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Economic Growth, Technological Progress and Energy Use in the US over the Last Century: Identifying Common Trends and Structural Change in Macroeconomic Time Series

Benjamin Warr
Robert Ayres
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Economic growth, technological progress and energy use in the US over the last century: Identifying common trends and structural change in macroeconomic time series.

Benjamin Warr*
And
Robert Ayres**

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"*Energy is eternal delight*" Walter Blake (1757-1827)

"Our energy is in proportion to the resistance it meets" William Hazlitt (1778-1830)

* Visiting Professor, IBiS, INSEAD, Boulevard de Constance, 77305 Fontainebleau Cedex, France.

** IIASA, Laxenburg, Austria.

Abstract

In this paper we argue two theses. First, we suggest that economies evolve along a long-term trajectory that corresponds closely to increases in the production and consumption of *useful work* (in the thermodynamic sense) rather than energy (exergy) inputs *per se*. Second, we argue that when economies experience sudden shocks and structural changes, due (for instance) to wars or major depressions, they are accompanied by significant changes in the quantity and patterns of energy (exergy) consumption and useful work output. To support these assertions we have performed unit root and structural change tests to characterise the temporal behaviour of the factors of production. These results have implications for understanding the role of energy in the economy, for modelling co-variation between output and factor inputs and for identification of the most appropriate form of the production function.

1. Rationale

Economies appear to evolve along a long term trajectory driven by technological progress, in which the factors of production maintain a fairly stable relationship to each other. This behaviour resembles a kind of "self-organisation". However, economies also react to sudden shocks or discontinuities. Commonly cited examples identified from previous time series analysis include major wars (WW I and WWII), the Great Depression (1930-34), and more recently the oil-price shock of 1973-74 (Dickey and Fuller 1979; Dickey and Fuller 1981; Perron 1989; Perron 1994). Long term economic growth reflects the underlying dynamics of technological progress. Discontinuities may correspond to clusters of major innovations focused on overcoming a barrier or exploiting a new opportunity. Not surprisingly these discontinuities also relate to important and sudden changes in the quantity, patterns and efficiency with which energy is used.

However, most time series analyses to date have not incorporated physical measures of energy (exergy) production, consumption or use.[1] Instead they have used aggregate energy prices, or production/consumption in monetary terms, as proxies. Yet, it is evident that each transitory shock (such as a war) was accompanied by major changes in the quantity, patterns and efficiency of energy consumption. These changes, in turn, are likely to have influenced – to differing degrees – both the cyclical fluctuations and long-term trends in output growth. The reasons for this neglect by previous studies can be partly attributed to the lack of availability of reliable time series describing the quantitative flows or energy (exergy) and useful work[2] inputs to the economy, by sector or function. Neoclassical theory, which sees energy inputs as a consequence of economic activity and growth, rather than as a co-driver, is also partly responsible for the lack of attention to the statistical attributes of these time series.

We have previously estimated a detailed time series of the exergy inputs and useful work delivered to the US economy from 1900 through 1998 (Ayres, Ayres et al. 2003), making it possible to undertake just such an empirical investigation. The immediate purpose of this paper is to characterise and compare the historical trends in factor inputs and output growth from a statistical perspective. This should provide information concerning the underlying data generating processes, as necessary for subsequent cointegration and causality analysis. The ultimate aim, of course, is to facilitate the selection of an appropriate production function to explain output growth.

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[1] Strictly speaking energy is conserved, exergy is consumed.

[2] We describe useful work in the following section.

2. Background

We have noted elsewhere (Ayres and Warr 2002; Ayres, Ayres et al. 2003; Ayres and Warr 2005) that technological progress in the past century, has led to consistent reductions in the cost of energy (*exergy*) and *useful work* (*exergy services*) delivered to a user. Moreover, we have argued that these innovations have been central to the economic growth process. A brief explanation of terminology is important at this point. Exergy, B is the technical term for useful (*available*) energy, i.e. the energy that can be used to do useful work, U. For example, high temperature steam is available to do work, whereas room temperature water is not. A precise definition of *availability* can be found in thermodynamic textbooks and need not trouble us here. Energy (exergy) inputs to the economic system include fossil fuels, of course, but also nuclear fission, solar heat, photovoltaic electricity (PV), wind, flowing water, and biomass.

Useful work consists of four distinct types. They are as follows: (1) *muscle work* by animals and humans, (2) *mechanical work* performed by machines, including internal combustion engines, and steam turbines (for electric power generation), (3) *electrical work* (e.g. lighting, electrolysis, motor drive) and (4) *thermal work,* including cooking, water heating and space heating. These are all examples of *energy (exergy) services*. Moreover, these services are quantifiable and can be calculated with reasonable accuracy, based on published statistics on the inputs plus some engineering data[3]. Hereafter we drop the familiar, but misleading term *energy* in favour of the correct term, *exergy*.

Power, a more familiar term, is a measure of useful work performed per unit time. However, power requirements (and outputs) for vehicles, for instance, are quite variable. Maximum power is needed only for acceleration or takeoff (e.g. of an airplane) but most engines operate far below maximum power output most of the time. There are statistics on the total rated (maximum) horsepower of prime movers installed in the US, but these data are not easily converted to useful work performed.

The ratio of exergy service output (for any category) to exergy inputs is a pure number between zero and unity. It can be interpreted as the *efficiency of conversion* of exergy inputs to service (work) outputs. Moreover, this thermodynamic efficiency is a quantitative measure of the state of technology, either by function (such as transport or space heating), or in the aggregate for the economy as a whole. N.B. thermodynamic efficiency as defined here must *not* be confused with economic efficiency, as that term is normally used by economists. In general, thermodynamic efficiency increases monotonically over time. Figure 1 shows our calculated estimate of the aggregate thermodynamic efficiency for the US for the period 1900-2000.

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[3] Our estimated time series of the energy inputs and the various components of useful work, from 1900 through 1998, have been published elsewhere (Ayres, Ayres et al. 2003) and for electricity use efficiency (Ayres, Ayres et al. 2005).

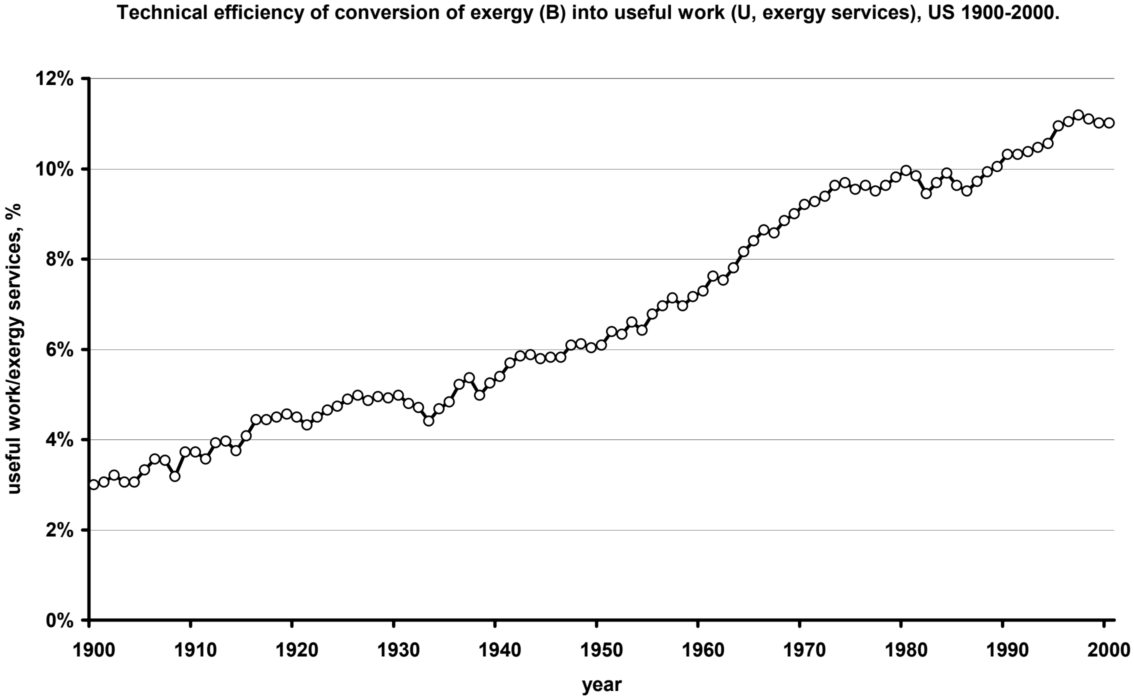

Figure 1. Exergy to useful work conversion efficiencies, US and Japan 1900 to 2000

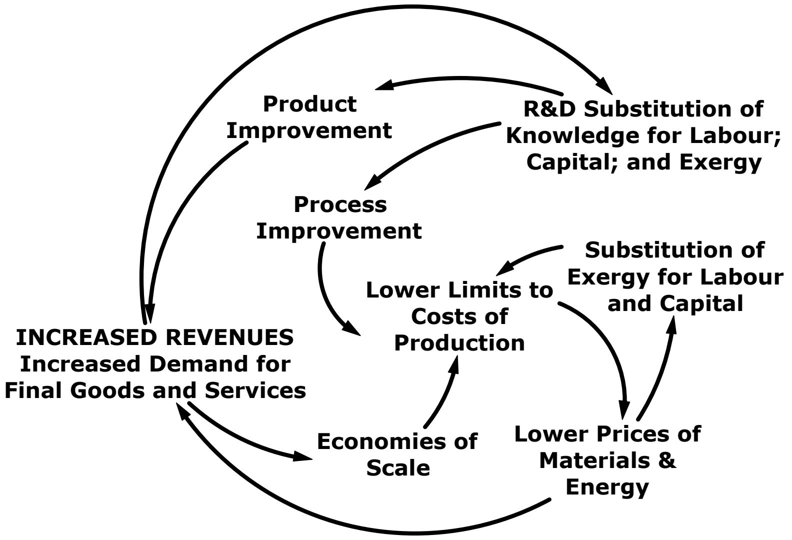

Figure 2. The Salter Cycle

The important point, for our present purposes, is that as the exergy conversion efficiency has increased, the cost of useful work (or power) delivered to a point of use, has declined. Indeed, it is qualitatively clear that the cost of power and work have been declining fairly steadily for more than two centuries. Declining costs drive year-on-year increases in energy/work consumption including all of the downstream goods and services depending on energy or useful work inputs. Unfortunately, except for electric power, direct cost-of-useful-work data for most functional categories are not readily available and must be estimated by indirect methods. Hence we have had to estimate the output of useful work by the economy, rather than the cost.

