Distinguishing between Economies of Scale and Technical Progress

by

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Distinguishing between Economies of Scale and Technical Progress[§]

Lawrence J. Lau and Jungsoo Park[1]

December 2021

Abstract: We show how economies of scale may be distinguished from technical progress and how both may be simultaneously identified in the empirical analysis of aggregate economic growth. Using the meta-production function framework and a cross-section of time-series macroeconomic data on inputs and outputs from a sample of developed, newly industrialised and developing economies, estimates of their individual degrees of returns to scale and rates of technical progress over different periods are obtained. It is not necessary to assume that the aggregate production functions of all economies are identical—they only need to be similar after suitable economy- and commodity-specific time-varying transformations of the quantities of the measured inputs and outputs, and these similarity assumptions can be and are explicitly tested. In addition, the individual economy-specific biases of returns to scale and technical progress, if any, are also identified. It is found that the degree of returns to scale of an individual economy depends on the size of its domestic market, represented by the size of its population, and the share of industry value-added in its GDP. It is also found that the rates of technical progress of individual East Asian economies depend on their tangible capital intensities.

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1. Introduction

Can economies of scale be distinguished from technical progress in the analysis of aggregate economic growth? We consider economies of scale at the level of an entire economy.[2] Constant returns to scale is a standard assumption which is frequently maintained in empirical studies of productivity. However, this hypothesis has also been frequently refuted by empirical analyses at both the microeconomic[3] and macroeconomic[4] levels. But if the assumption of constant returns to scale is not true, the estimates of the rates of technical progress, or equivalently growth of total factor productivity, based on that assumption will also be suspect. If there were in fact increasing returns to scale, the estimated rate of technical progress based on the assumption of constant returns to scale would have been too high, and vice versa. This is because for any single individual economy, given its growth path, economies of scale and technical progress can provide alternative explanations of exactly the same observed facts.

The objective of this paper is to show how economies of scale may be distinguished from technical progress and vice versa, and how both may be simultaneously identified and estimated in the empirical analysis of aggregate economic growth. Using the meta-production function[5] framework and a cross-section of time-series macroeconomic data on inputs and outputs[6] from a sample of developed, newly industrialised, and developing economies, estimates of their individual degrees of returns to scale and rates of technical progress over different periods are obtained. Our approach does not require the aggregate production functions of all economies to be identical—they only need to be similar after suitable economy- and commodity-specific time-varying transformations of the quantities of the measured inputs and outputs, and these similarity assumptions can and are explicitly tested.

In addition to the economy-specific degrees of returns to scale and rates of technical progress, the economy-specific biases of returns to scale and technical progress, if any, can

[2] We do not consider economies of scale at the microeconomic level, which is often associated with the economies of scale in the use of tangible capital.
[3] See, for example, Nerlove (1963) and Lau and Tamura (1972).
[4] See, for example, Boskin and Lau (1992).
[5] The concept of a meta-production function was introduced by Hayami and Ruttan (1970, 1985), extended by Lau and Yotopoulos (1989), and applied to the empirical analysis of aggregate time-series data of the "Group-of-Five (G-5)" countries by Boskin and Lau (1992).
[6] It is not necessary for the time-series of the individual economies to cover exactly the same time period.

also be identified. It is found that the degree of returns to scale depends on the size of the domestic market, represented by the size of the population, and the share of industry value-added in its GDP. It is also found that technical progress is simultaneously tangible- and human-capital-augmenting and that the individual East Asian economy-specific measured rate of technical progress depends on its tangible capital intensity—the higher the tangible capital intensity, the higher the rate of technical progress.

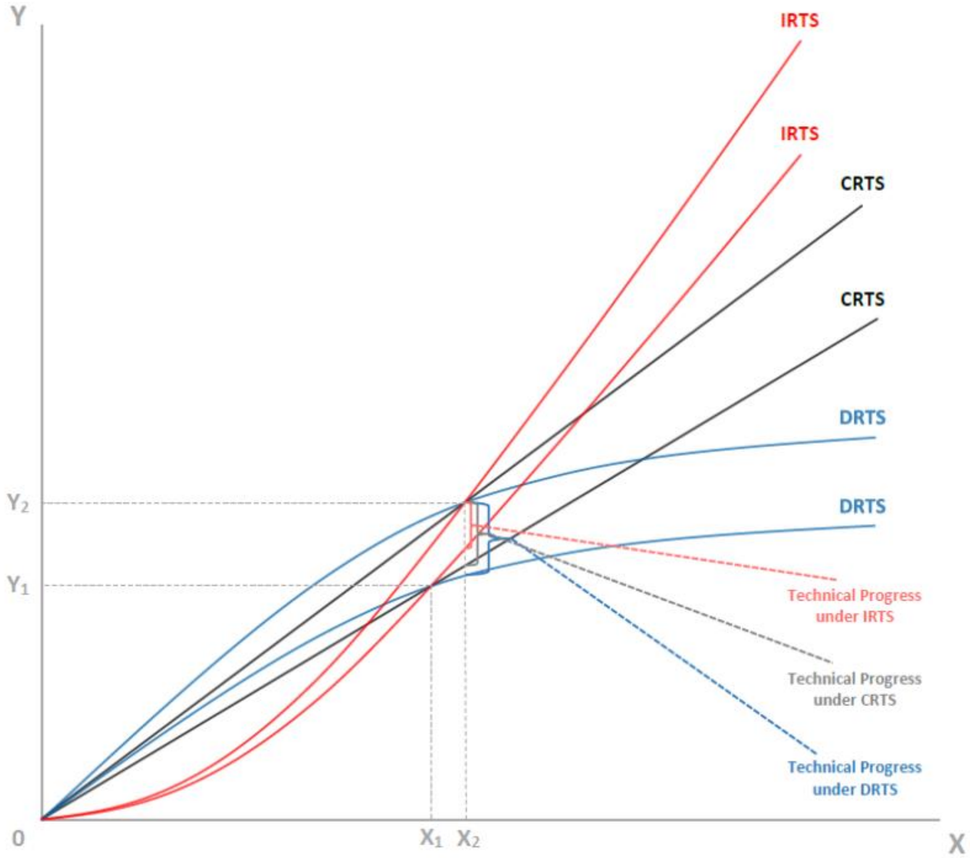
Large economies such as China and the U.S., and potentially India, all have the advantages of economies of scale, because of the sizes of their populations and hence large domestic markets, the opportunities for learning-by-doing through repetitious manufacturing of the same product for domestic demand (e.g., aircrafts, automobiles, ships and high-speed trains), and the larger numbers of individuals in the upper tails of the ability distributions of their respective populations.

