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QUASI-FIXED INPUTS AND LONG-RUN EQUILIBRIUM IN PRODUCTION: A COINTEGRATION ANALYSIS

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SUMMARY

This paper proposes a cointegration approach to testing the validity long-run equilibrium in production, where capital and labour are taken as quasi-fixed inputs. Previous studies consider only capital as the quasi-fixed input and do not take account of the time series properties of the variables, assuming implicitly that they are stationary. The canonical cointegrating regressions (CCR) procedure is employed to test for cointegration in both the single-equation and the seemingly unrelated regressions framework, and long-run equilibrium conditions are tested. The evidence from US manufacturing reveals that capital and labour are not fully adjusted to their long-run optimal values, casting doubt on the long-run equilibrium hypothesis.

1. INTRODUCTION

Most economic models rest on the assumption of long-run equilibrium, where all inputs (including capital) are fully and instantaneously adjusted due to changes in the economic environment, so that observed input levels reflect their long-run optimal levels. In many circumstances, however, firms are not in a position of long-run equilibrium. Rather, they may be at a short-run equilibrium with under- or over-utilization of capacity, or a short-run input usage that may differ from the long-run level.[1] Large input price fluctuations, high adjustment costs, regulatory and institutional constraints, and time lags introduced by physical constraints and learning effects would increase the likelihood of a short-run equilibrium. In this situation, a short-run, rather than long-run, model that allows for the fixity of capital or other inputs would be more appropriate and realistic.

A growing body of work based on short-run models examining issues in production and costs relating to input substitution, scale economics, capacity utilization, and productivity growth attests to the importance of a short-run equilibrium (see Brown and Christensen, 1981; Caves, Christensen, and Swanson, 1981; Halvorsen and Smith, 1986; Segerson and Squires, 1990; Kim, 1999). However, whether a long-run or short-run model is relevant is an empirical matter. To this end, there have been a few studies conducted to test for the validity of long-run equilibrium in production. Kulatilaka (1985), for instance, estimates a short-run cost function and tests whether observed and long-run values, or alternatively market and shadow prices, of capital are equal. He develops a t-test for equality at each sample observation and a chi-square test for joint equality for all observations. Schankerman and Nadiri (1986) employ the Hausman specification test. Their test

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[1] Long-run equilibrium is also referred to as full static or static equilibrium, and short-run equilibrium as partial static or temporary equilibrium (Brown and Christensen, 1981; Kulatilaka, 1985; Schankerman and Nadiri, 1986).

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involves instrumenting the capital variable and estimating a system of variable cost and factor demand equations by three-stage least squares. Conrad and Unger (1987) propose a likelihood ratio test. This test is based on the fact that, for the long-run equilibrium to be valid, the capital decision must reflect the firm's optimizing behaviour; thus the observed capital demand equation must be derived from the variable cost function.[2]

This study proposes an altogether different approach to testing the validity of long-run equilibrium in production and cost models. While previous studies consider capital as the only quasi-fixed input, labour use also appears to be constrained by many economic factors. This paper takes capital and labour as quasi-fixed inputs and considers stochastic technology shocks as the driving force of the short-run or long-run equilibrium process. In doing so, it presents a new econometric test based on cointegrating regression to examine the long-run equilibrium relation that might exist between observed and long-run quantities and/or prices of capital and labour. Previous studies do not explicitly allow for stochastic behaviour in the firm's optimization problem, and do not take into account the time series properties of the variables involved, assuming tacitly that they are stationary. If observed and long-run values of capital and labour are, in effect, non-stationary, then previous test procedures assuming the trend stationarity of variables may be inappropriate. Furthermore, as recent developments in time series analysis indicate, a necessary and sufficient condition for the existence of a long-run equilibrium between variables is that they are cointegrated. When observed and long-run quantities and/or prices of capital and labour are not cointegrated with some parameter restrictions, a long-run equilibrium does not hold.

Park's (1992) canonical cointegrating regression (CCR) procedure is employed to test for cointegration in the framework of both a single-equation and a system of seemingly unrelated regressions, and long-run equilibrium conditions are tested. The CCR procedure yields asymptotically efficient estimates that are free of nuisance parameter problems. It is especially useful in this study since it can deal with a system of structural equations.[3] The methodology is applied to annual US manufacturing data to ascertain whether a long-run or short-run equilibrium model is more appropriate in modelling the production structure.

The empirical evidence shows that capital and labour are not fully adjusted to their long-run optimal values, casting doubt on the long-run equilibrium hypothesis. This result is consistent with those of earlier studies that consider capital as the only quasi-fixed input (see Kulatilaka, 1985; Schankerman and Nadiri, 1986; Conrad and Unger, 1987). Moreover, the lack of cointegration and hence of a long-run run relationship found in this analysis is in accord with the standard assumption of non-stationary technology shocks (Rossana, 1995). It is also consistent with many economists' view that the unit root comes from the production side, and not the consumers' side. If many real economic variables are unit root non-stationary, then the non-stationarity must come from somewhere. The production side is the usual suspect (see King *et al.*, 1991; Ogaki, 1992).

2. QUASI-FIXED INPUTS AND STOCHASTIC LONG-RUN EQUILIBRIUM CONDITIONS IN PRODUCTION

In the long run, all inputs are instantaneously adjusted, so that their observed input levels reflect the long-run optimal levels. Thus, in the long run, all inputs are variable. In the short run, on the

[2] Another test that is often used is a partial adjustment or error-correction model (Friesen, 1992). This test, however, is not strictly a test of long-run equilibrium.

[3] Recently the structural form equations have attracted great attention in cointegration analysis. Pesaran (1997) forcibly argues for integration of cointegration analysis with structural econometric modeling.

other hand, some inputs are fully adjusted to their optimizing levels, but others are only partially adjusted. The former is referred to as variable inputs, and the latter as quasi-fixed inputs, i.e. fixed in the short run but variable in the long run. In this analysis, energy and materials are assumed to be variable inputs, while capital and labour are taken to be quasi-fixed inputs.