We have already argued that the increasing thermodynamic efficiency of the economy as a whole is closely related to the familiar measure of `total factor productivity' or TFP. We believe that this process has been the major driver of growth over the 19th and 20th centuries through a positive feedback mechanism outlined in Figure 2 (Ayres and Warr 2005). While information technology may have begun to have a measurable impact on growth in the past two decades, it is nevertheless worrying that costs of exergy (fuel) inputs are no longer falling and appear likely to rise as the cheapest sources of petroleum and natural gas are showing signs of exhaustion. Moreover, the rate of technological improvement – as reflected in the efficiency of conversion of exergy inputs to useful work, on the macroeconomic scale – has slowed over the past 20 years. Whether, under these conditions we can expect economic growth to continue indefinitely at historical rates is a major concern for economic and technology policy-makers, not to mention future generations.

As mentioned already, we argue that energy services, or more specifically useful work, in the above sense, is the key to a quantifiable endogenous theory of economic growth (Warr and Ayres). We have also demonstrated that a production function including useful work, along with capital and labour, as conventionally defined and measured, can "explain" past US growth without the need for an exogenous time-dependent multiplier (TFP). If this endogenous theory of growth can be substantiated, it follows that useful work is arguably an important - perhaps the most important - factor of production.

However, the validity of any theory of growth cannot be asserted *a priori* without further qualification. In brief, it depends upon whether the time series used in the model (capital, labour, exergy or useful work, and ratios thereof) truly represent coherent self-organized underlying processes driving output growth, and whether there is a consistent long-term relationship among them. More specifically, several questions need to be addressed, as follows:

1. *Do the time series have a common underlying data generating process? In ordinary language, does the value at any given time depend upon previous values, and if so how?*
2. *Do the different time series exhibit evidence of external shocks leading to structural changes at (more or less) the same times?*
3. *What are the implications for subsequent multivariate analysis? In particular does the implicit relationship among the variables remain the same, regardless of such shocks?*
4. *To what extent are structural changes and trends in output growth related to efficiency and quantities of energy supplies, labour productivity and capital accumulation, and ratios thereof?*

This paper addresses the above questions using statistical tools and tests.

3. Data and Methodology

We have compiled a number of historical macro-economic time series of GDP (Y) capital (K), labour (L), exergy (B) and useful work (U) for the US from 1900 to 1998, and indexed each series to 1900 (1900 = 1)[4], labelled using lower case letters (*y, k, l, b* and *u*). We used the indexed series to calculate ratios of the factors. For convenience, *extensive* (as contrasted with *intensive*) economic variables are usually transformed to logarithms in order to eliminate the exponential growth component. The logarithmic transform can then be regarded as the sum of an unpredictable stochastic component, and a predictable deterministic trend or combination of cyclic fluctuations. The stochastic component consists of random

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[4] We describe in detail the sources of the data and provide the time series in indexed form (1900 = 1°) in the appendix.

deviations and measurement errors as well as exogenous shocks that have permanent effects on the level of the transformed time series. However, classical regression analysis assumes that the stochastic terms are taken from a normal distribution that is invariant over time. If this condition is met the mean, variance and auto-covariance are constant and the data generating process is said to be *stationary*. In this case the standard statistical tests and regression procedures are valid. However, if the stochastic terms are taken from a distribution function that depends on time, i.e. the conditions for stationarity are not met, and the regressions may be *spurious* (Granger and Newbold 1974).

The principal tools to characterise the distribution of fluctuation - i.e. the underlying data generating process (DGP) - are so-called *'unit root'* tests (Dickey and Fuller 1979; Perron 1989). Unit root tests applied to a time series determine whether the mean, variance or autocorrelation exhibit permanent shocks over time or whether they do not remain within finite bounds. If the fluctuations are not bounded the time series is non-stationary and a unit root is said to exist. Non-stationary time series which possess a unit root and are stationary after differencing are said to be *integrated of order,* I(1), where the term 'integrated' refers to the summation of the error term over time. Such a variable exhibits systematic (non-random) behaviour, but the pattern of the variation may be hard to predict.

Statistical unit root tests are not perfect having a poor ability to detect a false null hypothesis if there is a structural change in the mean of the variable. In other words, they tend to be biased in favour of a unit root hypothesis in the presence of a structural break [Perron 1989; Perron 1990]. The implication of such a result is that every shock determines a new growth path, posing clear problems for forecasting. The problem arises because there is no attempt to distinguish between a unit root process from a trend stationary series with breaks in the trend function. If we can accept that that the series are not characterised by the presence of a unit root but by stationary fluctuations around a breaking deterministic trend, we can infer that the fluctuations in the series are transitory and that the long run growth path itself does not fluctuate (Li 2000). Clearly, forecasting long run output growth is simpler if the long run trend remains stable and shocks are transitory.

To overcome these problems, given the questions we seek to answer, our methodology necessarily involves both unit root tests and independent tests for structural change, as outlined in Figure 3. Each subsequent test enables us to refine our responses and correctly eliminate non-significant series. Once the existence of a common data generating process is confirmed, we test a series of alternative "production functions". This procedure serves two purposes, firstly to characterise the multivariate relations between the factor inputs, and secondly to identify the most suitable production function among those tested[5].

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[5] In this paper we consider only the Cobb-Douglas form of the production function.

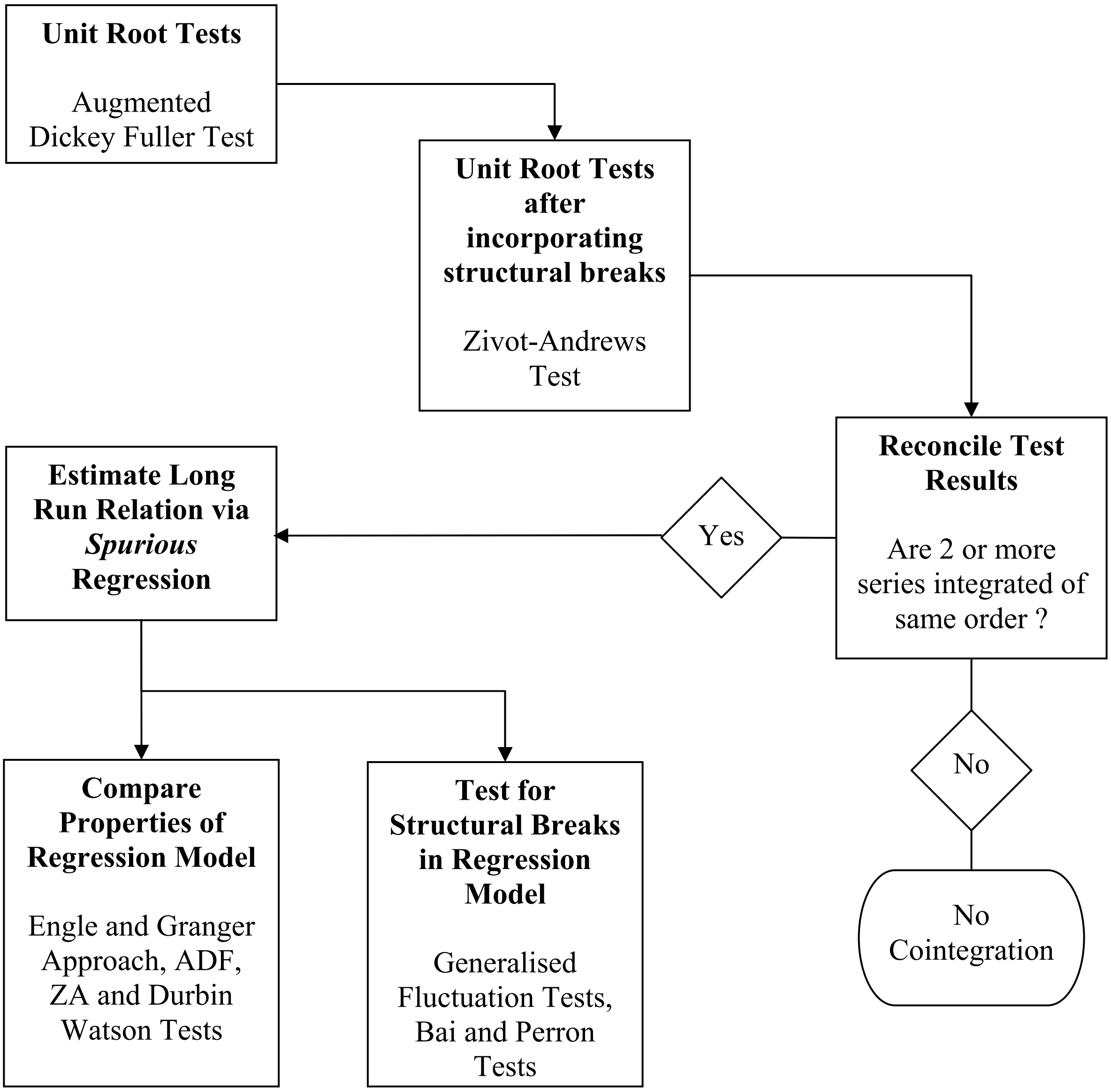

Figure 3. Methodological Framework

3.1 Unit root tests

Since the development of the first tests by Dickey and Fuller (DF tests) (Dickey and Fuller 1979) many alternative unit root tests and modifications have been formulated to deal with various assumptions and problems. In the next section we compare the results obtained by alternative methods. The DF test is applicable to the simplest first-order regressive model AR(1). Results are valid only under the assumption that there exists no serial correlation in the random disturbances. The Augmented Dickey-Fuller (ADF) test is an extension of DF applicable to *p*-th order auto-regressive AR(*p*) processes (Dickey and Fuller 1981), allowing a 'general-to-specific' approach (Seddighi, Lawler et al. 2000). The general model is as follows:

$$\Delta y_t = \alpha + \beta t + \delta t_{t-1} + \sum_{i=1}^{k} \delta_i \Delta y_{t-1} + \varepsilon_t \qquad \text{Equation 1}$$

where y_t is the variable of interest and ε_t is a random error term. The estimated model incorporates a constant and a linear trend. The lagged variables allow correction for serial correlation. The appropriate number of lags to use in the ADF tests is determined by minimising the value of the so-called Aikaike Information Criteria (AIC), using an ordinary least squares (OLS) approach (Brockwell and Davis 1991). The t-statistic (τ_τ) is computed to test whether the coefficient of the first-order auto-regressive coefficient $\delta = 0$. The null hypothesis is always that the series is non-stationary. Additional tests were performed for the significance of constant (drift) and deterministic trend terms (Table 1).