The paper is organised as follows. Section 2 explains the inherent problem in separately identifying degree of returns to scale and technical progress from the data of a single economy. Section 3 describes how the local degree of returns to scale and the local rate of technical progress can be separately measured in the case of two or more economies. Section 4 introduces the meta-production function methodology which provides a general empirical framework for the identification and estimation of the degree of returns to scale and the rate of technical progress from a sample of economies. Section 5 explains the data used in this study. In Section 6, the maintained hypotheses of the meta-production function model and the customary hypotheses on the nature of economies of scale and technical progress are tested. Section 7 reports the estimation results for the Group-of-Five (G5) (France, Germany, Japan, the U.K. and the U.S.) developed economies, the four East Asian Newly Industrialised Economies (EANIEs) (Hong Kong, South Korea, Singapore and Taiwan), and four ASEAN (Association of Southeast Asian Nations) (Indonesia, Malaysia, the Philippines and Thailand) developing economies. Section 8 presents estimates of the degree of returns to scale and the rate of technical progress for each economy. There are brief concluding remarks in Section 9.

2. The Under-Identification of the Degree of Returns to Scale and the Rate of Technical Progress in the Case of a Single Economy

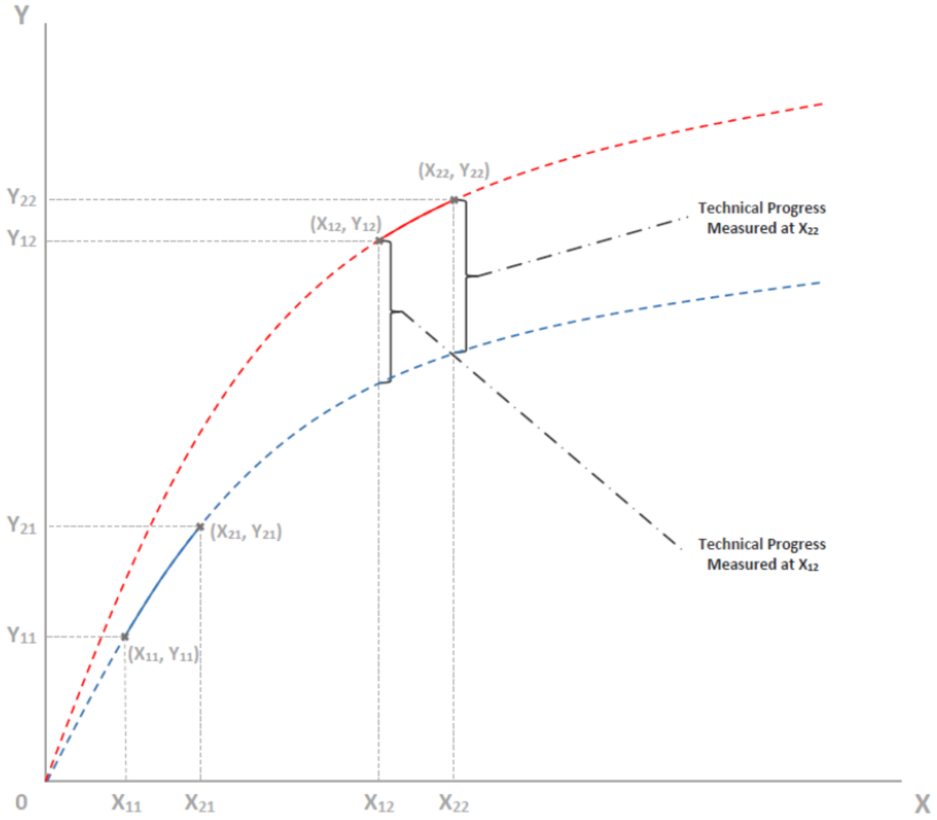
We begin by considering the one output, one input case for a single economy. In Figure 2-1, we plot the two observations, (X_1, Y_1) and (X_2, Y_2), where X_t and Y_t are the quantities of the input and output of the economy in the tth period respectively. We take $X_t > X_{t'}$ and $Y_t > Y_{t'}$, t > t'. We note, first of all, that if we assume constant returns to scale (CRTS), we can draw two straight black lines through the origin, one joining the point (X_1, Y_1), and the other joining the point (X_2, Y_2). These two lines may be considered the production functions relating the quantity of output to the quantity of input in the 1st and the 2nd periods respectively. The vertical distance between the two straight lines then represents the outcome of technical progress between the two periods. Alternatively, we can draw two concave blue curves through the origin, each passing through one of the two points. These two curves may also be considered the production functions in the 1st and the 2nd periods respectively. The concavity of the blue curves reflects decreasing returns to scale (DRTS), with the vertical distance between the two curves again representing technical progress. Finally, we can draw two convex red curves through the origin, each also passing through one of the two points, as the production functions of the two periods respectively. The convexity of the red curves reflects increasing returns to scale (IRTS), with the vertical distance between the two curves representing technical progress. Thus, the same time-series data on inputs and outputs can be consistent with decreasing, constant and increasing returns to scale and different measured rates of technical progress. Figure 2-1 clearly illustrates the under-identification of the degree of returns to scale and the rate of technical progress with data from a single economy in general. Moreover, the measured rate of technical progress declines as the degree of returns to scale changes from decreasing to constant to increasing, demonstrating that they can be alternative explanations for the same observed phenomena. With more than two observations, the situation is essentially the same: given the quantities of input, one can always explain the evolution of the quantities of output through alternative combinations of the degree of returns to scale and the rate of technical progress.