As a point of departure, we consider a short-run variable, or restricted, cost function.[4] The short-run cost function allows for the quasi-fixity of inputs and enables us to derive long-run equilibrium conditions. Moreover, random variation in data implies that the firm's choice involves a random or stochastic optimization problem. Incorporating the firm's random optimization behaviour, the short-run variable cost function can be written as

$$VC(y, \mathbf{w}, K, L, u, \varepsilon_K^+, \varepsilon_L^+) = G(y, \mathbf{w}, K, L) + \sum_{i=1}^{n} w_i u_i + K\varepsilon_K^+ + L\varepsilon_L^+ \tag{1}$$

where y is the output level, $\mathbf{w}$ is a vector of variable input prices, K and L are the quantities of capital and labour, and $VC = \sum iw_i x_i$ is the variable cost. Here w_i and x_i are the price and quantity of the ith variable input. In addition, u_i's, ε_K^+, and ε_L^+ represent stochastic technology shocks, which are assumed to be stationary. These shocks are assumed known to the firm but unknown to the researcher and to vary across firms according to a distribution that is free of y, $\mathbf{w}$, K, and L. In Equation (1), the firm's cost function is the sum of the deterministic cost function G (y, $\mathbf{w}$, K, L) and stochastic shocks for variable and quasi-fixed inputs.[5]

The short-run variable cost function (1) is linear homogeneous, non-decreasing, and concave with respect to $\mathbf{w}$ and non-increasing and convex in K and L. Application of Shephard's lemma gives the variable input demands:

$$x_i(y, \mathbf{w}, K, L, u_i) = \frac{\partial G}{\partial w_i} + u_i \tag{2}$$

Moreover, we have the following result:

$$-\frac{\partial G}{\partial K} \equiv P_K^*(y, \mathbf{w}, K, L) \tag{3}$$

and

$$-\frac{\partial G}{\partial L} \equiv P_L^*(y, \mathbf{w}, K, L) \tag{4}$$

where P_K^* and P_L^* are the shadow (or virtual) prices of capital and labour.

The short-run total cost C equals variable costs plus expenditures on capital and labour:

$$C(y, \mathbf{w}, P_K, P_L, K, L, u, \varepsilon_K^+, \varepsilon_L^+) = VC(y, \mathbf{w}, K, L, u, \varepsilon_K^+, \varepsilon_L^+) + P_K K + P_L L \tag{5}$$

where P_K and P_L are the market, rental prices of capital and labour. If capital and labour are, in effect, variable inputs, the firm will choose their optimal levels that minimize Equation (5), giving the equilibrium conditions:

$$P_K = -\frac{\partial VC}{\partial K^*} = P_K^*(y, \mathbf{w}, K^*, L^*) + \varepsilon_K^+ \tag{6}$$

[4] A theoretical discussion of a short-run model based on the variable cost function is provided by Brown and Christensen (1981); see also Caves, Christensen, and Swanson (1981).
[5] This specification of the stochastic cost function is an adaptation of McElroy (1987) and Brown and Walker (1995). Their analysis, however, rests on the long-run cost function and does not allow for stochastic properties of the time series.

and

$$P_L = -\frac{\partial VC}{\partial L^*} = P_L^*(y, \mathbf{w}, K^*, L^*) + \varepsilon_L^+ \tag{7}$$

where K^* and L^* are the optimal, equilibrium levels of capital and labour, and ε_K^+ and ε_L^+ represent short-run deviations from long-run equilibrium, resulting from technology shocks. These equations imply that capital and labour are at the equilibrium levels if and only if their market prices equal the shadow prices such that

$$K = K^+(y, \mathbf{w}, P_K, P_L) + \varepsilon_K \tag{8}$$

and

$$L = L^*(y, \mathbf{w}, P_K, P_L) + \varepsilon_L, \tag{9}$$

where $\varepsilon_K = (P_K^*)^{-1}(\varepsilon_K^+)$ and $\varepsilon_L = (P_L^*)^{-1}(\varepsilon_L^+)$, which have a distribution that is free of y, $\mathbf{w}$, P_K, and P_L. Now, when Equations (8) and (9) are substituted back into Equation (5), the long-run cost function C^* is obtained from the observed short-run cost function:

$$\begin{aligned} C^*(y, w, P_K, P_L, u, \varepsilon_K^+, \varepsilon_L^+) &= C(y, w, P_K, P_L, K^*(y, w, P_K, P_L) + \varepsilon_K, L^*(y, w, P_K, P_L) \\ &\quad + \varepsilon_L, u, \varepsilon_K^+, \varepsilon_L^+) \\ &= VC(y, w, K^*(y, w, P_K, P_L) + \varepsilon_K, L^*(y, w, P_K, P_L) + \varepsilon_L, u, \varepsilon_K^+, \varepsilon_L^+) \\ &\quad + P_K K^*(y, w, P_K, P_L) + P_L L^*(y, w, P_K, P_L) + P_K \varepsilon_K + P_L \varepsilon_L \end{aligned} \tag{10}$$

It is well known that the long-run cost curve is the envelope of short-run cost curves. If the firm is in long-run equilibrium in which both capital and labour are fully adjusted, the long-run cost equals the short-run cost. Algebraically, the long-run equilibrium condition is derived from the tangency point of short-run and long-run marginal cost curves. From Equation (5), we obtain the short-run marginal cost (SRMC) as

$$\text{SRMC} = \frac{\partial VC}{\partial y} \tag{11}$$

From Equation (10), the long-run marginal cost (LRMC) is given by

$$\text{LRMC} = \frac{\partial VC}{\partial y} + \frac{\partial VC}{\partial K^*}\frac{\partial K^*}{\partial y} + \frac{\partial VC}{\partial L^*}\frac{\partial L^*}{\partial y} + P_K\frac{\partial K^*}{\partial y} + P_L\frac{\partial L^*}{\partial y} \tag{12}$$

Equating SRMC and LRMC results in

$$\left(\frac{\partial VC}{\partial K^*} + P_K\right)\frac{\partial K^*}{\partial y} + \left(\frac{\partial VC}{\partial L^*} + P_L\right)\frac{\partial L^*}{\partial y} = 0 \tag{13}$$

which implies that Equations (6) and (7) are indeed the long-run equilibrium conditions when capital and labour are fully adjusted.

