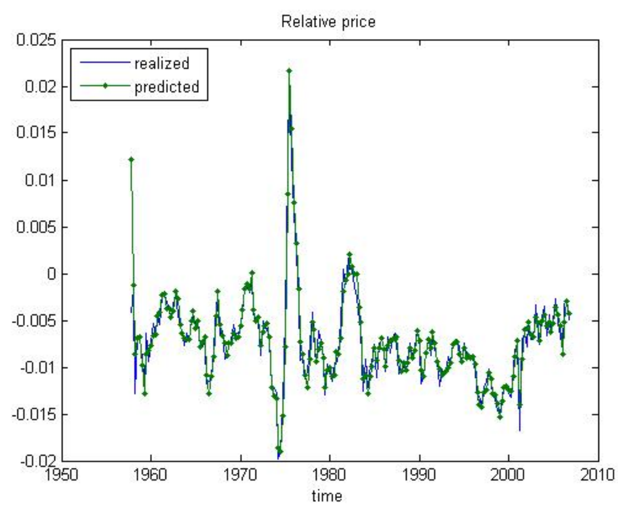

Figure 4: Change in Relative Price Fit

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