3.2 Tests for structural change

Perron extended the ADF test to allow for a structural change in the time trend, showing that the ADF test is not able to reject a null hypothesis of the presence of a unit root when the true model is trend stationary and there is structural change (Perron 1989; Hayashi 2005). Perron, using the Nelson and Plosser data for the US (Nelson and Plosser 1982) and Soejima for Japan found that most of the time series (GDP, private consumption, industrial production) were trend stationary if a structural break was included (Perron 1989; Soejima 1994). However, the Perron tests rely on an exogenous estimation of the date of the structural break and subsequent tests on sub-series of the data are required.

A better test was provided by Zivot and Andrews (Zivot and Andrews 1992). They extended the Dickey and Fuller (DF) unit root tests, to allow for the simultaneous estimation of possible breakpoints for the intercept and slope of the trend model. This overcame potential problems that can arise when choosing structural breakpoints by visual examination of the plots of the time series, because plots of drifting unit root processes are often very similar to processes that are stationary about a broken trend. The ZA test is based upon the recursive estimation of a test regression. The test statistic is defined as the minimum t-statistic of the coefficient of the lagged endogenous variable. The null hypothesis of the ZA test is that the time series is *integrated* (i.e. has a unit root) and no exogenous structural break. The unit-root null hypothesis is rejected if the test-statistic is more negative than the critical value. If this is the case the time series are considered trend stationary about a deterministic trend with a single breakpoint.

3.3 Cointegration analysis

Having determined that the variables (time series) have unit roots, are integrated of the same order, and are therefore possibly cointegrated, we can try to answer the next question: To what extent are structural changes and trends in output growth related to efficiency and quantities of energy supplies, labour productivity and capital accumulation? This, in turn, enables us to assist in the identification of suitable production function. Hereafter we estimate the parameters of a series of Cobb-Douglas aggregate production function, in logarithmic form. We then test models with and without a constant multiplier and with different constant returns-to-scale restrictions on the parameters. We also test each combination with alternative specifications for the third factor of production, namely B (exergy inputs) or U (useful work output), to attempt to validate, by statistical means, our original choice of useful work (U) as the most appropriate factor of production,

Stern [2000] imposed the usual restriction of 'constant returns' to capital and labour, but he allowed for increasing returns to scale for energy. We test a similar model, but we also test a model with constant returns-to-scale in all factors[6]. We do not constrain the parameters to be non-negative. In all a set of 9 Cobb-Douglas models are estimated (Table 1). We use the standard notation for the production coefficients of the function (α β γ), not to be confused with the coefficients of the AR(p) model of the same name, used in equation 1 for the ADF tests.

Table 1. Estimated production functions, models A to F.

Model	**Production function**
A	$\log(y) = \alpha^*\log(k) + \beta \log(l) + \gamma \log(u)$
B	$\log(y) = \text{constant} + \alpha^*\log(k) + \beta \log(l) + \gamma \log(u)$
C 1	$\log(y) = \alpha^*\log(k) + (1-\alpha) \log(l) + \gamma \log(u)$
C 2	$\log(y) = \alpha^*\log(k) + \beta \log(l) + (1-\alpha) \log(u)$
D 1	$\log(y) = \text{constant} + \alpha^*\log(k) + (1-\alpha) \log(l) + \gamma \log(u)$
D 2	$\log(y) = \text{constant} + \alpha^*\log(k) + \beta \log(l) + (1-\alpha) \log(u)$
E 1	$\log(y) = \text{constant} + \alpha^*\log(k) + \beta \log(l) + (1-\alpha) \log(u)$
F 1	$\log(y) = \alpha^*\log(k) + \beta \log(l) + (1-\alpha-\beta) \log(u)$
F 2	$\log(y) = \alpha^*\log(k) + (1-\alpha-\gamma) \log(l) + \gamma \log(u)$

For each model we test the residuals for serial correlation using the Durbin-Watson statistic and for the presence of a unit root using the ADF test (model 3 – no intercept no time trend) using critical values presented by Engle and Granger [Engle and Granger 1987]. These are more negative than those of Dickey and Fuller, because the estimate of δ in equation 1 is downward biased as the prior application of the OLS methodology seeks to produce stationary residuals. If we accept the unit root hypothesis the equation does not co-integrate. Together with the estimated coefficients these statistics indicate which of the six models (A-F) provides the best estimates and co-integrating properties for subsequent analysis.

3.5 Testing for the stability of cointegrating regressions

If the results from previous tests confirm the presence of (suspected) structural breaks in the time series modelled as AR(p) processes, it is possible that any classical regression model using these series may need to be recalibrated after the break or structural change in the economy. To test for this possibility we use two different independent methods to test for structural breaks in the selected linear regression models[7]. First, we apply a series of empirical fluctuation tests described in (Zeileis, Leisch et al. 2005). The idea behind these tests is simple: if there is structural change in the monitoring period the residuals can be expected to deviate systematically from their zero mean.

The second set of methods for estimating multiple breaks is based on testing deviations from stability in a classical linear regression model (Bai and Perron 2003). We use an extended version of this technique designed for simultaneous estimation of the number and timing of multiple breakpoints (Zeileis, Kleiber et al. 2003). The condition for multiple

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[6] In contrast to Stern (Stern 2000) we did not test any model with a time trend representing exogenous technological progress. All our tested models are, in effect, endogenous.

[7] All structural change tests are implemented in the statistical software package R, using the package strucchange (Zeileis, Leisch et al. 2002), while all other tests used the package urca developed by Bernhard Pfaff.

breakpoints is that the sum of the squared residuals (RSS), as a function of break date, can have a local minimum near each break date when there are multiple changes in the process. The global minimum (if significant) can be used to divide the time series into sub-samples for further analyses if other local minima are considered as candidate breakpoints. The optimal number of segments is chosen as that model which minimises the Bayesian Information Criterion (BIC) (Seddighi, Lawler et al. 2000).

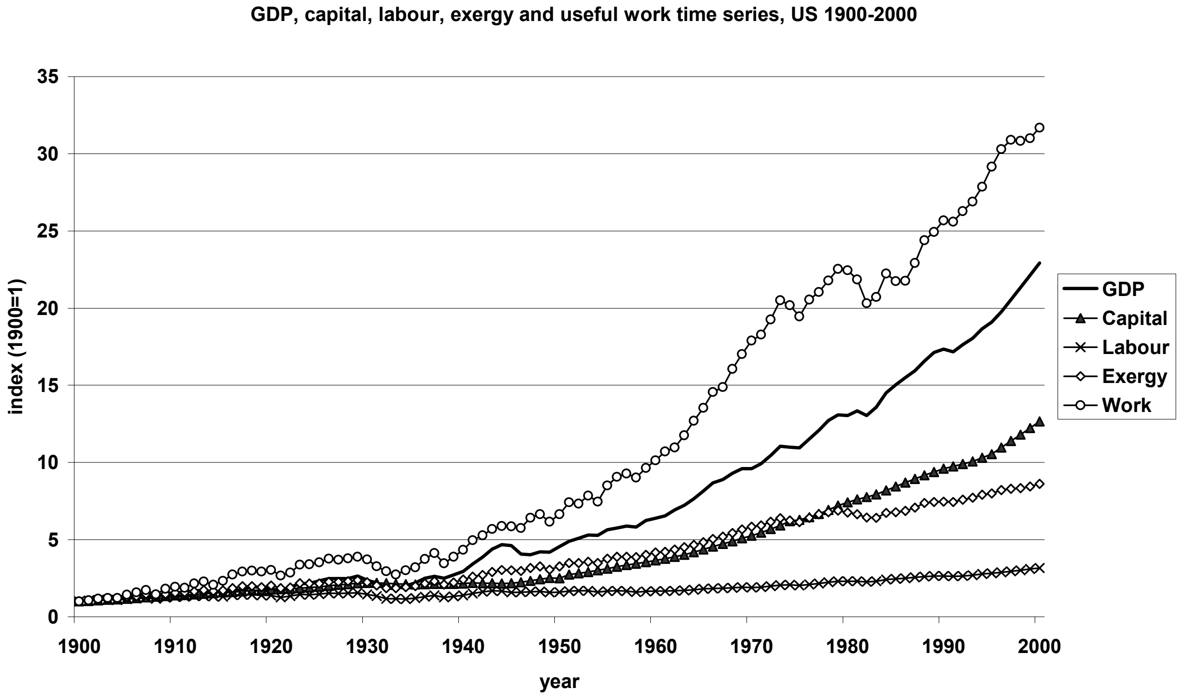
4. Results

We start our empirical analysis by a simple visual examination of the time series of GDP capital, labour, exergy and useful work and ratios of the factors (Figure 4). Analysed in conjunction with the factors of production these ratios provide important ancillary information to support our interpretation of the results of subsequent analysis.

The factors of production all show an almost continuous, increasing exponential trend. The rate of increase of useful work exceeds that of GDP and the other factors of production. Labour grows at the slowest rate. Breaks which correspond to shocks to the economic system are evident, but are subtle in comparison to the discontinuities in the time series of the ratios of factors. The useful work to capital ratio (*u/k*) exhibits the most marked changes in the direction of slope. The changes of slope coincide with major shocks. Carefully looking at the factor ratios we can identify 4 distinct time periods. The first extending from 1900 to 1933 reveals a trend of increasing work intensity of capital and declining labour intensity of capital (increasing *k/l*). Notable shocks in 1904, 1908, 1914, 1921 and 1933 coincide with sudden decreases in the work and labour intensity of capital and concomitant substitution of useful work for labour. The concomitant instability of the ratios in this pre-1933 period is not characteristic of the rest of the century. Shocks cause factor substitution and technical change that lead to new paradigms for industry through intensification to automation and re-intensification finally to the growth of the service sector and decline of 'heavy' industry.