This discussion suggests that there are two alternative measures of testing for long-run equilibrium: quantity and price measures (see Kulatilaka, 1985). The quantity measure underlying Equations (8) and (9) involves testing whether the observed levels of capital and labour equal their associated long-run levels. The price measure composed of Equations (6) and (7), in contrast, checks whether the market (observed) prices of capital and labour equal their associated shadow (long-run) values. If the firm is in long-run equilibrium, the observed and long-run series should differ only because of sampling error. Large observed differences in the movements of the two series imply (subject to sampling error) statistically—and economically—important deviations from the long-run equilibrium. In this situation, the hypothesis of long-run equilibrium cannot be accepted.

The stationarity of technology shocks summarizes the long-run equilibrium implications. If technology shocks are stationary, any short-run divergences of capital and labour from long-run equilibrium will tend to be eliminated over time by equilibrating forces. Conversely, if the firm is in long-run equilibrium, then when a random shock disturbs the differential between observed and long-run quantities or prices of capital and labor, its effects are temporary and economic forces should cause the observed values to return to their optimal values over time. We then expect that $K - K^*(P_K - P_K^*)$ and $L - L^*(P_L - P_L{}^*)$ are jointly stationary.[6] This suggests that $K(P_K)$ and $L(P_L)$ are jointly cointegrated with $K^*(P_K^*)$ and $L^*(P_L{}^*)$ with a known normalized cointegrating vector $(1, -1)'$. However, if technology shocks are non-stationary, random shocks would permanently change the level of the variables so that observed and long-run values would drift apart over time in response to a shock. In that case, there would be no inherent tendency for observed values to maintain an optimal relationship with their long-run values, and a long-run equilibrium will not be obtained.[7]

3. ECONOMETRIC PROCEDURES: CANONICAL COINTEGRATING REGRESSION (CCR) APPROACH

This section discusses an econometric approach based on the CCR procedure applied to a system of cointegrating equations to test the long-run equilibrium hypothesis in production. We first consider the following system of equations:

$$K(t) = \alpha_K + \beta_K K^*(t) + \varepsilon_K(t) \tag{14}$$

and

$$L(t) = \alpha_L + \beta_L L^*(t) + \varepsilon_L(t) \tag{15}$$

or

$$P_K(t) = \alpha_K^+ + \beta_K^+ P_K^*(t) + \varepsilon_K^+(t) \tag{16}$$

and

$$P_L(t) = \alpha_L^+ + \beta_L^+ P_L^*(t) + \varepsilon_L^+(t) \tag{17}$$

where $K(t)(K^*(t))$ and $L(t)(L^*(t))$ are the observed (long-run) quantities of capital and labour at time t; $P_K(t)(P_K^*(t))$ and $P_L(t)(P_L{}^*(t))$ are the market (shadow) prices of capital and labour at time t; and α's ($\alpha^{+'}$s) and β's ($\beta^{+'}$s) are parameters to be estimated. The disturbances $\varepsilon(t) = (\varepsilon_K(t)$ and $\varepsilon_L(t))'(\varepsilon^+(t) = (\varepsilon^+{}_K(t), \varepsilon^+{}_L(t))')$ are assumed to follow a multivariate normal distribution with zero mean vector and non-zero variance–covariance matrix. Equations (14) and (15) pertain

[6] In this case, observed and long-run series have common stochastic trends (see Stock and Watson, 1988; King *et al.*, 1991).

[7] See Rossana (1995) for a similar discussion in the context of a cointegration analysis of input (labour) demand and input prices.

to the quantity measure, while (16) and (17) are relevant to the price measure used to test the long-run equilibrium conditions. In particular, long-run equilibrium requires that observed series, $K(t)(P_K(t))$ and $L(t)(P_L(t))$, be jointly cointegrated with their long-run values, $K^*(t)(P_K^*(t))$ and $L^*(t)(P_L{}^*(t))$, with the restrictions: $\alpha_K\ (\alpha^+{}_K) = \alpha_L(\alpha^+{}_L) = 0$ and $\beta_K(\beta^+{}_K) = \beta_L(\beta^+{}_L) = 1$, while these series are difference stationary.[8]

To estimate and test for a cointegrating relationship and long-run equilibrium, we consider the system of equations comprised of two equations, either (14) and (15) or (16) and (17), or four equations including all of them, as the system of seemingly unrelated regressions (SUR). It is now well known that the inference based on the classical asymptotic theory is often inappropriate for non-stationary series unless regressors are strongly exogenous (see Phillips and Durlauf, 1986; Stock, 1987; Park and Phillips, 1988). These authors demonstrate that the asymptotic distributions of OLS estimators typically involve some nuisance parameters. The CCR is a transformed regression formulated in such a way that the least squares procedure yields efficient estimates that are free of nuisance parameters. The required transformations involve adjustments of the integrated processes using the stationary components of the model. They are intended to correct for the presence of serial correlation in the residuals and for endogeneity caused by regressors and regression errors. Wald tests on the coefficients can be constructed to test hypotheses on the parameters of the cointegrating vectors.

The CCR procedure has some distinctive features. The CCR estimators have been shown to have good small-sample properties (Park and Ogaki, 1991; Han, 1996). The CCR procedure can deal with a system of structural equations and exploits the system-wide information on the presence of unit roots in individual series and the system error covariance structure. Since our analysis examines whether there is a cointegration for a system of two or four structural equations, the CCR procedure is particularly useful. While Johansen's (1988, 1991) VAR framework has been very useful in cointegration analysis, it is not appropriate for a structural model of a system of equations. The CCR procedure is extended to a system of seemingly unrelated cointegrating regressions by Park and Ogaki (1991).[9] The CCR method is combined with the variable addition approach (Park, 1990, 1992) to test for cointegration, taking the null of cointegration against the alternative hypothesis of no-cointegration. The commonly used tests of Engle and Granger (1987) and Johansen (1988) use no-cointegration as the null hypothesis. The variable addition approach simply adds superfluous regressors and tests whether the added terms are significant. When the regression has stationary errors, the usual Wald test should detect if the added regressors are superfluous. If, however, the regression has integrated errors, it is spurious (no cointegration) and the added regressors would be significant.

The CCR test is based on the following system of cointegrating regressions:

$$K(t) = \alpha_K + \beta_K K^*(t) + \sum_{i=1}^{q} \gamma_{Ki} Z_i(t) + \varepsilon_K(t) \tag{18}$$

[8] Thus long-run equilibrium is viewed here as an average relationship. Kulatilaka (1985), however, views it as holding for every observation.

