



## Analysis

## Useful work and information as drivers of economic growth

Benjamin Warr <sup>a,\*</sup>, Robert U. Ayres <sup>a,b</sup><sup>a</sup> European School of Business Administration, INSEAD, 77305 Fontainebleau, France<sup>b</sup> International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria

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## ABSTRACT

A semi-empirical endogenous growth theory was proposed by the authors in 2005. It is based on a model of the economy as a two-stage materials/energy processing system. Growth is simulated by a two-parameter production function with two traditional factors, labor and capital, and a non-traditional factor, namely 'useful work'. The non-traditional factor is calculated from primary energy inputs multiplied by an empirically estimated average energy conversion efficiency, which is a function of changing technology over time. This model 'explains' past US growth from 1900 through 1973–74 with satisfactory accuracy but it slightly underestimates subsequent growth (*i.e.* it leaves a small unexplained but increasing residual) for the period after 1975. However, by subdividing capital stock into traditional and ICT components, we are able to extend the theory to explain US economic growth accurately. In this paper we also extend the results to Japan. The revised production function has only three independent parameters. The new model also has implications for future economic growth, energy and environmental policy that differ significantly from the traditional growth theory. These implications are discussed briefly.

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## 1. Introduction

This paper is about explanations of economic growth, with special reference to the role of energy and information and communication technologies (ICT). A semi-empirical endogenous growth theory was proposed by the authors in an earlier paper (Ayres and Warr, 2005), wherein growth is simulated by a two-parameter production function with two traditional factors, labor and capital, and a non-traditional factor, namely 'useful work'. The non-traditional factor is calculated from primary energy inputs multiplied by an empirically estimated average energy conversion efficiency, which is a function of technology and time.<sup>1</sup> The resulting time series of useful work for the US was used to reproduce output growth using a production function of capital, labor and useful work using the LINEX function with useful work as a third factor, and parametric fits determined econometrically (Ayres and Warr, 2005). The results provide a fairly satisfactory fit to real GDP for the period 1900–1975, but the fit is not so good after that time. In other words, after 1975, the US economy grew faster than any of the three factors.

While the focus of our original model was on the role of the improving efficiency of energy conversion technologies, we accept the

proposition that observed improvements derive from flows of ideas from an increasing stock of useful knowledge (Warr and Ayres, 2006). We argue that not all knowledge and derived technologies are equal and that those pertaining to energy productivity provide the greatest productivity enhancements and spillover potential. We suggest that the most promising means of measuring the impact of increased knowledge about energy conversion is through an economy wide evaluation of the aggregate energy (exergy) to useful work efficiency. As a result we choose to use a quantifiable output measure of implemented efficiency–productivity improvements as opposed to an immeasurable input – the productivity potential of a stock of (recombinant) ideas and the allocation of resources to ensure their development which can only poorly reflect the real value of intangibles such as experience, competence and know-how<sup>2</sup> (Weitzman, 1998).

We suspect that future economic growth will be increasingly driven by information and communications technologies (ICT). In this paper we test the hypothesis that ICT inputs might account for the growing discrepancy between actual and predicted GDP using the model. The role of capital is modified to distinguish traditional physical capital (machines, structures, objects) from ICT capital. We find that with differentiation of ICT capital stock and inclusion into the LINEX production function as a 1st order approximation improves

\* Corresponding author. Tel.: +00 33 6 48 48 38 15.

E-mail address: [benjamin.warr@insead.edu](mailto:benjamin.warr@insead.edu) (B. Warr).

<sup>1</sup> A database of exergy and useful work has been collated for the US and (Ayres et al., 2003) and more recently extended to the other three countries (Warr and Ayres, 2010; Warr et al., 2008a, 2008b; Williams et al., 2008). For details of the methodology, see the original papers.

<sup>2</sup> It is worth noting that the productivity potential of a given type of knowledge cannot be 'valued' as independent from the context or the specific problem that needs to be overcome. Therefore knowledge *per se* does not have a unique value that can be measured independently of context and time and on a unique and bounded scale that remains valid faced with a constantly evolving problem set.

the quality of the historical estimates of GDP. Importantly, the marginal productivities of the factors of production differ markedly from their cost shares in the national accounts with capital taking the lions share, useful work much of the remainder and labor only a very small fraction.

The following Section 2 provides an introduction and review of the state of growth theory since the 1950s along with various efforts to deal with faults and gaps in the standard theory, mainly the absence of energy, and the laws of thermodynamics. This seems appropriate, inasmuch as to justify our approach we need to understand the historical reasons for that disconnect. The next Section 3 deals with the thermodynamic inputs to the new theory and discusses our view of the economy as a materials–energy–information processing system. Section 4 discusses the proposed modification to incorporate a role for information/communications technology (ICT) in our previous version of growth theory. Section 5 summarizes the empirical results of the modification. Section 6 discusses implications and offers responses to the usual criticisms.

## 2. Background and Theoretical Perspective

During the 19th and early twentieth century, most economists assumed that the accumulation of capital per capita was the primary driving force for growth. In the early 1950s, after GDP and other economic time series since the 19th century had been reconstructed for the first time, empirical research revealed a drastically reduced role for capital<sup>3</sup> (Abramovitz, 1956; Fabricant, 1954; Kendrick, 1956).