From 1933, and until 1944, the trend *k/l* ratio briefly changes direction of slope from the predominant century long increasing trend. Over the same period the useful work to capital ratio grows more rapidly than over any other period. Traditional heavy industries expanded rapidly, which required large amounts of labour and exergy, as the output growth of the post-1933 US economy picked up. This suggests that there was a greater increase in economies of scale rather than widespread application of new technologies. Nevertheless the continuous decline in the *l*/u ratio implies that capital embodied technological progress and changes in relative factor costs led to substitution of useful work for labour.

After the perturbations of WWII the slope of the *k/l* ratio changes sign, repeating the pre 1933 trend of declining labour intensity of capital. The *k/l* ratio continues to decline at a stable rate for the rest of the century, reflecting technical progress and the increased automation of the economy also factor substitution driven by the increasing costs of labour relative to capital and exergy. Post 1946 the substitution of both capital and useful work for labour continue along their pre-1933 trajectories. The useful work intensity of capital grows at an increasing rate until 1973. However, importantly, in 1973 there is a sudden change of slope of the useful work to capital ratio. After 1973 this ratio declines from 3.5 times to 2.5 times its 1900 level. It is interesting to note that this date coincides with the first Oil Crisis and is 3 years after US peak oil production. It also roughly coincides with a slowdown in the growth rate of the exergy to useful work conversion efficiency (Figure 1), but the rapid growth of the less energy intensive service sector.



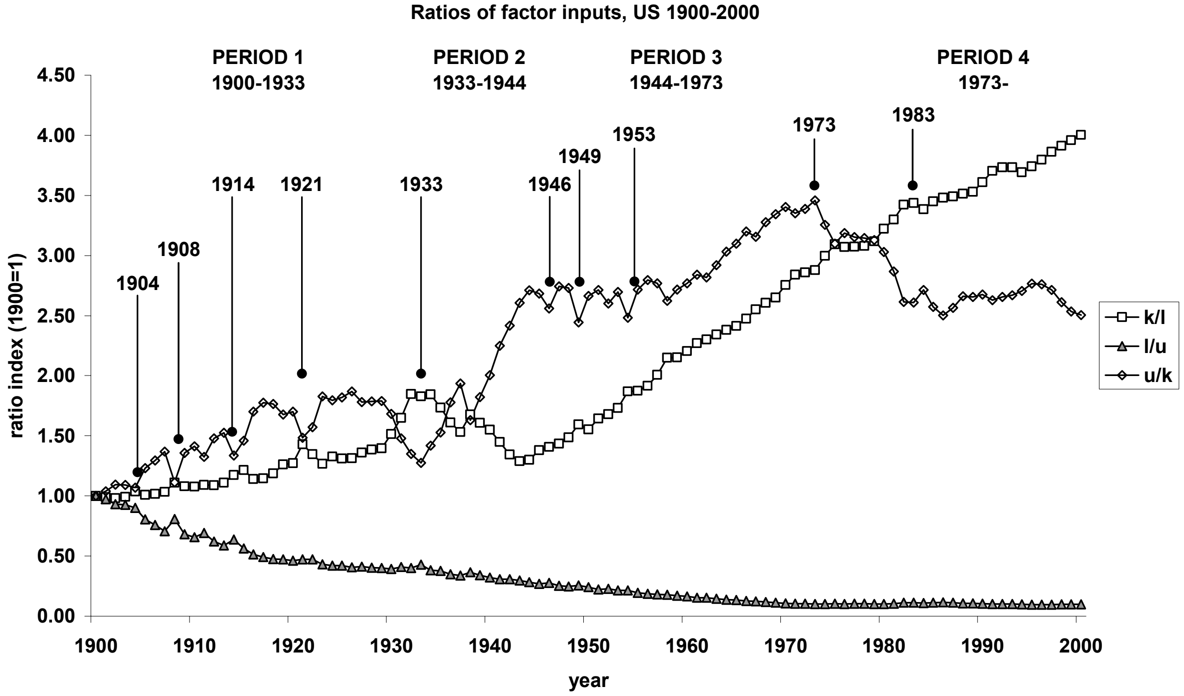


Figure 4. Plots of time series, US 1900 to 2000 , (for clarity of presentation ratios are presented for useful work only)

4.2. Unit root tests

The Augmented Dickey Fuller tests provide evidence of the order of integration of the time-series. The test results are presented in Table 2. The first noteworthy feature of the results is the optimal number of lags *p,* identified for each auto-regressive AR(*p*) model used in the tests. For the log transforms of the various factors, the number of lags yielding the best predictions (*p*) ranged from 2 for log(*y*)*,* log(*l*) and log(*b*), to 3 for log(*k*), reflecting the longer range of autocorrelation in the capital time series (Figure 4). For the ratios of factors and log(*u*), the optimal lag seems to be shorter, being unity for *k/l*, and 2 for both *u/k* and *(l+u)/k* . However for the ratio *l/u* it seems that long lags ($p > 10$) continued to reduce the AIC. Plots of the series show that the *l/u* ratio has comparatively very little short-term variability, but a clear downward trend from 1900 to 1950, reflecting the substitution of labour by useful (mechanical) work, through mechanisation. All other series show considerable short term variability superimposed over (breaking) trends. The unit root hypothesis is accepted for all ADF tests, for output and for all factors at the 5 % level of significance. After differencing these variables are stationary[8]. We can therefore conclude that all series are integrated of order (1) and are possibly cointegrated. Only at the lower (10 %) level of significance is the unit root hypothesis rejected for *y* (model #1) and the ratio (*l/u*) (model #3).

Tests for the significance of the drift and time trend terms then proceed from model #1 to model #3 (right to left in Table 2). These results split the variables into two groups; the majority (log(*k*)*, log(l*)*, l/u, u/k* and *(l+u)/k*) for which we accept the hypotheses ϕ_2, $\tau_{\alpha\tau}$ and $\tau_{\beta\tau}$ and the others (log(*y*)*,* log(*b*)*,* log(*u*) and (*k/l*)). We infer that the former series are unit root processes, while GDP, exergy, work and the capital to labour ratio are more accurately characterized as random walks about a trend. The $\tau_{\alpha\tau}$, $\tau_{\beta\tau}$ and ϕ_3 statistics indicate, for the latter group, which of the trend components is most significant: we infer from the $\tau_{\alpha\tau}$ test that the drift component is significant for exergy, log(*b*) and work, log(*u*), while the $\tau_{\beta\tau}$ result indicates that GDP (*y*) may contain a time trend.

The model #1 test results for the significance of the drift term (ϕ_3) is not powerful for the series log(*y*) and *k/l* in the presence of a time trend in the regression. Indeed, (Dolado, Jenkinson et al. 1990) and subsequently Stern (Stern 2000) suggest exclusion of the deterministic time trend *a priori*. Given that the objective of including useful work in a production function is to remove the requirement of an exogenous time trend, by factoring in energy technology progress, we consider the results from model #2 to be more suitable and robust. The model #2 results ϕ_1 and $\tau_{\alpha\mu}$ imply the significance of the intercept (drift term) in the GDP and *k/l* series, and confirm the results from model #1 indicating that exergy log*(b)*, useful work *log(u)*, GDP log*(y)* and the *k/l* ratio are unit root processes about a stochastic drift, while the remaining series are unit root processes from which the stochastic drift can be excluded. However, at this point of the analysis, given the known bias of the unit root tests in the presence of structural change and the indication from plots of the breaking / trending properties of most of the time series, we need to interpret these results with caution. Results from tests for structural change should indicate whether the data generating process underlying these time series can indeed be modelled as stationary processes about a breaking trend as opposed to unit root processes.

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[8] We do not present the results of ADF tests on the differenced time series for clarity of presentation.

Table 2. ADF unit root test results (US, 1900-2000).

Model		3	2			1				
Test		τ	τ_μ	$\tau_{\alpha\mu}$	ϕ_1	τ_τ	$\tau_{\alpha\tau}$	$\tau_{\beta\tau}$	ϕ_3	ϕ_2
Critical values (5%)		-1.95	-2.89	2.54	4.71	-3.45	3.11	2.79	6.49	4.75
Variables	Lags									
US										
log(*y*)	2	2.83	-0.25	*2.36*	**7.01**	*-3.21*	1.10	***3.20***	5.17	**8.56**
log(*k*)	3	2.04	0.89	1.74	3.65	-1.44	1.02	1.64	1.75	3.58
log(*l*)	2	2.07	0.02	1.15	2.81	-2.05	1.23	2.16	2.32	3.50
log(*b*)	2	2.89	-1.39	**3.33**	**10.18**	-2.35	**4.00**	2.16	3.34	**8.60**
log(*u*)	1	3.00	-1.46	**3.38**	**10.75**	-3.13	**4.12**	2.28	3.69	**9.21**
k/l	2	3.29	0.99	0.64	***5.56***	-1.49	1.39	1.89	2.29	***5.00***
l/u	>10	**-2.67**	*-2.62*	1.01	*4.10*	-1.68	0.42	-0.25	3.42	2.72
u/k	1	0.52	-1.83	2.07	2.29	-1.14	1.09	0.21	1.68	1.53
(l+u)/k	1	0.10	-1.91	1.96	1.93	-1.60	1.89	-1.61	1.87	1.31
Significance Level for Rejection										
		τ	τ_μ	$\tau_{\alpha\mu}$	ϕ_1	τ_τ	$\tau_{\alpha\tau}$	$\tau_{\beta\tau}$	ϕ_3	ϕ_2
99%	**bold**	-2.60	-3.51	3.22	6.70	-4.04	3.78	3.53	8.43	6.22
95%	***bold italics***	-1.95	-2.89	2.54	4.71	-3.45	3.11	2.79	6.49	4.75
90%	*italics*	-1.61	-2.58	2.17	3.86	-3.15	2.73	2.38	5.47	4.07

Unit root tests

τ_τ	$H_0 : \delta = 0$, if $t > \tau_\tau$
τ_μ	$H_0 : \delta = 0$, if $t > \tau_\mu$
τ	$H_0 : \delta = 0$, if $t > \tau$

Conditional hypothesis tests

$\tau_{\beta\tau}$	$H_0 : \beta = 0$ given $\delta = 0$, $\lvert t\rvert < \lvert\tau_{\beta\tau}\rvert$
$\tau_{\alpha\tau}$	$H_0 : \alpha = 0$ given $\delta = 0$, $\lvert t\rvert < \lvert\tau_{\alpha\tau}\rvert$
$\tau_{\alpha\mu}$	$H_0 : \alpha = 0$ given $\delta = 0$, $\lvert t\rvert < \lvert\tau_{\alpha\mu}\rvert$

Joint hypothesis tests

ϕ_1	$H_0 : \alpha = \delta = 0$, if $F < \phi_1$
ϕ_3	$H_0 : \beta = \delta = 0$, if $F < \phi_3$
ϕ_2	$H_0 : \alpha = \beta = \delta = 0$, if $F < \phi_2$

4.3. Tests for structural change

We can now apply the Zivot-Andrews (ZA) test for three models, as follows: the encompassing ZA model #1 (equation 1), including both drift (intercept) and time trend terms, and two variants of this model. These are the ZA model #2a, excluding the time dependent term β (equivalent to model #2 in the ADF tests), and ZA model #2b, from which the drift term α is dropped. The results are presented in Table 3 and the yearly values of the test statistic and residuals are shown in Figure 5.