[9] This study probably represents the first real application of the system-based CCR procedure within the context of SUR. Ogaki and Park (1998) and Ogaki (1992) also apply the system-based CCR procedure, but in a slightly different form mainly to deal with a cointegrated system with a trend stationary process. For applications of the single-equation CCR procedure, see Fisher and Park (1991), Corbae, Lim, and Ouliaris (1992), Baxter and Crucini (1995), and Cooley and Ogaki (1996).

and

$$L(t) = \alpha_L + \beta_L L^*(t) + \sum_{i=1}^{q} \gamma_{Li} Z_i(t) + \varepsilon_L(t) \tag{19}$$

or

$$P_K(t) = \alpha_K^+ + \beta_K^+ P_K^*(t) + \sum_{i=1}^{q} \gamma_{Ki}^+ Z_i(t) + \varepsilon_K^+(t) \tag{20}$$

and

$$P_L(t) = \alpha_L^+ + \beta_L^+ P_L^*(t) + \sum_{i=1}^{q} \gamma_{Li}^+ Z_i(t) + \varepsilon_L^+(t) \tag{21}$$

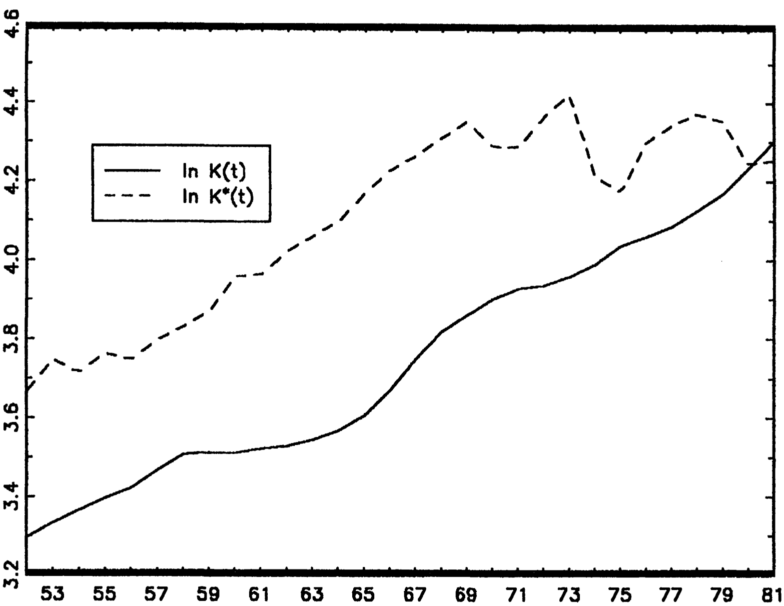
where the quantity and price series of capital and labour are transformed using an estimate of the long-run covariance matrix (see Park and Ogaki, 1991), and $Z_i(t)$ describes a set of spurious or superfluous regressors. Cointegration entails the restriction: $\gamma_{K1}(\gamma_{K1}^+) = \cdots \gamma_{Kq}(\gamma_{Kq}^+) = \gamma_{L1}(\gamma_{L1}^+) = \cdots = \gamma_{Lq}(\gamma_{Lq}^+) = 0$. The long-run equilibrium requires that the cointegration restriction be satisfied, with the additional restrictions: $\alpha_K(\alpha_K^+) = \alpha_L(\alpha_L^+) = 0$ and $\beta_K(\beta_K^+) = \beta_L(\beta_L^+) = 1$. Let $\mathrm{H}(p, q)$ (for $p < q$) be a Wald statistic that is calculated maintaining that the regression model contains a p th term of $Z_i(t)$, while $q - p$ terms of higher-order terms are added to test for the correctness of the model. The $\mathrm{H}(p, q)$ statistic is distributed asymptotically $\chi^2(q - p)$ under the null of cointegration.

4. TEST RESULTS

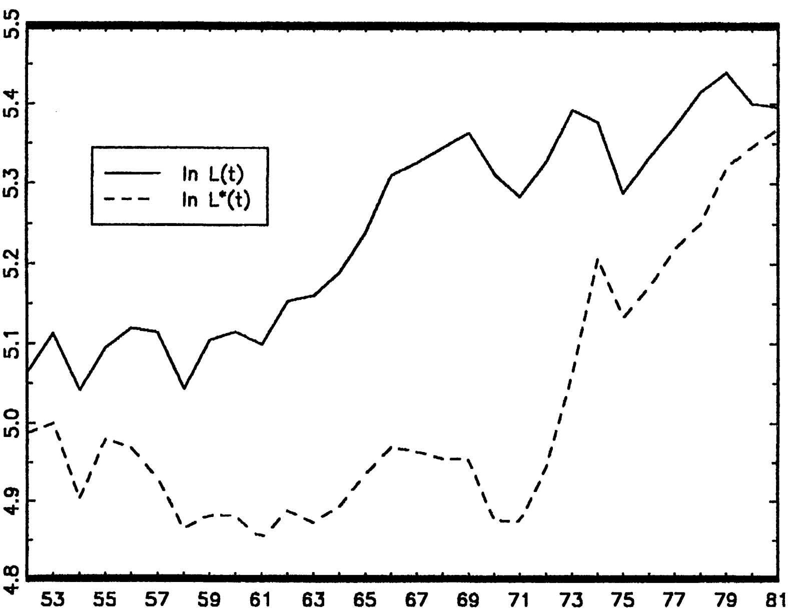
To test the long-run equilibrium conditions, we need the data series on observed and long-run quantities of capital and labour and their counterpart, market and shadow prices. The required data come from Morrison (1990). Morrison estimated the short-run variable cost function (1) for US manufacturing, 1952–81. Energy and materials are specified as variable inputs, and capital and labour are assumed to be quasi-fixed inputs. A generalized Leontief functional form is used to specify the variable cost function (1), and the three-stage least squares method is used to estimate it together with the variable input demand functions for energy and materials given in Equation (2). From the estimated cost function, Morrison obtained estimates of the optimal quantities and shadow prices of capital and labour, utilizing Equations (6) and (7). The data constructed by Morrison, of course, may suffer from measurement errors, but these errors are likely to be stationary.[10]

For empirical analysis, log forms are taken for the variables under study. The time paths of the four series used in this analysis are plotted in Figure 1. For the capital series, $\ln K^*$ has a slightly higher mean than $\ln K$, but $\ln K$ has a greater variability. For the labour series, $\ln L$ and $\ln L^*$ have approximately the same means, but $\ln L^*$ has a higher variance. For the capital price series, there are noticeable differences in means and variances for $\ln P_K$ and $\ln P_K^*$. $\ln P_K$ has a negative mean

[10] There could be possible measurement errors of raw variables such as capital and output series. Since shadow values of capital and labour are calculated from these raw series, these measurement errors will exacerbate the problem. However, as long as these errors are stationary, they may not affect our cointegration results. If they are non-stationary, the test results could be affected by their presence, and the result of non-cointegration may just reflect the existence of non-stationary measurement errors. Given the limitation of the data, we could not pursue further analysis on this matter, and they are assumed to be stationary.