The next step was the explicit introduction of an aggregate production function of capital stock and labor supply (Solow, 1956; Swan, 1956). However, this model, as applied to the period 1909–1949, also left most of the historical growth unexplained. The ‘Solow residual’ still accounted for about 87% of the per capita growth in output. Solow named this residual ‘technological progress’ or, ‘a measure of our ignorance’. More recently, it has been renamed ‘total factor productivity’. Factor productivity calculations, derived from various data series and periods, have since become a mini-industry. However, measuring and naming a phenomenon is not the same as explaining it.

Apart from a number of other questionable simplifications, the standard theory suffers from a crucial deficiency: it does not actually explain economic growth in terms of either economic or physical variables. The neoclassical paradigm as articulated by Solow and others does not allow for ‘real’ material flows. Production and consumption are abstractions, linked only by money: payments for labor, payments for products and services, savings and investment. These money flows, in turn, are presumably governed by equilibrium-seeking market forces (the ‘invisible hand’). Energy and physical laws are never mentioned. The Solow–Swan model implies no deep fundamental connection between the physical world and the economy.

There are a number of other serious problems with the neoclassical growth-in-equilibrium assumption. Detailed critiques of the equilibrium assumption itself exist, e.g. (Kaldor, 1979; Kornai, 1973). However, our approach (Section 4) is consistent with growth-in-equilibrium. Assuming the economy consists of a large numbers of price-taking producers of a single composite good, from two factors (capital and labor) in equilibrium, it can be shown that the two factors are needed in proportion to their productivities and the output elasticities of the two factors are equal to their cost shares (Mankiw, 1997). The cost shares are the same as the income allocation between the factors. The cost-share theorem has been accepted by mainstream economists as justification for the omission of energy as a factor of production on account of its historically small cost share (Denison, 1979a, 1979b). However, in a multi-sector model with a sequential

I–O structure, it can be shown that there is no correspondence of payment shares in the National Accounts and factor productivities if a third factor (such as energy) is introduced (Ayres, 2001). Kuemmel et al. have shown, more recently, that the existence of a mathematical constraint on the ratio of the two (or more) factors invalidates the assumed equality between marginal productivities and cost shares (Kuemmel et al., 2010).

The assumption of ‘constant returns to scale’ is defensible because it means that large countries are not necessarily more productive than small ones. It is also mathematically very convenient, since it sharply limits the mathematical forms of allowable production functions to homogeneous functions of the first order, also known as the Euler condition. The form of the production function is relevant because it determines the potential for substitution between the variables. The simplest mathematical form is the well-known Cobb–Douglas form, which implies perfect substitutability between capital and labor, or capital, labor and other driving variables such as energy. A variant, the constant elasticity of substitution (CES) function was introduced in 1961 (Arrow et al., 1961). This function allows for imperfect substitutability (elasticities less than unity) among the variables, but still assumes that there will be no changes over time.<sup>4</sup> A more flexible function, the linear-exponential (LINEX) form, which permits the introduction of variable output elasticities, was introduced by Kuemmel in the 1980s (Kuemmel et al., 1985).

Since the mid-1980s some theorists have experimented with the idea that growth-in-equilibrium may be explained by allowing positive returns to scale, justified by the notion that knowledge accumulated in one field of production can have spillover effects in other fields. Paul Romer postulated a trade-off between current consumption and investment in ‘knowledge’, which he assumes could be monopolized long enough to be profitable to the discoverer, but yet almost immediately becomes available as a free good (spillover) accessible to others (Romer, 1986). A number of other models have been introduced, exhibiting a variety of variants on the idea. For instance, Robert Lucas (1988), building on some ideas of Uzawa (1965), focuses on ‘social learning’ and the trade-off between consumption and the development of ‘human capital’. In the Lucas version the spillover is indirect: the more human capital the society possesses, the more productive its individual members will be. This externality is embedded in the production function itself, rather than in the knowledge variable.

Other recent models revert to the older Harrod–Domar AK formalism by assuming that all input factors are accumulable, hence can be considered as ‘capital’ of some kind. One version allows two kinds of capital, ‘real’ and human (King and Rebelo, 1990). An alternative version assumes one kind of capital but two sectors, one of which produces only capital from itself (Rebelo, 1991). Another approach was to allow non-constant returns bounded from below by preserving the distinction between accumulable and non-accumulable factors (e.g. labor, land) and modifying the production function to prevent capital productivity from vanishing even with an infinite capital/labor ratio e.g. (Jones and Manuelli, 1990).

The development of endogenous growth theory along neoclassical lines has culminated, for the present, with the work of Aghion and Howitt (1992, 1998) and Barro and Sala-i-Martin (1995) and Weitzman (1998). These authors (like Romer) focus on investment in knowledge itself – in ideas generated by education and experience (and the means to develop them through R&D financing) as a core concept. We agree that knowledge is the fundamental source of efficiency improvements and our ability to design, build and use information-communication technologies. However, all of the so-called ‘endogenous

<sup>3</sup> For example, Fabricant estimated that capital accumulation only accounted for 10% of US economic growth since the middle of the 19th century.

<sup>4</sup> Stern and Kander (2010) set up a version of the CES model which allows for both biased technical change and an elasticity of substitution less than one between energy and the combination of labor and capital. With these relaxations they show that energy exerts a larger influence on growth over a longer time period in the Swedish economy.

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