We can now reject the null hypothesis of a unit root in favour of the alternative hypothesis of 'breaking' trend stationarity for all variables except exergy, useful work and the *l/u* ratio, for which no significant breakpoint can be identified. For ZA model #1 two groups emerge, those for which the breakpoint occurred towards the early 1930s, namely capital, labour and *l/u* and those for which the break occurred in the late 1930s. No significant breakpoint can be identified for either useful work or exergy.

For ZA model #2 a, the grouping of time series is somewhat different, but nevertheless the potential breakpoints for all variables are consistently within the 1929 to 1939 period, except for exergy and useful work (1955). In contrast to ZA model #1 the unit root null hypothesis is accepted for GDP.

Finally the results from ZA model #2b (which exclude the stochastic trend term but include a deterministic time trend) allow us to accept the null hypothesis for all time series except GDP and two ratios, *k/l* and *u/k and (l+u)/k.* This implies that these series, and importantly GDP are stationary about a breaking trend, while all other time series are unit root processes with no structural breakpoint in a deterministic time trend. For ZA model #2b, the years selected as likely breakpoints vary erratically, such that a grouping of variables is less evident. For labour a break appears to have occurred in 1961, a radical deviation from the results from the other models which point to 1930 as the year of the break. For capital a break seems to occur in 1943, whereas ZA models #1 and #2a indicate a break in 1930. Interestingly, for the *u/k* and *(l+u)/k* ratios, the potential (but not significnant) breakpoint year was apparently in the early 1950s, while for useful work the year of the break was 1974, a year after the Arab boycott and the so-called ‘oil crisis’.

Table 3. ZA test results using lags identified earlier using univariate AIC values (figures in brackets).

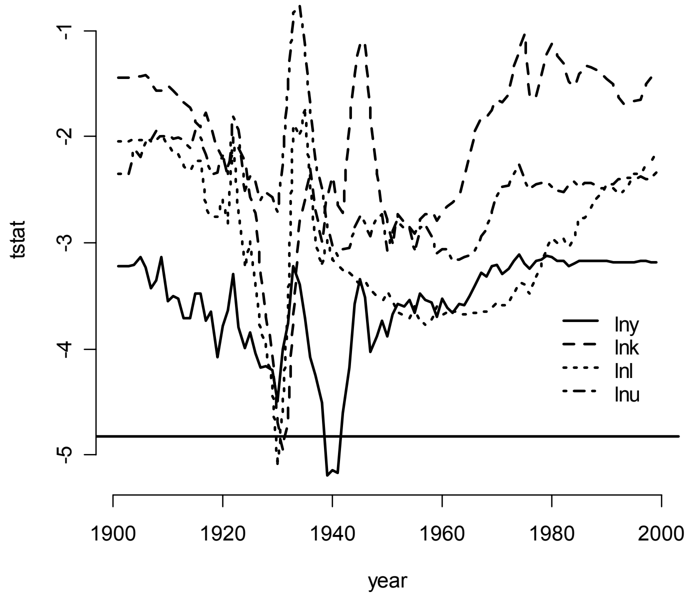
	ZA Model 1 both		**ZA Model 2a intercept**		**ZA Model 2b time trend**	
	t-statistic	Potential breakpoint	t-statistic	Potential breakpoint	t-statistic	Potential breakpoint
log(*y*)	***-5.19***	39	-4.30	30	*-4.11*	33
log(*k*)	*-4.94*	31	-4.38	30	-3.61	43
log(*l*)	***-5.11***	30	***-5.15***	30	-3.76	61
log(*b*)	-3.17	62	-3.09	55	-2.57	34
log(*u*)	-3.61	63	-3.16	55	-2.96	74
k/l	**-6.29**	38	***-4.82***	29	***-4.73***	32
l/u	-4.42	30	-4.39	29	-3.70	32
u/k	**-7.08**	39	**-7.17**	38	**-4.96**	50
(l+u)/k	**-7.09**	38	**-6.62**	39	***-4.82***	53
Model 1	Critical values: 1% = **-5.57**, 5% = ***-5.08***, 10% = *-4.82*					
Model 2a	Critical values: 1% = **-5.34**, 5% = ***-4.80***, 10% = *-4.58*					
Model 2b	Critical values: 1% = **-4.93**, 5% = ***-4.42***, 10% = *-4.11*					

It is now useful to consider these results in light of the ADF test results discussed previously. Firstly we consider the time series of exergy and useful work. The ADF tests for model #1 suggest both are unit root process about a stochastic trend. The ZA tests indicate that this trend does not contain a significant structural break. Nevertheless, the plot of the ZA t-statistic does reveal a period of instability extending from the 1930s to the 1960s. Next we consider the remainder of this group, identified from previous (ADF model #1) tests as being trend stationary, namely log(GDP) and the ratio *k/l.* The ZA tests confirm theses results but imply that the trend should contain a structural break occurring in 1938-39.

The lack of power of the ADF tests in the presence of a possible structural break is revealed by the remaining time series. The ADF test accepts the unit root null hypothesis, whereas the ZA unit root test rejects the null hypothesis in favour of the alternative hypothesis of breaking trend stationarity.

A closer examination of the plots of the time series of the test statistics provides further insight into the temporal behaviour of the related time series (**Figure 1**). Together they show that the series shift away from an initial stable relationship after 1905 for the log transformed factors and the *k/l* ratio, but later and more suddenly for the other ratios. This shift away from 'stability' accelerated and reached a maximum in the early to late 1930s. Not until the early 1970s do the plots of the t-statistics 're-stabilise'.

(a) factors



(b) ratios

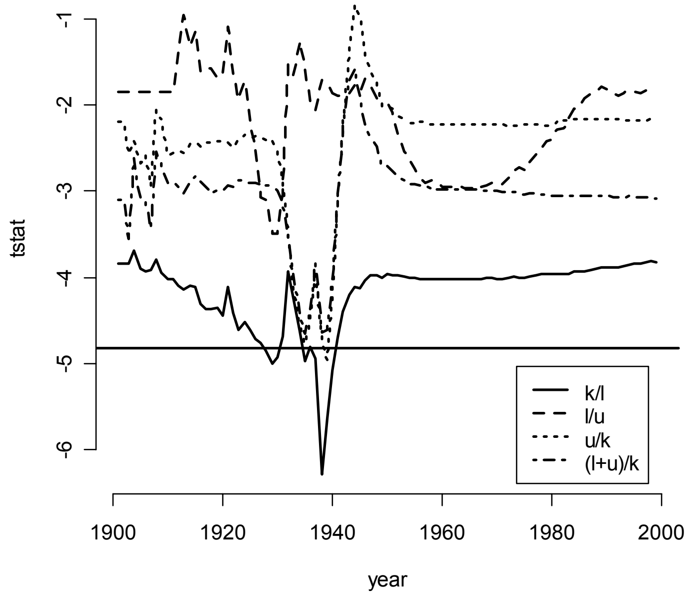


Figure 5. Test statistic for the ZA model 1 test, US 1900 to 2000 (solid line = 5% confidence interval).

4.4. Cointegration regressions

Table 4 presents estimates of the 9 different Cobb-Douglas aggregate production functions (from Table 1). Stern (Stern 2000) notes that these “are static co-integrating (or spurious) regressions”, corresponding to the long run relation between the variables. We draw attention to several characteristics of the results, namely the elasticities of the factors and the returns-to-scale properties of the models. The calculated elasticity coefficient for labour varies erratically from model to model but is generally insignificant. For constrained models using exergy input log(b), the elasticity coefficients for labour are negative; using log(u) they are positive but almost zero. Clearly labour provides little explanatory power in the model when either exergy or useful work is introduced as a factor of production.

The elasticity coefficients for useful work and exergy are almost without exception larger than the coefficients for the other factors of production. In turn, the coefficient for exergy is systematically larger than that for useful work. Both series exhibit very similar short term variability. Therefore this difference simply reflects the fact that the exergy input series grows at a slower rate than the series of useful work output. The latter increases, not only as exergy consumption *per se* grows, but also due to efficiency improvements in the delivery of energy services. Therefore it seems – as we have said earlier – that ‘useful work’ is effectively a surrogate for ‘technological progress’. As a result, the sum of the coefficients for (incompletely constrained) models using useful work as a factor of production is systematically smaller than for those models using exergy, which also consistently exhibit increasing returns to scale.