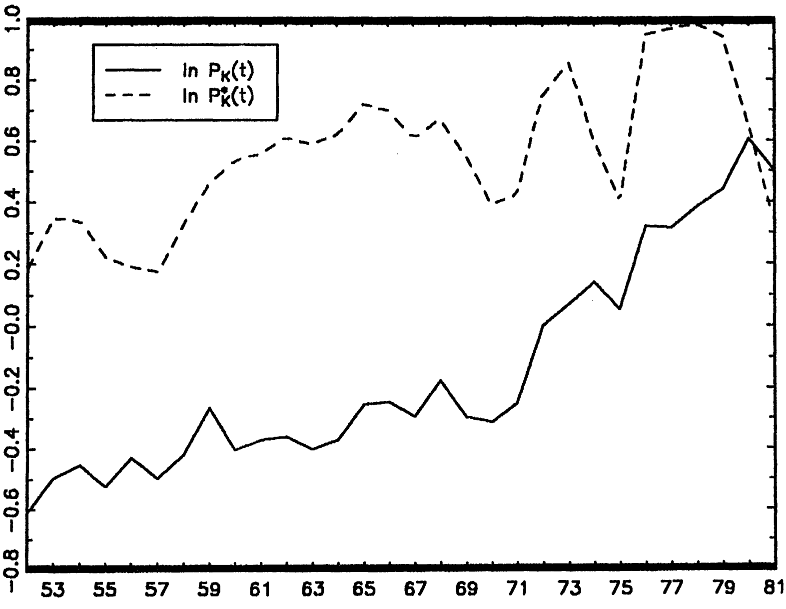


(a) Capital series

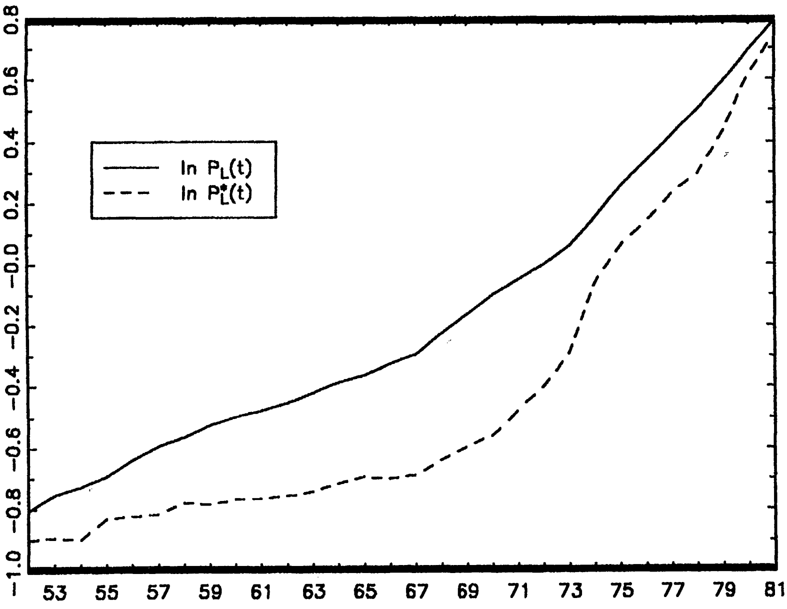


(b) Labor series

Figure 1. Plot of the data



(c) Capital price series



(d) Labor price series

Figure 1. (*continued*)

and has a greater variance than $\ln P_K^*$. Finally, for the labour price series, while there are some differences in the means of $\ln P_L$ and $\ln P_L{}^*$, the variances are roughly the same.

We first examine whether the variables of interest are difference stationary. Several unit root tests are employed: the augmented Dickey–Fuller (ADF) test (τ-statistic) (Said and Dickey, 1984, 1985), the Phillips–Perron (PP) test ($Z(t_\alpha)$) (Phillips and Perron, 1988), and the $\mathrm{J}(p, q)$ test of Park and Choi (1988) and Park (1990), which is based on the variable addition approach, employing polynomial time trends as superfluous regressors. These tests are based on the null of a unit root against the stationarity alternative. We also consider the KPSS test (Kwiatkowski *et al.*, 1992), taking the null hypothesis of stationarity. In addition, Andrew's (1991) automatic bandwidth selection procedure is used for most tests which requires estimates of the long-run error variances. Since the choice of the kernels is not critical, the results using the Parzen kernel are reported.

The results of the unit root and stationarity tests are presented in Table I.[11] The tests are conducted with and without a linear trend. The ADF and Phillips–Perron tests show that the unit root hypothesis is not rejected for all variables. For the $\mathrm{J}(p, q)$ test, the J(0,3) statistic does not allow for a linear trend, while the J(1,3) statistic allows for it. The results of the ADF and Phillips–Perron tests do not differ from the $\mathrm{J}(p, q)$ test. Meanwhile, the KPSS test provides mixed results. Taken together, these results suggest that it is reasonable to characterize the quantity and price series of capital and labour as being difference stationary. This finding in general does not depend on whether or not there is a time trend. We have also checked the possibility of a higher order of integration using the differenced series, but fail to find it.