Figure 2-1: The Under-Identification of the Degree of Returns to Scale and the Rate of Technical Progress in a Single Economy, the One-Output, One-Input Case



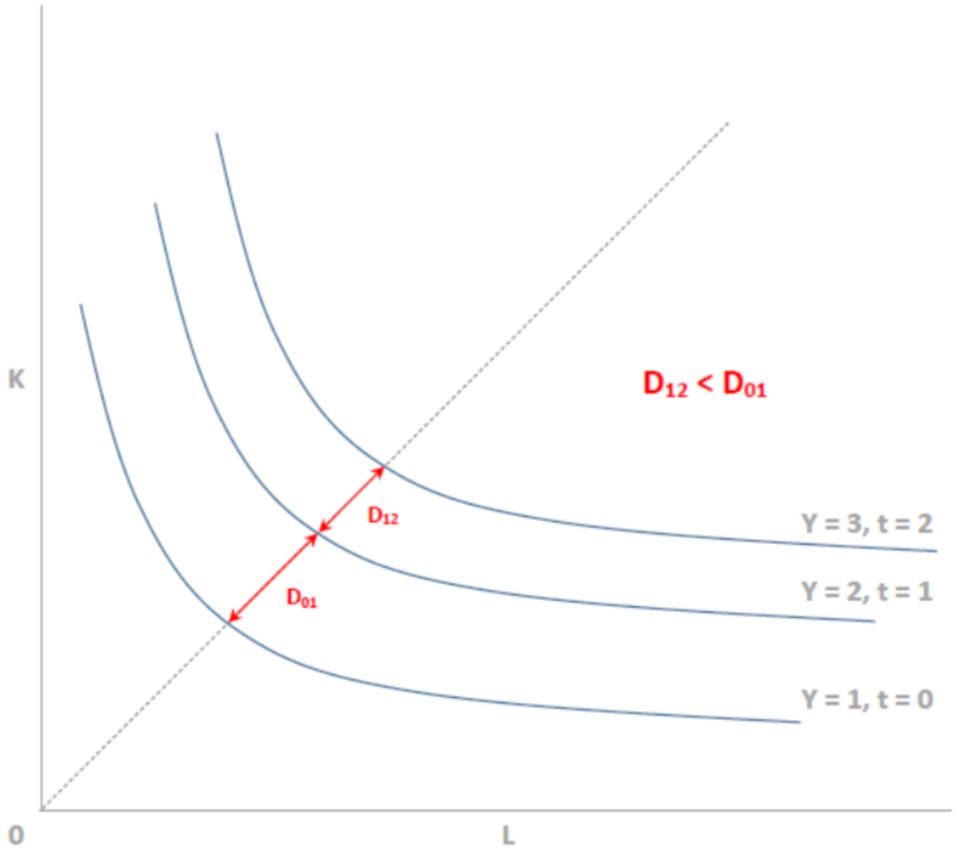
However, with two or more economies, identification of both the degree of returns to scale and the rate of technical progress becomes possible. In Figure 2-2, we plot the four observations, (X_{11}, Y_{11}), (X_{12}, Y_{12}), (X_{21}, Y_{21}) and (X_{22}, Y_{22}), two from each economy, where X_{it} and Y_{it} are the quantities of the inputs and outputs of the ith economy in the tth period respectively. We take $X_{it} > X_{it'}$ and $Y_{it} > Y_{it'}$, $t > t'$. Since there are two observations for each period, the production function in each period is constrained to pass through the two points and can no longer be drawn arbitrarily. We note, first of all, that if we join the two points (X_{11}, Y_{11}) and (X_{21}, Y_{21}), we obtain part of the production function in the 1st period. And if we join the other two points (X_{12}, Y_{12}) and (X_{22}, Y_{22}), we obtain part of the production function in the 2nd period. The vertical distance between the two curves (and their respective extrapolations) then represents the technical progress between the two periods. Figure 2-2 clearly illustrates the possibility of the separate identification of the degree of returns to scale and the rate of technical progress simultaneously in the case of two economies. Here we have assumed that the production functions of the two economies are identical, but the assumption is actually not necessary, as will be shown below in Section 4.

Figure 2-2: The Identification of the Degree of Returns to Scale and the Rate of Technical Progress in Two Economies, the One-Output, One-Input Case



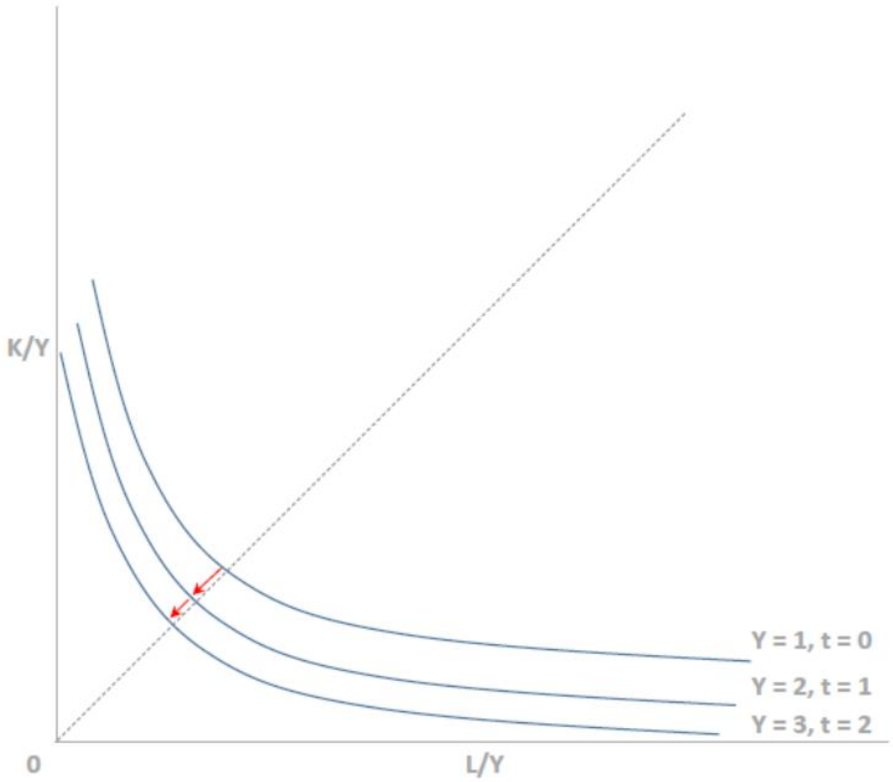
In the case of one output (Y) and two inputs (K and L), returns to scale can be represented as movements of the isoquants outward from the origin in accordance with the quantity of output but in decreasing sizes of steps (see Figure 2-3). However, in general, the movement of the isoquants outwards from the origin may not necessarily be curvature-preserving, that is, with the successive isoquants being exact copies of one another, aside from location and labelling. In Figure 2-3, we can see that the distances between the isoquants corresponding to the output levels of 1, 2 and 3, at t=0, 1 and 2 respectively, are getting closer, reflecting the existence of economies of scale. We note that, by assumption, there is no technical progress in this case.