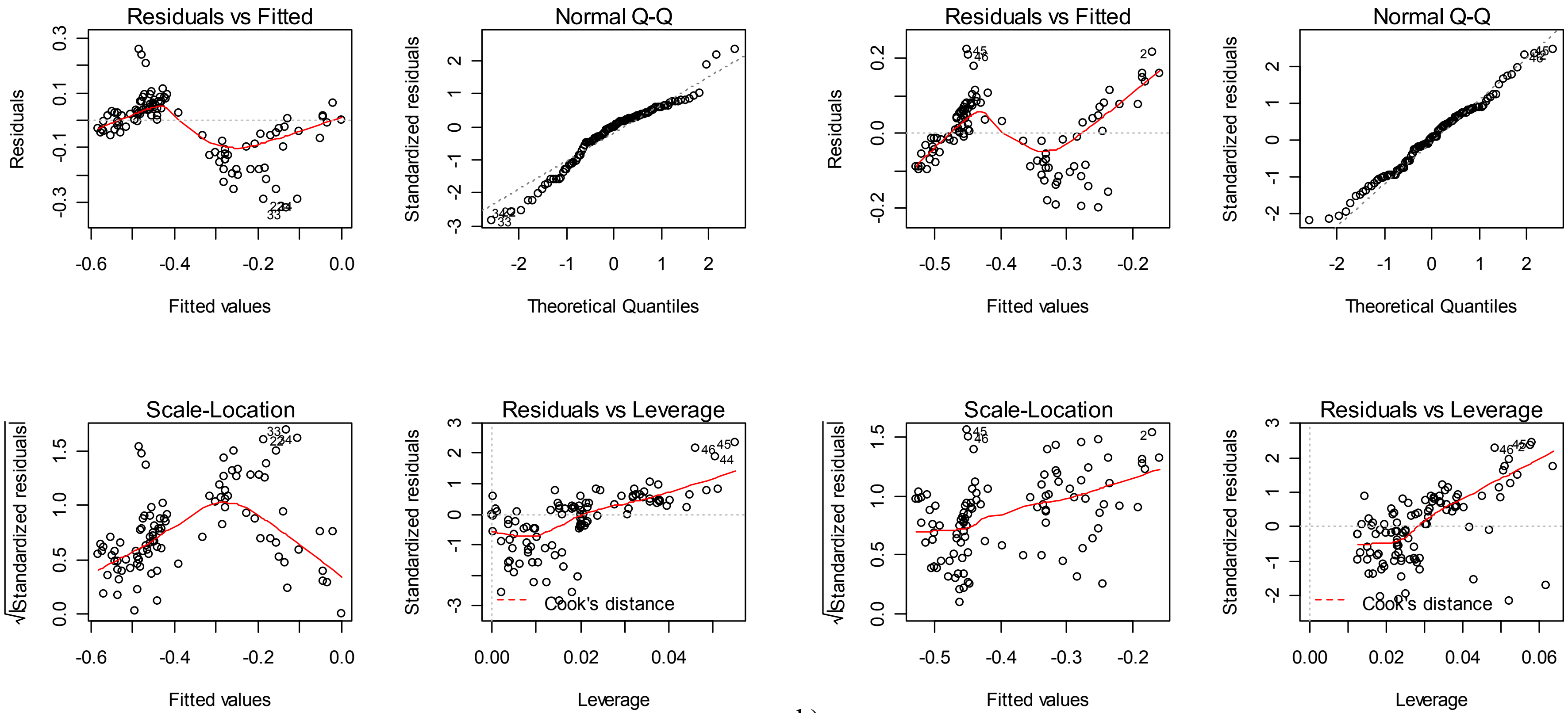
We have already noted the erratic labour coefficient estimates, but this is a feature common to all coefficients of the unconstrained models. It is likely to be a result of collinearity. In contrast, for constrained models, it does not matter which coefficient is estimated directly or from the relation $1-\alpha-\beta$. This result favours use of the constrained models for subsequent tests. To further narrow the choice of which model represents the most suitable production function we next consider the coefficient values in light of the diagnostic statistics calculated on the residuals.

All of the models generate very small residual squared errors that are systematically lower when we introduce the useful work variable (as opposed to exergy) and a constant in the production function. Similarly the Durbin-Watson statistic was close to its ideal value of 2 (implying no serial correlation) for all models except model C. Inclusion of a constant term improved the DW statistic. From the ADF test, we cannot reject the unit root hypothesis for the residuals of models C, D and F, using log(u). However the ZA test results and visual examination of the residuals do provide clear evidence of a structural break.

In conclusion, if we exclude from our choice, those production function models that do not meet the constraint of constant returns to scale, and consider only those models having non-negative elasticity estimates, and a residual with no evidence of serial correlation or integration, we are left to conclude that only models E and F using useful work, instead of exergy, as a factor of production are suitable to estimate historical output growth. The stability of the coefficient estimates, regardless of which variable coefficient was estimated directly, favours Model F over Model E. Indeed diagnostic plots of the (Figure 6) indicate that the Model F residual is smaller, than for model E and better approximates the normal distribution.

Estimated	A		B		C				D				E				F			
	No constant		Constant		No constant				Constant				No constant, full CRS				Constant, full CRS			
	log(y)		log(y)		log(y/l)		log(y/b)		log(y/l)		log(y/b)		log(y/l)		log(y/b)		log(y/l)		log(y/b)	
	using b	*using u*	*using b*	*using u*	*using b*	*using u*	*using b*	*using u*	*using b*	*using u*	*using b*	*using u*	*using b*	*using u*	*using b*	*using u*	*using b*	*using u*	*using b*	*using u*
Constant			-0.2	-0.19					-0.2	-0.19	-0.24	-0.16					-0.11	-0.16	-0.11	-0.16
log(k)	0.52	0.49	0.18	0.16	0.53	0.49	0.38	0.54	0.2	0.16	-0.12	0.38	0.67	0.52	0.56	0.52	0.54	0.28	0.54	0.28
log(l)	*0.07*	*0.21*	0.35	0.54	0.47	0.51	0.75	*0.01*	0.8	0.84	0.95	*0.12*	-0.58	-0.03	-1.88	*0.04*	-0.71	0.01	-0.71	*0.01*
log(b) or log(u)	0.77	0.46	1.14	0.66	0.6	0.38	0.62	0.46	0.91	0.57	1.12	0.62	0.91	0.51	2.32	0.44	1.17	0.71	1.17	0.71
Sum	1.36	1.16	1.67	1.36	1.6	1.38	1.75	1.01	1.91	1.57	1.95	1.12	1	1	1	1	1	1	1	1
Durbin-Watson (DW)	0.12	0.11	0.23	0.21	0.1	0.09	0.1	0.09	0.19	0.2	0.19	0.2	0.17	0.12	0.17	0.12	0.2	0.17	0.2	0.17
ADF - t-statistic	*-1.91*	*-1.74*	*-2.59*	*-2.64*	-1.6	-1.52	-1.6	-1.52	-2.06	-2.35	-2.06	-2.35	*-2.42*	*-1.91*	*-2.42*	*-1.91*	*-2.66*	-2.53	*-2.66*	-2.53
ADF - ϕ_1			3.4	3.29					2.27	2.95	2.27	2.95					3.55	3.22	3.55	3.22
Residual Standard Error (RSE)	0.11	0.11	0.09	0.09	0.12	0.12	0.12	0.12	0.09	0.09	0.09	0.09	0.12	0.11	0.12	0.11	0.11	0.09	0.11	0.09

Table 4. Regression analysis results.



a)

b)

Figure 6. Diagnostic plots of the residual from a) model E and b) model F using useful work as a factor of production.

4.5. Tests for structural breaks in the regression model

Figure 7 shows the results of the empirical fluctuation tests (EFP) on the residual and the regression coefficients for model F 2 (using U as a factor of production) identified in the last section as having the most suitable properties for use as a production function[9]. Structural changes correspond to strong shifts in the test statistic which cross the 5% significance threshold, shown as parallel lines. Table 5 and Figure 8 exhibit the results from the Bai and Perron tests to identify multiple breakpoints. Considered together, there is quite strong evidence for multiple (up to 5) breakpoints in the regression model, corresponding to the major non-economic events that have impacted US economic growth since 1900. All of the tests indicate that there was a significant structural break in the growth trajectory corresponding to the Great Depression and the early 1930s. The Bai and Perron test systematically selected 1931 as a significant break date. The 'fluctuation' and ME tests also indicate a prior break in 1915-16, coinciding with the 1st World War; the OLS-MOSUM and ME tests provide evidence of a significant structural change coinciding with World War II. These results are confirmed by the Bai and Perron test, which point to 1915/16 and 1946 as significant break dates.

	No. of Significant breaks		Dates	
Model F	BIC	RSS	BIC	RSS
using B	4	4	15, 30, 46, 78	15, 30, 46, 78
using U	4	5	16, 31, 46, 82	16, 31, 46, 70, 85

Table 5. Bai and Perron test results.

None of the EFP tests identify a significant structural break in the post-WWII period. However the plots do show that the test statistic does shift strongly over the period extending from the early 70s to the mid 80s, coinciding with the so-called `oil crises' of 1973-74 and 1979-80. In contrast the Bai and Perron tests suggested that a significant break did occur in that decade. Depending on which result we consider, there was either a single break in 1978 or 1982, or two major breaks in 1970 and 1985. The latter two dates coincide reasonable closely with the two crises noted above. It might be significant that 1970 was the year US domestic oil production peaked and imports began to rise dramatically. The year 1985 was when oil prices dropped dramatically from previous highs, and large capital accumulations in OPEC countries (and the USSR) eroded rapidly.

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[9] The results for this model were also representative of those provided by the others (A to F), not shown for the sake of simplicity of presentation.