We next test whether Equations (18) and (19), or (20) and (21), constitute a cointegrated system. As a preliminary experiment, we have applied the Phillips–Oularias (1990) test and the Johansen (1988, 1991) test. In contrast to the CCR test, these tests take no-cointegration as the

Table I. Unit root and stationarity tests

		$\ln K$	$\ln K^*$	$\ln L$	$\ln L^*$	$\ln P_K$	$\ln P_K^*$	$\ln P_L$	$\ln P_K^*$
ADF test[a]	Without trend	0.945	−1.79	0.551	0.517	1.23	−2.00	2.29	1.58
	With trend	−2.20	−0.240	−1.76	−1.38	−0.651	−0.206	0.283	−0.192
PP test[a]	Without trend	1.98	−1.90	−1.10	0.485	0.175	−2.43	5.90	4.77
	With trend	−0.386	−1.19	−2.80	−1.43	−1.88	−2.34	1.70	0.865
$\mathrm{J}(p, q)$ test[b]	J(0,3)	72.1	16.4	9.03	9.97	18.8	1.04	*671.0*	93.0
	J(1,3)	0.561	2.43	0.300	3.92	2.02	0.127	31.5	16.4
KPSS test[c]	Without trend	0.890	0.779	0.828	0.612	0.802	0.576	0.865	0.777
	With trend	0.129	0.209	0.100	0.212	0.204	0.084	0.227	0.228

Notes: The Parzen kernel and the optimal bandwidth selection procedure are used for the PP tests. For the ADF and the KPSS tests, the results with three augmented terms and four truncation lags are reported, respectively.
[a] Critical values of the ADF and PP t-tests without the trend are −3.58, −2.93 and −2.60 at the 1%, 5% and 10% levels, respectively, for the sample size 50, and they are −4.15, −3.50 and −3.18 for the tests with the trend.
[b] Critical values of the $\mathrm{J}(p, q)$ test are 0.010, 0.066 and 0.116 at the 1%, 5% and 10% levels. These are obtained from the Gauss COINT 2.0 package. The null of a unit root is rejected if the statistic is less than the critical value.
[c] Critical values of the KPSS test without the trend are 0.739, 0.463, and 0.347 at the 1%, 5% and 10% levels, respectively, and they are 0.216, 0.146 and 0.119 for the tests with the trend.

[11] All computations of the tests used in this paper were performed using and modifying the GAUSS software package COINT 1.5.

Table II. Preliminary cointegration tests

	$(\ln K, \ln K^*)$		$(\ln L, \ln L^*)$		$(\ln P_K, \ln P_K^*)$		$(\ln P_L, \ln P_L^*)$	
Phillips and Ouliaris[a]	$Z(\alpha)$	$Z(\tau)$	$Z(\alpha)$	$Z(\tau)$	$Z(\alpha)$	$Z(\tau)$	$Z(\alpha)$	$Z(\tau)$
Without trend	−0.649	−0.198	−3.95	−1.83	2.76	0.819	−4.76	−1.93
With trend	−5.77	−1.69	−13.2	−2.80	−5.63	−1.71	−14.2	−2.91
Johansen LR statistic[b]	$r \leq 0$	$r \leq 1$	$r \leq 0$	$r \leq 1$	$r \leq 0$	$r \leq 1$	$r \leq 0$	$r \leq 1$
$k = 2$	3.95	0.297	4.42	0.395	12.7	4.33	9.36	0.172
$k = 4$	6.45	0.373	6.23	0.002	9.43	2.86	11.3	0.570
	System with four variables $(\ln K, \ln K^*, \ln L, \ln L^*)$				System with four variables $(\ln P_K, \ln P_K^*, \ln P_L, \ln P_L^*)$			
Johansen LR statistic[c]	$r \leq 0$	$r \leq 1$	$r \leq 2$	$r \leq 3$	$r \leq 0$	$r \leq 1$	$r \leq 2$	$r \leq 3$
$k = 2$	60.74	35.33	17.33	4.70	59.81	29.70	15.82	4.16
$k = 4$	133.19	71.57	29.49	9.03	89.56	35.40	14.75	6.81

Notes: The Parzen kernel and the optimal bandwidth selection procedure are used for the Phillips and Ouliaris tests. For the Johansen LR test, the results imposing the no-trend restriction are reported.
[a] Critical values at the 5% level of the Phillips–Ouliaris test without the trend are −20.5 and −3.37 for the $Z(\alpha)$ and $Z(\tau)$ tests, respectively. With the trend, they are −21.5 and −3.42.
[b] Critical values at the 5% level of the Johansen LR test are 17.84 for the hypothesis $r \leq 0$, and 8.08 for the hypothesis $r \leq 1$, respectively, where r is the number of cointegrating vectors.
[c] Corresponding critical values at the 5% level are 48.42, 31.26, 17.84 and 8.08 for $r \leq 0, r \leq 1, r \leq 2, r \leq 3$ respectively.

null hypothesis. The test results are presented in Table II. The Phillips–Ouliaris test results show that the null hypothesis of no cointegration is decisively not rejected for all equations at the 5% significance level. This result does not depend on whether or not there is a time trend. The Johansen tests are performed using each of Equations (18) to (21). The same tests are performed additionally for a system of four variables with either quantity or price variables. We use the different VAR lag lengths (k), and the results using $k = 2$ and 4 are reported. The test results provide evidence against cointegration for all equations, and they are robust to the trend specifications and the lag selections. Overall these results suggest that observed and long-run series of capital and labour are not cointegrated regardless of whether the quantity or price measure is used. Note, however, that they are obtained from a pair of variables from the single equations or from a set of variables of different measures.

We now provide the CCR test results using both single-equation and system estimation methods. To test for cointegration, we have considered several choices of superfluous regressors. We have first employed polynomial time trends suggested by Park (1990) and Ogaki and Park (1998). This procedure requires a correct specification of the deterministic trend terms. Higher orders of the trend terms are obviously not appropriate in our case, and we have accordingly chosen to use $\mathrm{H}(0, q)$ and $\mathrm{H}(1, q)$ statistics. The $\mathrm{H}(0, q)$ statistic tests for the null hypothesis of cointegration without a linear trend, but the $\mathrm{H}(1, q)$ statistic allows for a linear trend.[12] As an alternative superfluous regressor, we have considered the random walk process. Since the cointegration test result is governed by the generated random walk process, we have adopted a simple Monte Carlo experiment with 5000 replications in which we repeatedly generate q

[12] If the series contains a trend, the $\mathrm{H}(0, q)$ test is viewed as a test for deterministic cointegration, while the $\mathrm{H}(1, q)$ test is used as a test for stochastic cointegration (see Ogaki, 1992; Ogaki and Park, 1998).