Figure 2-3: Isoquants of Production Functions with Increasing Returns to Scale, the One-Output, Two-Input Case



However, the same isoquants in Figure 2-3 can also be reinterpreted as having been generated by a production function with a positive rate of technical progress under constant returns to scale. In the case of one output and two inputs, technical progress can be represented as movements of the unit-output isoquants inward towards the origin in accordance with time, starting from t=0. The unit-output isoquant at t=1 uses less of both K and L compared to the unit-output isoquant at t=0, and the unit-output isoquant at t=2 uses even less. By assumption, there are constant returns to scale, so that all the increased efficiency in production may be attributed to technical progress. Using the same data as in Figure 2-3, we can construct unit-output isoquants at t=0, 1 and 2, with their corresponding different levels of output, Y = 1, 2 and 3. This is shown in Figure 2-4, with the two axes measuring K/Y and L/Y respectively. The unit-output isoquants move inward towards the origin as t=0, 1 and 2 and the level of output increases from 1 to 3—the inputs required per unit output decreases with time, signifying technical progress. We note, however, that we can simply relabel the output isoquants in Figure 2-3 by t=0, 1 and 2, and attribute all the movements of the isoquants to technical progress instead of returns to scale. The fact that the same data can result in both Figures 2-3 and 2-4, the former with increasing returns to scale but no technical progress and the latter with constant returns to scale but positive technical progress is evidence of the under-identification of the degree of returns to scale and the rate of technical progress with data from only a single economy. As long as there is only one observation in each period, it is not possible to distinguish between economies of scale and technical progress.

Figure 2-4: Unit-Output Isoquants of a Production Function with Technical Progress, the One-Output, Two-Input Case



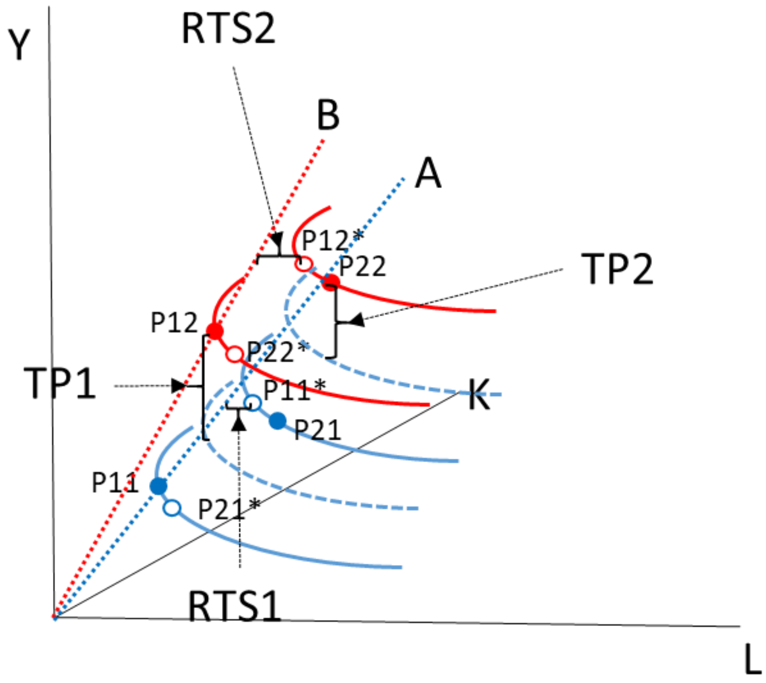
The same reasoning can be used to show that with the aggregate time-series data of the output and multiple (more than two) inputs of only a single economy, it is impossible to identify separately the degree of returns to scale and the rate of technical progress. Intuitively, with data from only a single economy (and hence a single time-series), each time period is only observed once, one can therefore always increase the degree of returns to scale and decrease the rate of technical progress or vice versa to fit any given body of data. It is possible to attribute the entire increased productivity to either returns to scale or technical progress, or to any combination of the two.

However, with two or more economies, identification becomes possible, because at any given time there are more than two observations of output and inputs, thereby enabling the partial identification of the production function for that period. In Figure 2-5, we plot, in three dimensions, the four input-output points for two economies in the two periods: P11(K_{11},L_{11},Y_{11}), P12(K_{12},L_{12},Y_{12}), P21(K_{21},L_{21},Y_{21}) and P22(K_{22},L_{22},Y_{22}), two from each economy, where K_{it} , L_{it} and Y_{it} are the quantities of capital, labour and outputs of the ith economy in the tth period respectively.

If $Y_{11} = Y_{21}$ and $Y_{12} = Y_{22}$, then in principle we have two points on each of the isoquants for the first and second periods, and thus they can be approximately identified. The horizontal distance between the two isoquants provides a way to estimate the degree of returns to scale in conjunction with the differences in the quantities of output between periods 1 and 2. The vertical distance between the two isoquants provides a measure of the rate of technical progress between the two periods, if any. However, it is possible that all four observed output levels are different. In that case, we need to construct a hypothetical output surface for each period. We begin by posing the question: with what inputs would economy 1 be able to produce the output of economy 2 in period 1? They will be approximately given by the point P11*($K_{11}Y_{21}/Y_{11}$,$L_{11}Y_{21}/Y_{11}$,Y_{21}).[7] Similarly, economy 2 would be able to produce the output of economy 1 in period 1 at the point P21*($K_{21}Y_{11}/Y_{21}$,$L_{21}Y_{11}/Y_{21}$,Y_{11}). We thus have the partial isoquants for output levels Y_{11} and Y_{21}. The two isoquants can be connected to form an output surface in period 1. Similarly, we can construct hypothetical points P12* and P22* and form an output surface in period 2. The vertical distance between the two surfaces provides an estimate of the rate of technical progress between periods 1 and 2. The horizontal distances (RTS1 and RTS2) between the two surfaces and the rays A and B from the origin provides a way to estimate the degree of returns to scale. Figure 2-5 clearly illustrates the possibility of the simultaneous separate identification of the degree of returns to scale and the rate of technical progress in the case of two economies.

[7] If there were constant returns to scale, this would be exactly the output-input combination.

Figure 2-5: Isoquants of Production Functions with Variable Returns to Scale and Non-Neutral Technical Progress in Two Economies, the One-Output, Two-Input Case



Intuitively, the possibility of separate identification of the returns to scale and technical progress with two or more economies can be understood in the following way. With two or more economies, at any given time, there are different scales operating and the same scale can be observed at different times. Thus, it is possible to disentangle the effects of economies of scale and technical progress.