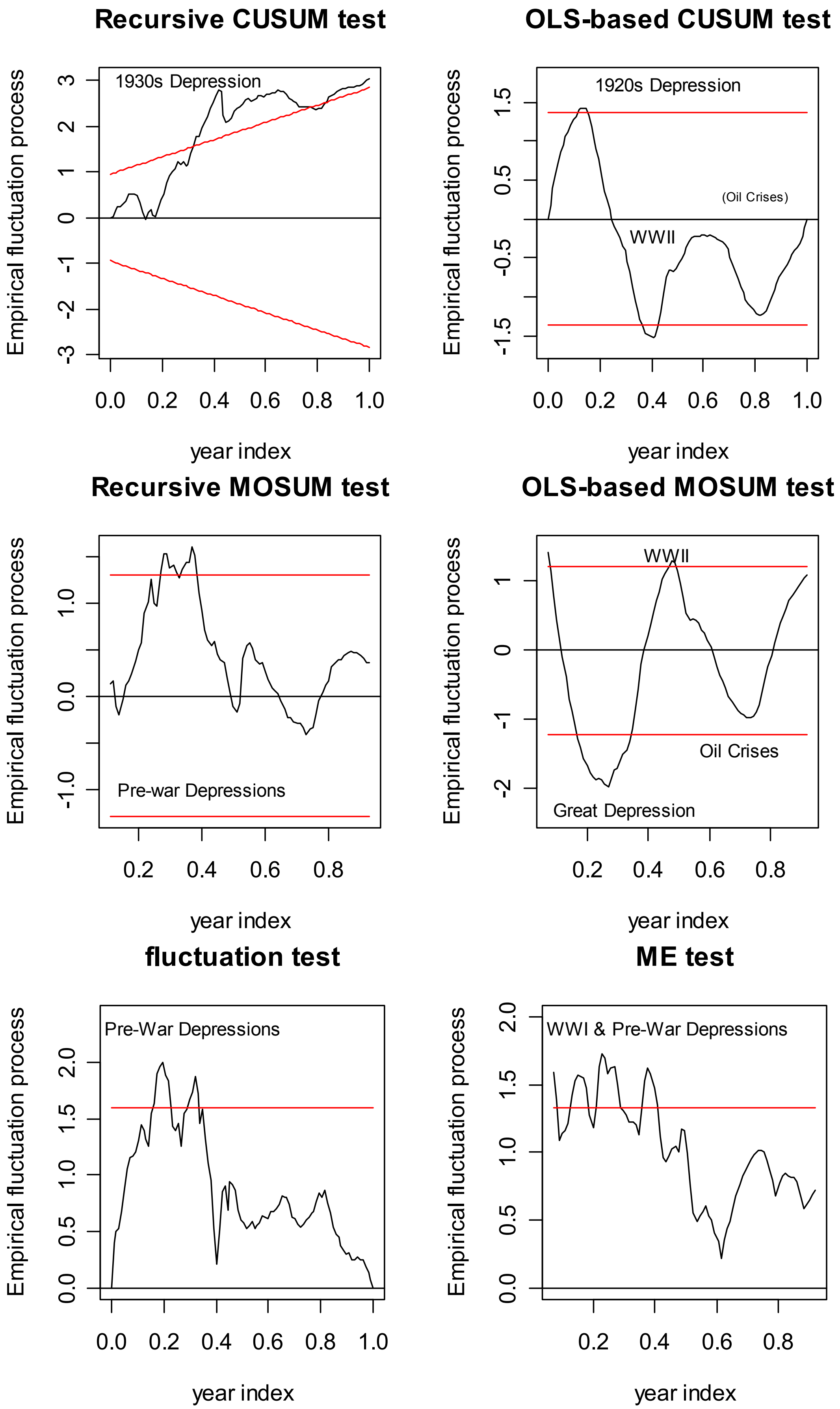

Figure 7. Empirical fluctuation test diagnostic plots: Model F using useful work, log(U) (grey line = 5% confidence interval.)

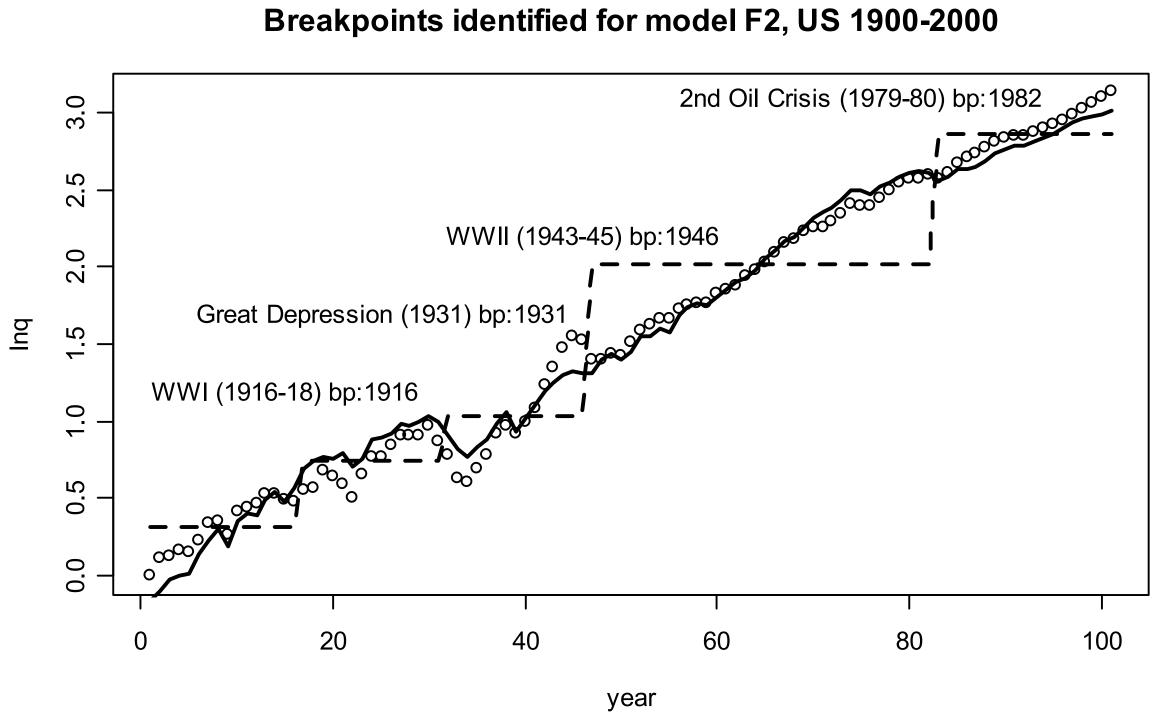

Figure 8. Breakdates from Bai and Perron test, for Model F using useful work, U. (dots – empirical data, solid line – estimate, broken line – breaks in intercept. *bp* indicates identified date)

5. Discussion and Conclusions

In this paper we have applied a series of tests to characterise the data generating process of historical macroeconomic time series. As far as we are aware no other study has considered such a long time period (1900 to 1998). This is the first such analysis to investigate the time series of *useful work*, making direct comparison with other studies findings difficult. Nevertheless, our results do confirm several prior observations and hypotheses. We address the questions we posed earlier in sequence.

Do the time series show common trends and structural breaks? The ADF tests (model 2), assuming structural constancy provided a strong indication that GDP and the factors of production are unit root processes about a stochastic trend, but difference stationary and hence integrated of order (1). However, the unit root null hypothesis was rejected for all time series in favour of trend stationarity, on inclusion of a stochastic trend with a single breakpoint occurring in the 1930s. This confirms Perron's (1989) theorem that a unit root test which ignores a structural change when it exists, does not reject the null hypothesis of a unit root, even if the true model is trend stationary (as did the results provided by Hayashi (Hayashi 2005)). More specifically, the Zivot-Andrews test results also confirmed those of Dickey and Fuller who provided evidence of trend stationarity allowing for a breakpoint coinciding with the Great Depression for the majority of economic time series they studied (Dickey and Fuller 1979; Dickey and Fuller 1981). The Great Depression coincided with a major shift in the ratio of capital to useful work as capacity utilisation of heavily mechanised industries dropped sharply, and a concomitant a rise in the *k/l* ratio, as labour intensive industries laid off employees.

The most significant structural break in the AR(p) models coincided with the Great Depression. But it appears that the economy was highly 'unstable' at several points over the entire pre-WW II period. Plots of the ZA test statistic and residuals suggest considerable instability over a much longer time period extending both pre- and post-war until the early

1980s. Interestingly, the ZA tests did not provide evidence to confirm Perron's results, which implied that a significant structural change occurred after the first oil crisis of 1973 (Perron 1989; Perron 1994). However, Perron analysed only the post WWII period and excluded the far more volatile pre WWII period. Allowing for only a single break point over both periods, the ZA test clearly identifies the 1930 instability as having greater significance.

All the time series are evidently far more volatile over the first half of the century. Depressions in the early 1920s and the Great Depression in the 1930s, also the first and second World Wars, had a far greater 'impact' on the time series than subsequent events. Post WWII the US economy seems to have 'stabilised' towards a more stable long term growth trajectory. This suggests that each successive structural change has reduced the sensitivity or increased the resilience of the economy to shocks, such as war and energy supply shortages. We note that the energy crises of 1973 marked the introduction of energy-saving technologies into the capital stock, thereby softening the impact of subsequent energy price increases.

Changes in the factor ratios could be caused by either factor substitution or biased technical change, perhaps concomitant but happening over different time scales. With this in mind factor substitution could be more important over the short term, coinciding with sudden shocks and affecting all ratios, while biased technical change could be more important over the long term, reflected by major changes in slope in individual factor ratios, such as the useful work to capital ratio post 1930 and 1973. The interaction of the two dynamic processes is revealed by the observation that major changes in the slope of ratios, that persist over decades and define "periods" (1900 to 1930, 1930 to 1946, 46 to 73 and post 73) coincide with the sudden peaks in factor substitution. The latter may have been responsible for triggering innovation-diffusion (breaking barriers to technological progress), that lead to major shifts in the patterns of investment, employment and energy consumption relations.

Although we provide evidence for several major structural breaks, we have also shown that the time series of factors and output are cointegrated. A necessary but not sufficient condition for cointegration is that each of the variables should be integrated of the same order (greater than zero), or that both series should contain a common trend. We have shown that all of the time series possess are integrated of at least order 1. We show that it is possible to model output growth accurately using a constant returns to scale (in all factors) Cobb-Douglas production function (model F) with useful work, rather than raw exergy as a factor of production. The estimated model coefficients are all non-negative, while the equivalent model (model F 1) using exergy failed to provide non-negative coefficients. The fit-generated residuals weakly stationary residuals with very little serial autocorrelation (Durbin-Watson statistic close to 2). The estimated coefficients (the elasticities of production) represent the (spurious) long-run relationships between the factors and output. The elasticity of output is largest with respect to useful work and smallest for labour. It seems plausible that much of long run output growth has been driven by an incremental process of learning-by-doing in energy production and consumption technologies, where significant structural breaks correspond to shocks that have generated invention-innovation breakthroughs and altered the long run trends of factor substitution. Nevertheless, the linear relationship between these factors exists over a long period of time. This means that it is feasible to make long term forecasts of long-run output growth, despite the major structural changes that have occurred based on extrapolating useful work production and consumption patterns, just as it has been possible to estimate historical GDP.

Acknowledgements

All applications have been completed using the statistical software package R (R Development Core, Team, 2003; see http://www.R-project.org/). We would like to thank David Stern for comments on an early draft.

Appendix

We have compiled a number of historical data sets for the US from 1900 to 1998, indexed to 1900. Series up to 1970 are found in (United States Department of Commerce Bureau of Economic Analysis 1973) *Long Term Economic Growth 1860-1970,* US Department of Commerce, Bureau of Economic Analysis, Tables (Series A68 and A65 respectively). More recent data (1947-1998) came from (United States Council of Economic Advisors 1996) *Economic Report of the President, 1999* (Tables B32 and B34). Labour is counted as man-hours actually worked. The series describing exergy and useful work were developed by the authors and are described in detail in a previous publication (Ayres, Ayres et al. 2003). The series for useful work differ from the series therein, the efficiency of electricity use having been incorporated into the estimate of aggregate technical efficiency (Ayres, Ayres et al. 2005).