Table III. Cointegration and long-run equilibrium tests: Single-equation CCR

Superfluous regressors	Test statistics	$(\ln K, \ln K^*)$		$(\ln L, \ln L^*)$		$(\ln P_K, \ln P_K^*)$		$(\ln P_L, \ln P_L^*)$	
		Coint. test[a]	Joint test[b]	Coint. test[a]	Joint test[b]	Coint. test[a]	Joint test[b]	Coint. test[a]	Joint test[b]
Polynomial trends	H(0,1)[c]	0.003	231.0	0.020	167.0	3.92	*1307.0*	0.054	96.1
		(0.959)	(0.000)	(0.889)	(0.000)	(0.048)	(0.000)	(0.817)	(0.000)
	H(0,2)[c]	11.73	243.5	27.76	195.6	7.24	*1311.0*	12.84	*1416.0*
		(0.003)	(0.000)	(0.000)	(0.000)	(0.027)	(0.000)	(0.002)	(0.000)
	H(0,3)[c]	13.04	244.8	28.96	196.8	112.0	*1416.0*	13.74	109.7
		(0.005)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.003)	(0.000)
	H(1,2)[c]	11.73	71.83	27.74	95.90	3.32	209.0	12.79	43.22
		(0.001)	(0.000)	(0.000)	(0.000)	(0.068)	(0.000)	(0.000)	(0.000)
	H(1,3)[c]	13.0	78.1	28.9	97.1	108.0	*314.0*	13.7	42.1
		(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
Random walk	H(0,3)[d]	17.3%	0.0%	22.9%	0.0%	21.3%	0.0%	31.2	0.0%
	H(1,3)[d]	13.4%	0.0%	11.4%	0.0%	0.42%	0.0%	21.3%	0.0%
		Estimated parameters[e]							
		Coeff. (t stat.)		Coeff. (t stat.)		Coeff. (t stat.)		Coeff. (t stat.)	
	α_K	−0.661 (−1.77)							
	β_K	1.07 (11.80)							
	α_L			2.60 (3.92)					
	β_L			0.529 (4.01)					
	α_K^+					−0.615 (-4.80)			
	β_K^+					0.895 (4.12)			
	α_L^+							0.221 (5.27)	
	β_L^+							0.902 (11.40)	

Notes: The Parzen kernel and the optimal bandwidth selection procedure are used for estimating error variances.
[a] Wald statistics for the hypotheses that the coefficients of superfluous regressors are insignificant. The degree of freedom of the test is $(q-p)$ for H(p, q) tests.
[b] Wald statistics for the joint hypothesis that the coefficients of superfluous regressors are insignificant and the long-run equilibrium restrictions are satisfied. The degree of freedom of the test is $(q-p)+2$ for H(p, q) tests.
[c] P-values in parentheses.
[d] Percentages of acceptances at the 10% level from 5000 replications for the hypothesis that the coefficients of superfluous random walk regressors are insignificant.
[e] t-values in parentheses. They are obtained from the CCR estimation of the model where no linear trend is allowed.

random walk processes and evaluate the percentages of acceptance for the null hypothesis of cointegration.[13]

Table III reports test results from the single-equation CCR procedure, which does not use the cross-equation information. When polynomial time trends are used as superfluous regressors, the null hypothesis of cointegration is rejected at the 5% level for all cases from the H(0,2), H(0,3), H(1,2), and H(1,3) tests, except for the H(0,1) test[14] (see columns with 'Coint. test'). The tests with $q > 3$ produce the same results (not reported). These results suggest that cointegration does not

[13] Park (1990, p. 119) shows that the asymptotic distribution of the Wald tests using random walk processes is χ^2 distributed asymptotically. Referees, however, point out that this result could be interpreted as *ad-hoc* evidence, since the asymptotic behaviour of the simulation-based tests is not yet examined.

[14] The H(0,1) test indicates that the null hypothesis is not rejected for all cases, except for a pair of $\ln P_k$ and $\ln P_K^*$ for which the null is marginally rejected at the 5% level, but not at the 2.5% level.

exist for all equations. When random walk processes are used as alternative superfluous variables, the percentage of acceptance at the 10% significance level ranges from 0.42% to 31.2%, indicating substantial rejections of cointegration. Thus we conclude that observed and long-run quantities or prices of capital and labour are not cointegrated.[15]

The test of cointegration is a precursor to the long-run equilibrium test, and the absence of cointegration indicates that long-run equilibrium is not satisfied. However, the long-run equilibrium conditions require that observed and long-run series of capital and/or labour be cointegrated with the cointegrating vector $(1, -1)'$. Thus a cointegration analysis with these parameter restrictions would be desirable. A Wald test for the joint hypothesis of cointegration and long-run equilibrium restrictions is conducted. The results in Table III (columns with 'Joint test') show that the joint hypotheses are not accepted for all cases, which clearly suggests the absence of long-run equilibrium. Table III also presents the estimated parameters from the CCR estimation imposing the no-trend restriction. While these estimates may be informative for usual hypothesis testing, they are not useful in our case since there is no cointegrating relationship between variables.

The system estimation results for the CCR test are displayed in Table IV. For the system-based CCR procedure, we take the equations consisting of (18) and (19), or alternatively (20) and (21), as a system of seemingly unrelated regressions, and test whether they form a cointegrated system. Additionally, we have considered a system of equations using all four equations and tested the same hypothesis. The system estimation method offers a potential to improve upon the single-equation estimation method by exploiting information in cross-equation correlations of the disturbances. The system-based CCR test statistic also follows the chi-square distribution (Park and Ogaki, 1991). As in the case of the single-equation CCR procedure, two different measures of superfluous variables are considered. When polynomial time trends are used as superfluous regressors, the $H(0, q)$ and $H(1, q)$ statistics indicate that cointegration does not exist between the observed and long-run series for all systems of equations. When random walk processes are used as superfluous regressors, the percentage of acceptance of cointegration at the 10% significance level ranges from 4.32% to 22.9%, suggesting substantial rejections of cointegration. Thus there appears abundant evidence against cointegration. This result holds whether the quantity or price measure, or both measures, is used. The Wald tests also reject the joint hypothesis of cointegration and long-run equilibrium restrictions for all cases, suggesting the absence of long-run equilibrium.