3. The Measurement of the Local Degree of Returns to Scale and the Local Rate of Technical Progress and Their Possible Biases

There is, of course, no a priori reason why a production function will always have the same degree of returns to scale, independently of the quantities of the inputs, or the same constant rate of technical progress at all times. We therefore define local measures of the degree of returns to scale and rate of technical progress below.

Let Y = F(X, t), be the production function in the one-output-one-input case. The (local) degree of returns to scale, defined as the proportional change in output in response to a proportional change in input, at a given quantity of input and time, is given by:

$$\frac{\partial \ln F(\lambda X,t)}{\partial \ln \lambda}\Big|_{\lambda=1} = \frac{\partial \ln F(X,t)}{\partial \ln X},$$

the elasticity of output with respect to input at time t. The (local) rate of technical progress is given by the proportional change in output, or the natural-logarithmic derivative of the production function, with respect to time:

$$\frac{\partial \ln F(X,t)}{\partial t}.$$

In the case of three inputs, tangible capital (K), human capital (H) and labour (L), the production function becomes F(K,H,L,t). The degree of (local) returns to scale, defined as the proportional change in output in response to a proportional change in inputs, is given by:

$$\frac{\partial \ln F(\lambda K,\lambda H,\lambda L,t)}{\partial \ln \lambda}\Big|_{\lambda=1} = \frac{\partial \ln F(K,H,L,t)}{\partial \ln K} + \frac{\partial \ln F(K,H,L,t)}{\partial \ln H} + \frac{\partial \ln F(K,H,L,t)}{\partial \ln L},$$

that is, the sum of the elasticities of output with respect to the inputs at time t. In general, the local degree of returns to scale is also a function of K, L, H and t.[8] The (local) rate of technical progress is defined as the proportional change in output, or the natural-logarithmic derivative of the production function with respect to time:

$$\frac{\partial \ln F(K,H,L,t)}{\partial t}.$$

There is no theoretical reason why returns to scale should be neutral, that is, independent of the relative factor proportions. Thus, different combinations of K, L and H

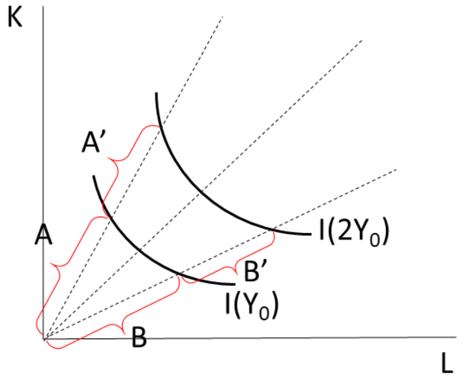
---

[8] However, if F(.) is homogeneous of any degree, not necessarily one, in K, L and H, the local degree of returns to scale is a constant. More generally, if F(.) is homothetic in K, L and H, the local degree of returns to scale is a real-valued function of F(.) and does not depend on the specific relative factor proportions. In these cases, the returns to scale is said to be neutral or unbiased.

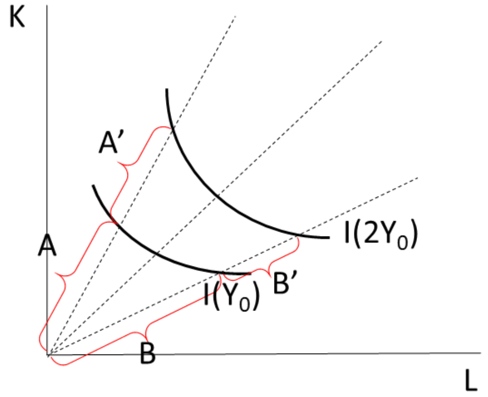
can have different effects on the magnitude and the bias of the economies of scale. For example, it can be more capital-saving than labour-saving (see Figure 3-1) or vice versa.

Figure 3-1: Isoquants of Production Functions with Neutral and Biased Returns to Scale

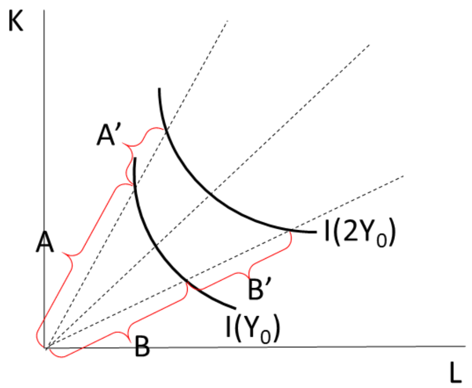
A. Neutral Economies of Scale
(A'/A = B'/B <1)



B. Labour-Biased Economies of Scale
(1 > A'/A > B'/B)



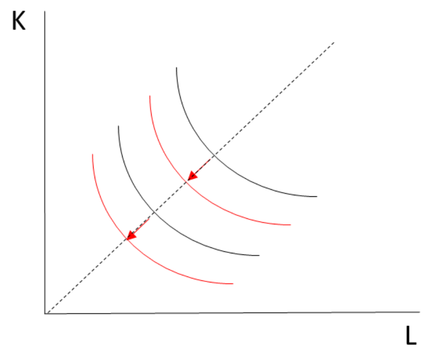
C. Capital-Biased Economies of Scale
(A'/A < B'/B <1)



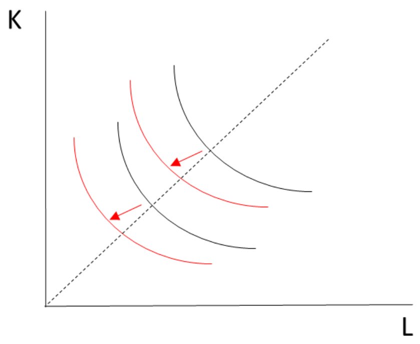
Similarly, technical progress does not need to be the type that shifts all isoquants uniformly inward. If technical progress shifts all isoquants uniformly inward towards the origin, it is said to be Hicks-neutral, or purely output-augmenting. However, technical progress can also be Harrod-neutral, that is, purely labour-augmenting. Alternatively, it can also be Solow-neutral, that is, purely capital augmenting. Examples are shown in Figure 3-2.