Table 6. Historical time series of indices of GDP, capital, labour, exergy and useful work, US 1900 to 2000.

Time	GDP 1990 = 354 1992$ billion	Capital 1990 = 2012 1992$ billion	Labour Index of hours worked	Exergy 1990 = 0.64 EJ	Work 1990 = 0.018 EJ
1900	1	1	1	1	1
1901	1.12	1.03	1.04	1.05	1.07
1902	1.13	1.07	1.09	1.09	1.17
1903	1.18	1.11	1.12	1.19	1.21
1904	1.17	1.14	1.1	1.2	1.22
1905	1.25	1.17	1.16	1.29	1.44
1906	1.4	1.22	1.2	1.33	1.58
1907	1.42	1.27	1.23	1.47	1.74
1908	1.3	1.31	1.18	1.37	1.46
1909	1.52	1.34	1.24	1.47	1.82
1910	1.56	1.38	1.28	1.57	1.95
1911	1.6	1.42	1.3	1.58	1.88
1912	1.69	1.46	1.34	1.65	2.16
1913	1.71	1.5	1.35	1.74	2.29
1914	1.63	1.55	1.32	1.66	2.07
1915	1.62	1.59	1.31	1.71	2.32
1916	1.74	1.61	1.41	1.85	2.74
1917	1.76	1.65	1.44	1.98	2.93
1918	1.97	1.7	1.43	1.99	3
1919	1.9	1.74	1.38	1.92	2.92
1920	1.82	1.78	1.4	2.03	3.03
1921	1.66	1.8	1.26	1.86	2.67
1922	1.92	1.82	1.35	1.91	2.86
1923	2.16	1.85	1.46	2.18	3.38
1924	2.15	1.9	1.43	2.16	3.41
1925	2.33	1.94	1.48	2.17	3.53
1926	2.47	2.01	1.53	2.27	3.76
1927	2.47	2.07	1.52	2.27	3.69
1928	2.48	2.12	1.53	2.3	3.79
1929	2.65	2.18	1.56	2.37	3.9
1930	2.38	2.21	1.46	2.24	3.72
1931	2.2	2.21	1.34	2.04	3.27
1932	1.87	2.18	1.18	1.87	2.94
1933	1.84	2.14	1.17	1.86	2.73
1934	2	2.12	1.15	1.93	3.01
1935	2.2	2.1	1.21	1.99	3.21

1936	2.51	2.11	1.31	2.15	3.75
1937	2.64	2.13	1.39	2.3	4.12
1938	2.51	2.13	1.27	2.09	3.47
1939	2.72	2.14	1.33	2.23	3.9
1940	2.95	2.17	1.4	2.41	4.35
1941	3.43	2.2	1.52	2.61	4.95
1942	3.87	2.19	1.63	2.71	5.29
1943	4.38	2.18	1.69	2.9	5.68
1944	4.69	2.17	1.67	3.04	5.88
1945	4.61	2.18	1.58	3.02	5.85
1946	4.06	2.25	1.6	2.97	5.76
1947	4.03	2.34	1.63	3.17	6.42
1948	4.21	2.44	1.64	3.27	6.66
1949	4.18	2.52	1.58	3.06	6.16
1950	4.55	2.5	1.61	3.28	6.66
1951	4.9	2.73	1.66	3.48	7.41
1952	5.08	2.82	1.68	3.48	7.33
1953	5.31	2.91	1.68	3.56	7.85
1954	5.28	3.01	1.61	3.49	7.47
1955	5.65	3.13	1.67	3.77	8.5
1956	5.76	3.24	1.69	3.9	9.06
1957	5.87	3.35	1.67	3.9	9.27
1958	5.81	3.44	1.6	3.88	9.02
1959	6.24	3.55	1.65	4.03	9.64
1960	6.39	3.66	1.66	4.17	10.13
1961	6.54	3.77	1.66	4.22	10.71
1962	6.93	3.89	1.69	4.36	10.96
1963	7.23	4.03	1.72	4.52	11.76
1964	7.65	4.19	1.76	4.67	12.71
1965	8.14	4.37	1.81	4.83	13.54
1966	8.67	4.55	1.84	5.05	14.56
1967	8.89	4.72	1.85	5.2	14.89
1968	9.3	4.9	1.88	5.44	16.05
1969	9.59	5.09	1.92	5.67	17.02
1970	9.6	5.26	1.91	5.84	17.9
1971	9.92	5.45	1.92	5.92	18.27
1972	10.46	5.69	1.99	6.16	19.27
1973	11.06	5.93	2.06	6.4	20.5
1974	10.99	6.2	2.07	6.25	20.18
1975	10.94	6.28	2.03	6.13	19.46
1976	11.53	6.45	2.1	6.41	20.55
1977	12.07	6.67	2.17	6.64	21.03
1978	12.72	6.93	2.25	6.78	21.79
1979	13.08	7.2	2.31	6.88	22.53
1980	13.04	7.41	2.3	6.75	22.45
1981	13.34	7.62	2.31	6.66	21.85
1982	13.05	7.77	2.27	6.44	20.31
1983	13.57	7.94	2.31	6.42	20.72
1984	14.52	8.19	2.42	6.74	22.23
1985	15.04	8.45	2.45	6.77	21.75
1986	15.5	8.7	2.5	6.86	21.76
1987	15.96	8.94	2.56	7.08	22.93
1988	16.57	9.17	2.61	7.37	24.4
1989	17.12	9.39	2.66	7.44	24.93

1990	17.33	9.6	2.66	7.46	25.68
1991	17.17	9.74	2.63	7.45	25.6
1992	17.64	9.89	2.65	7.59	26.27
1993	18.05	10.08	2.7	7.72	26.9
1994	18.67	10.3	2.79	7.92	27.85
1995	19.1	10.55	2.82	8	29.17
1996	19.76	10.97	2.89	8.22	30.29
1997	20.54	11.39	2.95	8.29	30.89
1998	21.33	11.81	3.02	8.33	30.83
1999	22.13	12.23	3.09	8.45	31
2000	22.93	12.65	3.16	8.62	31.69

References

Ayres, R. U., L. W. Ayres, et al. (2005). "On the efficiency of electricity usage since 1900." Energy **30**(7): 1092-1145.

Ayres, R. U., L. W. Ayres, et al. (2003). "Exergy, power and work in the US economy, 1900-1998." Energy **28**(3): 219-273.

Ayres, R. U. and B. Warr (2002). Economic growth models and the role of physical resources. Unveiling wealth: On money, quality of life, and sustainability. P. Bartelmus. Dordrecht/Boston/London, Kluwer Academic Publishers. **Chapter V:** 171-188.

Ayres, R. U. and B. Warr (2005). "Accounting for growth: The role of physical work." Structural Change & Economic Dynamics **16**(2): 181-209.

Bai, J. and P. Perron (2003). "Computation and analysis of multiple structural change models." Journal of Applied Econometrics **18**: 1-22.

Brockwell, P. J. and R. A. Davis (1991). Time Series and Forecasting Methods, Second edition.

Dickey, D. A. and W. A. Fuller (1979). "Distributions of the estimators for autoregressive time series with a unit root." Journal of American Statistical Association **74**: 427-431.

Dickey, D. A. and W. A. Fuller (1981). "Likelihood ratio statistics for autoregressive time series with a unit root." Econometrica **49**: 1057-1072.

Dolado, J. J., T. Jenkinson, et al. (1990). "Cointegration and unit roots." Journal of Economic Survey **4**: 249-273.

Granger, C. W. J. and P. Newbold (1974). "Spurious regression in econometrics." Journal of Econometrics **35**: 143-159.

Hayashi, N. (2005). "Structural changes and unit roots in Japan's macroeconomic time series: is real business cycle theory supported?" Japan and the World Economy **17**(2): 239-259.

Li, X.-M. (2000). "The great leap forward, economic reforms, and the unit root hypothesis: Testing for breaking trend functions in Dhina's GDP data." Journal of Comparative Economics **28**: 814-827.

Nelson, C. R. and C. I. Plosser (1982). "Trends and random walks in macro-economic time series." Journal of Monetary Economics **10**: 139-162.

Perron, P. (1989). "The great crash, the oil price shock, and the unit root hypothesis." Econometrica **57**: 1361-1401.

Perron, P. (1994). Trend, unit root, and structural change in macro-econonomic time series. Cointegration for the Applied Economist. B. Bhaskara Rao.

Seddighi, H. R., K. A. Lawler, et al. (2000). Econometrics: A Practical Approach. London and New York, Routledge.

Soejima, Y. (1994). "Unit-root tests for Japan's macroeconomic variables." Journal of monetary Research, Bank of Japan **13**(4): 97-129.

Stern, D. I. (2000). "A multivariate cointegration analysis of the role of energy in the US macroeconomy." Energy Economics **22**(2): 267-283.

United States Council of Economic Advisors (1996). Economic report of the president together with the annual report of the council of economic advisors. Washington DC, United States Government Printing Office.

United States Department of Commerce Bureau of Economic Analysis (1973). Long term economic growth 1860-1970. Washington DC, United States Government Printing Office.

Warr, B. and R. Ayres "REXS: A forecasting model for assessing the impact of natural resource consumption and technological change on economic growth." Structural Change and Economic Dynamics **In Press, Corrected Proof**.
Zeileis, A., C. Kleiber, et al. (2003). "Testing and dating of structural changes in practice." Computational Statistics & Data Analysis **44**: 109-123.
Zeileis, A., F. Leisch, et al. (2002). "strucchange: An R package for testing for structural change in linear regression models." Journal of Statistical Software **7**: 1-38.
Zeileis, A., F. Leisch, et al. (2005). "Monitoring structural change in dynamic econometric models." Journal of Applied Econometrics **20**: 99-121.
Zivot, E. and D. W. K. Andrews (1992). "Further evidence on the Great Crash, the Oil Shock and the unit root hypothesis." Journal of Business and Economic Statistics **10**(3): 251-270.

Europe Campus
Boulevard de Constance,
77305 Fontainebleau Cedex, France
Tel: +33 (0)1 6072 40 00
Fax: +33 (0)1 60 74 00/01

Asia Campus
1 Ayer Rajah Avenue, Singapore 138676
Tel: +65 67 99 53 88
Fax: +65 67 99 53 99

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