A comparison of single-equation and system-based CCR methods suggests that the results are robust to the choice of an estimation method. Moreover, the finding that long-run equilibrium is not valid for US manufacturing is in accord with that of Kulatilaka (1985) who used almost the same data. Schankerman and Nadiri (1986) and Conrad and Unger(1987) also found that long-run equilibrium does not exist for other industries. Segerson and Squires (1990), on the other hand, found that long-run equilibrium holds for the fishing industry. These studies, however, considered capital as the only quasi-fixed input, and none of them has employed the cointegration procedure.

5. CONCLUSION

This paper has adopted a cointegration test to examine the validity of long-run equilibrium in production and cost models. Single-equation and system-based CCR methods are used to test

[15] In an earlier version (integrated) variable input prices were considered as superfluous regressors, which shows the lack of cointegration. A referee has pointed out that if these input prices are actually stationary, then the variable addition test does not work and that if they are integrated and cointegrated with long-run values, then the coefficients are not identified and the test breaks down again.

Table IV. Cointegration and long-run equilibrium tests: System-based CCR

Superfluous regressors	Test statistics	Two equations ($\ln K, \ln K^*$) ($\ln L, \ln L^*$)		Two equations ($\ln P_K, \ln P_K^*$) ($\ln P_L, \ln P_L{}^*$)		Four equations ($\ln K, \ln K^*$) ($\ln L, \ln L^*$) ($\ln P_K, \ln P_K^*$) ($\ln P_L, \ln P_L{}^*$)	
		Coint. test[a]	Joint test[b]	Coint. test[a]	Joint test[b]	Coint. test[a]	Joint test[b]
Polynomial trends	H(0,1)[c]	0.055	121.0	0.108	63.7	39.03	2971.7
		(0.973)	(0.000)	(0.948)	(0.000)	(0.000)	(0.000)
	H(0,2)[c]	27.16	355.0	66.6	562.0	84.80	5135.7
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	H(0,3)[c]	34.50	429.7	127.5	790.7	107.4	6325.1
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	H(1,2)[c]	27.14	125.1	77.72	241.0	31.06	1872.7
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	H(1,3)[c]	34.50	151.0	126.0	336.0	45.89	2276.7
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Random walk	H(0,3)[d]	17.3%	0.0%	22.9%	0.0%	4.32%	0.0%
	H(1,3)[d]	19.3%	0.0%	6.60%	0.0%	8.70%	0.0%
		Estimated parameters[e]					
		Coeff. (t stat.)		Coeff. (t stat.)		Coeff. (t stat.)	
	α_K	−0.669 (−1.77)				1.32 (2.64)	
	β_K	1.08 (7.00)				0.592 (4.87)	
	α_L	2.39 (2.30)				3.77 (6.56)	
	β_L	0.571 (2.76)				0.295 (2.58)	
	α_K^+			−0.567 (−2.25)		−0.167 (−5.01)	
	$\beta_K{}^+$			0.757 (1.88)		0.055 (0.110)	
	α_L^+			0.242 (3.83)		0.124 (5.78)	
	$\beta_L{}^+$			0.944 (8.11)		0.672 (21.6)	

Notes: The Parzen kernel and the optimal bandwidth selection procedure are used for estimating error variances.
[a] Wald statistics for the hypotheses that the coefficients of superfluous regressors are insignificant. The degree of freedom of the test is $2 \times (q - p)$ for $H(p, q)$ tests.
[b] Wald statistics for the joint hypothesis that the coefficients of superfluous regressors are insignificant and the long-run equilibrium restrictions are satisfied. The degree of freedom of the test is $2 \times (2 + q - p)$ for $H(p, q)$ tests.
[c] P-values in parentheses.
[d] Percentages of acceptances at the 10% level from 5000 replications for the hypothesis that the coefficients of superfluous random walk regressors are insignificant.
[e] t-values in parentheses. They are obtained from the CCR estimation of the model where no linear trend is allowed.

for cointegration, and long-run equilibrium conditions are then tested. The results show that the assumption of long-run equilibrium is not valid for US manufacturing. Given the power of tests based on large sample size, this conclusion, however, should be interpreted as suggestive rather than conclusive because of the small sample utilized and the rather low power of the tests with such a sample.[16]

[16] In addition, our—and existing—cointegration tests are based on linearity in cointegrating relationships. However, even if there exists no linear long-run relationships between the main variables of the model, it does not necessarily follow that there are no long-run relations (possibly non-linear ones) among the variables. In fact, it is very likely that when the process of technological shock contains a unit root, the long-run relations of the model (when they exist) would be non-linear. Binder and Pesaran (1996) explicitly consider the issue of a unit root in technology shocks in the context of the Solow growth model. In this case, the long-run relationship they find is non-linear and involves output growth and the

The rejection of the long-run equilibrium hypothesis implies the relevance of a short-run framework that accounts for quasi-fixity of capital and labour in empirical analysis. Most analyses have treated labour as a variable input, which is not substantiated here. The short-run model is capable of separating the short-run and long-run effects. However, a short-run model is also appropriate even if the firm is in long-run equilibrium. Here, the observed, short-run levels of capital and labour coincide with their long-run optimal levels; hence, short-run and long-run equilibrium conditions are equivalent and either model is appropriate. Moreover, in this study, adjustment costs are not included in the test of long-run equilibrium in order to ensure that rejection or acceptance does not depend on the specification of the dynamic adjustment process.[17] However, to the extent that capital and labour are not fully adjusted in response to changes in economic conditions, adjustment costs become a source of a short-run equilibrium. Adjustment costs would then have to be incorporated explicitly into the short-run model. Several empirical studies on production and labour have appeared using the dynamic adjustment cost framework (see Morrison and Berndt, 1981; Kim, 1989; Hamermesh, 1992). A cointegration analysis with the dynamic adjustment cost model appears to be a fruitful direction to pursue in examining many issues of production and costs that static models cannot adequately address.[18]

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capital–output ratio. While logs of output and capital are not linearly cointegrated in their model, the growth of output and a non-linear function of the capital–output ratio form a cointegrating relation. We are grateful to M. Hashem Pesaran for pointing this out to us.

[17] All previous tests of long-run equilibrium are based on this assumption.

[18] See Pfann and Palm (1993) for such an attempt in the context of dynamic labour demand.

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