Figure 3-2: Isoquants of Production Functions with Neutral and Biased Technical Progress

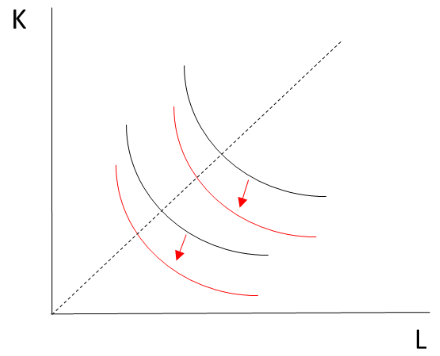
A. Hicks-Neutral (output-augmenting)



B. Harrod-Neutral (labour-augmenting)



C. Solow-Neutral (capital-augmenting)



Diamond and McFadden (1965) and Diamond, McFadden and Rodriguez (1978) show that the elasticity of substitution and the biases of technical progress cannot be identified from time-series data on aggregate inputs and output (of a single economy) alone. However, with time-series macroeconomic data from a cross-section of economies, and under the assumption of the existence of a meta-production function, it is not only possible to distinguish between economies of scale and technical progress, but also to identify the biases in economies of scale and technical progress, if any. Also, with a cross-section of time-series macroeconomic data, there is likely to be greater variability across the quantities of inputs and outputs, which also facilitates econometric identification.

4. The Meta-Production Function Model

The methodology used in this study follows closely the meta-production function approach used in Boskin and Lau (1992). There are three basic assumptions for the meta-production function model. They are, for the three-input (tangible capital, human capital and labour) case:

(1) All economies have the same underlying aggregate meta-production function F(.) in terms of standardised, or "efficiency-equivalent", quantities of outputs and inputs, i.e.

(4.1) $Y_{it}^{*} = F(K_{it}^{*}, H_{it}^{*}, L_{it}^{*})$, i=1,...,n,

where Y_{it}^*, K_{it}^*, H_{it}^* and L_{it}^* are the quantities of "efficiency-equivalent" outputs and tangible capital, human capital, and labour of the ith economy in the tth period, respectively, and n is the number of economies.[9]

(2) The measured quantities of outputs and inputs of the different economies may be converted into the unobservable standardised, or "efficiency-equivalent", units of outputs and inputs by multiplicative economy-, output- and input-specific time-varying augmentation factors, A_{ij}(t)'s, i=1,...,n; j=output (0), capital (K), human capital (H), and labour (L):

(4.2) $Y_{it}^{*} = A_{i0}(t)Y_{it}$;

(4.3) $K_{it}^{*} = A_{iK}(t)K_{it}$;

(4.3) $H_{it}^{*} = A_{iH}(t)H_{it}$;

(4.4) $L_{it}^{*} = A_{iL}(t)L_{it}$; i=1,...,n.

[9] Note that F(.) itself is assumed to be independent of t. t affects the production function only through its effects on the commodity-augmentation factors. Thus, technical progress is assumed to be representable in the "commodity-augmentation" form. This is an assumption that will also be tested.

The commodity-augmentation factors reflect differences in climate, natural resources, infrastructure, quality and technical efficiencies across economies. In this study, the commodity-augmentation factors are assumed to have a constant geometric form with respect to time.

(4.5) $Y_{it}^{*} = A_{i0}\ (1 + c_{i0})^{t} Y_{it}$;

(4.6) $K_{it}^{*} = A_{iK}\ (1 + c_{iK})^{t} K_{it}$;

(4.6) $H_{it}^{*} = A_{iH}\ (1 + c_{iH})^{t} H_{it}$;

(4.7) $L_{it}^{*} = A_{iL}\ (1 + c_{iL})^{t} L_{it}$, i=1,..., n,

where the A_{i0}'s, A_{iK}'s, A_{iH}'s, A_{iL}'s, c_{i0}'s, c_{iK}'s, c_{iH}'s and c_{iL}'s are constants. A_{i0}'s, A_{iK}'s, A_{iH}'s and A_{iL}'s are referred to as augmentation level parameters and c_{i0}'s, c_{iK}'s, c_{iH}'s and c_{iL}'s as augmentation rate parameters. Since the augmentation level parameters can only be identified relative to some standard, without loss of generality, the augmentation level parameters for one economy, say the United States, are all assumed to take values of unity. With this normalisation, all of the remaining level and rate parameters are estimable without further restrictive assumptions.

(3) A flexible functional form is chosen for F(.) in order to accommodate the wide range of variations of the quantities of inputs in the pooled multiple-economy sample and also to allow the possibility of non-neutral returns of scale and technical progress. In this study, the meta-production function is specified to be the transcendental logarithmic (translog) functional form introduced by Christensen, Jorgenson and Lau (1973). With three inputs, tangible capital, human capital, and labour, the translog production function takes the following form.

(4.8)

$$\begin{aligned} lnY_{it}^{*} &= lnY_{0} + a_{K} lnK_{it}^{*} + a_{H} lnH_{it}^{*} + a_{L} lnL_{it}^{*} \\ &+ B_{KK}(lnK_{it}^{*})^{2}/2 + B_{HH}(lnH_{it}^{*})^{2}/2 + B_{LL}(lnL_{it}^{*})^{2}/2 \\ &+ B_{KL}(lnL_{it}^{*})(lnK_{it}^{*}) + B_{HK}(lnH_{it}^{*})(lnK_{it}^{*}) + B_{HL}(lnL_{it}^{*})(lnH_{it}^{*}). \end{aligned}$$

Equation (4.8) consists entirely of unobservable variables and cannot be econometrically estimated. However, by substituting equations (4.5) through (4.7) into equation (4.8) and simplifying, we obtain an equation consisting entirely of observable variables:

(4.9)

$$
\begin{aligned}
lnY_{it} = {} & lnY_0 + lnA_{i0}^{*} + a_{iK}^{*} lnK_{it} + a_{iH}^{*} lnH_{it} + a_{iL}^{*} lnL_{it} \\
& + B_{KK}(lnK_{it})^2/2 + B_{HH}(lnH_{it})^2/2 + B_{LL}(lnL_{it})^2/2 \\
& + B_{KL}(lnL_{it}lnK_{it}) + B_{HK}(lnH_{it}lnK_{it}) + B_{HL}(lnL_{it}lnH_{it}) \\
& + c_{i0}^{*} t \\
& + (B_{KK}ln(1+c_{iK}) + B_{HK}ln(1+c_{iH}) + B_{KL}ln(1+c_{iL}))(lnK_{it})t \\
& + (B_{HK}ln(1+c_{iK}) + B_{HH}ln(1+c_{iH}) + B_{HL}ln(1+c_{iL}))(lnH_{it})t \\
& + (B_{KL}ln(1+c_{iK}) + B_{HL}ln(1+c_{iH}) + B_{LL}ln(1+c_{iL}))(lnL_{it})t \\
& + (B_{KK}(\ln(1+c_{iK}))^2 + B_{HH}(\ln(1+c_{iH}))^2 + B_{LL}(\ln(1+c_{iL}))^2 \\
& + 2B_{KL}ln(1+c_{iK})ln(1+c_{iL}) + 2B_{HL}ln(1+c_{iH})ln(1+c_{iL}) \\
& + 2B_{HK}ln(1+c_{iH})ln(1+c_{iK}))t^2/2 \\
& i=1,\ldots,n,
\end{aligned}
$$

where the A_{i0}^{*}, c_{i0}^{*}, a_{iK}^{*}, a_{iH}^{*} and a_{iL}^{*}'s are economy-specific constants. B_{KK}, B_{HH}, B_{LL}, B_{KL}, B_{HL} and B_{HK} are the only common parameters across economies under the maintained hypothesis of a single identical meta-production function for all economies. Thus, one can test the hypothesis of a single identical meta-production function by testing whether these parameters are identical across economies. Another feature of the representation in equation (4.9) is that for each economy, the parameter for the t^2 term is completely determined by the other identifiable parameters for that economy. This is a direct implication of the assumption that technical progress can be represented in the commodity-augmentation form in the meta-production function model. Thus, one can test the hypothesis of the commodity-augmentation representation of technical progress by testing whether this restriction holds. In our empirical implementation, equation (4.9) is estimated for all the economies simultaneously.[10]

Once the parameters of equation (4.9) are estimated, one can calculate the degree of returns to scale and the rate of technical progress for each economy given the quantities of K, H, L and the time t, using the formulae in Section 3 above. As we can see, it is not necessary

[10] Without loss of generality, the above derivation can be generalised to the case of any finite number of inputs.

to assume that the production functions of all economies are identical in order to distinguish between economies of scale and technical progress. All that is necessary is an assumption that the production functions are sufficiently similar, as in the meta-production function model. Moreover, the assumptions underlying the validity of the meta-production function approach can be statistically tested. In mathematical terms, under these assumptions, the production functions of the different economies form a "group" as they can be transformed into one another under suitable operations.

5. The Data and the Empirical Implementation

(1) The data

In this study, we apply the meta-production function model to thirteen economies: The Group-of-Five (G-5) economies, the four EANIEs (Hong Kong, South Korea, Singapore and Taiwan) and four ASEAN developing economies (Indonesia, Malaysia, Philippines, and Thailand). We distinguish one-output, real GDP, and three inputs: tangible capital, human capital, and labour. The inclusion of economies at different stages of development should provide the variations in the data that enable the more precise identification and estimation of the parameters of the aggregate meta-production function.

For the G-5 economies, the sample period is 1958-2010 except for the U.S., which is 1950-2010, and Germany (1991-2010).[11] The definition of the variables and the construction of data basically follow Boskin and Lau (2002). The macroeconomic data for the four EANIEs and the four ASEAN developing economies used in Kim and Lau (1995, 1996) are extended to include on average twenty additional years (1991-2010).[12] The variables included are real GDP, Y, utilized tangible capital stock, K, total labour hours worked, L, and human capital stock, H. The real GDP and utilized tangible capital stocks are in constant 1980 U.S. dollars. The utilised tangible capital stocks are obtained by multiplying the capacity utilization rates in the manufacturing sector to the tangible capital stocks. The construction

[11] This is after German reunification.
[12] The specific sample periods for these economies are as follows: Hong Kong, 1966-2010; South Korea, 1960-2010; Singapore, 1966-2010; Taiwan, 1953-2010; Indonesia, 1970-2010; Malaysia, 1970-2010; the Philippines, 1966-2010; and Thailand, 1966-2010. The details of relevant data sources are discussed in Kim and Lau (1995) and Park (1999).

of the gross tangible capital stock from gross investment data is based on the perpetual inventory method with given retirement rates. In economies where data on the capacity utilization rates are not available, they are estimated by the "peak-to-peak" method and normalised through a scalar adjustment.[13]

The annual total number of labour hours per (employed) person is obtained by multiplying factors of 52 or 12 to average weekly or monthly hours.[14] The human capital input is defined as the average number of years of schooling (including primary, secondary and tertiary education) of the working age population (defined to be persons of age between 15 and 64, inclusive), multiplied by the actual employment. It is derived from the accumulation of annual aggregate educational enrolment figures using the perpetual inventory method, taking into account the survival rates of the different age groups.[15] As for the East Asian economies, the human capital series have been extended and revised based on the data of Kim and Lau (1995).[16] Data for working-age population are taken from *Labour Force Statistics*, OECD for the G-5 developed economies and from economy-specific statistical yearbooks for the four EANIEs and the four ASEAN economies. The average annual rates of growth of outputs and inputs of the different economies are presented in Table 5.1 for their entire sample periods.

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[13] For a detailed discussion, see Kim and Lau (1995).

[14] For Indonesia, data on average hours worked are not available—the average of the average numbers of hours worked per person per week for Malaysia, the Philippines and Thailand is used instead. Furthermore, in order to adjust for the effect of vacations or leaves, a month is taken out.

[15] For detailed discussions, see Kim and Lau (1995).

[16] The basic approach which accumulates long historical time series of enrolment data is used for South Korea and Singapore. However, due to the lack of long historical time series for enrolment and the potential impacts of large population movements due to wars and natural calamities, the benchmark approach is used for Hong Kong (1971 census), Taiwan (1956), Indonesia (1969), Malaysia (1957), the Philippines (1970) and Thailand (1960). The enrolment figures for the subsequent and prior years to the respective benchmark year are successively added to the benchmark distributions of the human capital stock to derive estimates of the average educational attainment levels for each year. As for Hong Kong, the levels of average schooling years are further adjusted to match the educational attainment figures for all census years after 1961 census of Hong Kong.

Table 5.1: Average Annual Rates of Growth of Inputs and Outputs (%)

	Sample Period	Output (Real GDP)	Tangible Capital Stock	Utilized Tangible Capital	Employment	Total Labour Hours	Average Years of Education of the Working-Age Population[1]	Total Years of Education of the Working-Age Population[1]
Hong Kong	1967-2010	6.06	7.74	7.83	2.08	2.00	1.80	3.96
South Korea	1961-2010	7.57	11.18	11.18	2.45	2.42	2.91	4.92
Singapore	1968-2010	7.68	9.16	9.45	3.76	3.83	2.24	4.5
Taiwan	1954-2010	7.31	10.32	10.32	2.25	1.92	2.27	4.49
Indonesia	1971-2010	5.89	8.59	8.64	2.72	2.97	3.47	5.92
Malaysia	1971-2010	6.38	8.79	8.99	2.85	3.58	2.02	5.07
Philippines	1971-2010	3.75	4.08	4.16	2.74	2.91	1.21	4.13
Thailand	1971-2010	5.94	6.97	6.97	2.15	2.24	2.12	4.48
Japan	1948-2010	4.17	6.28	6.34	0.74	0.21	0.88	1.52
France	1958-2010	1.26	1.78	1.78	0.25	-0.22	0.22	0.11
Germany	1991-2010	2.48	3.24	3.28	0.36	0.00	0.81	1.18
United Kingdom	1958-2010	3.05	3.42	3.38	0.52	0.01	1.38	2.11
United States	1958-2010	3.26	2.87	2.87	1.31	0.96	0.73	1.97

(2) The empirical implementation

For the G-5 economies, the oil shocks of 1973 and 1980 may have affected their augmentation rates. We have therefore allowed for a temporary shift in their augmentation rates for the 1974 to 1985 period. Given that the four EANIEs have also been undergoing significant economic transformation over time, their augmentation rates are also allowed a shift after a break year. Thus, for the four EANIEs, their $c_{iK}'s$ are defined as ($c_{iK1} + c_{iK2} \cdot break_i$)'s, where $break_i$ is an indicator function taking the value one after the critical year specific to each of the four countries.[17] A single augmentation rate is allowed for each of the four ASEAN economies, as these economies have yet to enter a growth transition. Our regression also includes crisis dummies for the eight East Asian economies for the East Asian currency crisis of 1998-1999 and crisis dummies for all economies for the global financial crisis of 2008-2009.

Since macroeconomic time-series data often display non-stationarity, our estimation of equation (4.9) is done in the first-differenced form. In order to avoid potential biases that may result from endogeneity of the factor input variables, the method of nonlinear instrumental

[17] The break or critical year for each country was chosen as the year when the country reached 6 years of average schooling years. Furthermore, we have assumed 10 years of steady transition from one augmentation rates to another.

variables two-stage least-squares is used (See Gallant and Jorgenson (1979)). The stochastic disturbance terms of the aggregate production function are further adjusted for possible heteroscedasticity.

The instrumental variables used in the estimation include lagged output, lagged employment, economy dummies, world population, male and female population, arable land, male and female life expectancy, contemporaneous and lagged world prices of cotton, oil and iron ore relative to the world price of wheat. Data on world and economy-specific total, male and female populations are taken from *United Nations Statistical Yearbook*. Data on world prices of cotton, oil, iron and wheat are taken from *International Financial Statistics*.

6. Tests of the Meta-Production Function Model and Customary Hypotheses

Our full meta-production function model for thirteen economies has a large number of independent parameters, but many of them have to satisfy restrictions if they were to be consistent with the meta-production function model. The six second-order parameters of the translog production function, B_{KK}, B_{HH}, B_{LL}, B_{KL}, B_{HL} and B_{HK}, must be identical across economies. With 13 economies, there are 72 (12 x 6) restrictions. In addition, for each economy, the parameter for the t^2 term in equation (4.9) is not independent but is completely determined by the other identifiable parameters for that economy. With thirteen economies, there are thirteen such nonlinear restrictions, one for each economy. Both sets of restrictions are necessary for the validity of a single identical meta-production function for all economies.

So, the first set of hypotheses we test is whether the meta-production function model is valid, which consists of two hypotheses, the identity of the second-order translog parameters across economies, and the nonlinear restrictions for every economy. It turns out that neither of these two hypotheses can be rejected at any reasonable level of significance. (See Table 6.1 below, where we have also provided the p-values for each of the hypotheses.)

Conditional on the validity of the meta-production function model, we proceed to test other hypotheses of interest. The second set of hypotheses we test is that of constant returns to scale, a common assumption in the empirical analysis of economic growth. This we do in two different ways. First, we test the hypothesis of homogeneity of the production function, which implies three restrictions on the second-order translog parameters, and which is also a necessary condition for homogeneity of degree one (constant returns to scale). Second, we directly test the hypothesis of homogeneity of degree one, which implies one additional restriction on the sum of the first-order translog parameters (it must be equal to unity). Both hypotheses are decisively rejected.

The third set of hypotheses that we test have to do with the nature of the production technology itself. We first test whether the augmentation level parameters for tangible capital, human capital, and labour respectively are identical across economies. These hypotheses cannot be rejected at any reasonable level of significance. We then test four hypotheses on the nature of technical progress: whether it is purely output-augmenting (Hicks-neutral), purely tangible-capital-augmenting (Solow-neutral), purely human-capital-augmenting, or purely labour-augmenting (Harrod-neutral). It turns out that we can reject the hypotheses of purely output-augmenting and purely labour-augmenting[18], but cannot reject the hypotheses of purely tangible-capital- and human-capital-augmenting.

[18] At a 5-percent level of significance.

Table 6.1: Tests of Hypotheses (G-5 and 8 East Asian Economies)

Tested Hypothesis	Maintained Hypothesis	No. of Restrictions	p-value
I. Maintained Hypotheses of the Meta-production Function Model			
(1) Single Meta-Production Function	Unrestricted	72	0.9900
(2) Commodity Augmentation	I(1)	13	0.7039
II. Traditionally Maintained Hypotheses			
(1a) Homogeneity	I	3	0.0000[1]
(1b) Constant Returns to Scale	I	4	0.0000[1]
III. The Nature of the Production Technology			
A. Hypotheses on Augmentation Levels			
(1) Identical Augmentation Levels for Tangible Capital	I	12	0.4638
(2) Identical Augmentation Levels for Labour	I	12	0.9933
(3) Identical Augmentation Levels for Human Capital	I	12	0.9054
B. Hypotheses on Augmentation Rates			
Purely Output-Augmenting[2]	I	39	0.0058
Purely Tangible-Capital-Augmenting	I	39	0.1923
Purely Labour-Augmenting	I	39	0.0464
Purely Human-Capital-Augmenting	I	39	0.1411

Notes: 1. Due to rounding.

The only possible form for a production function to be simultaneously purely tangible-capital-augmenting and purely human-capital-augmenting is, as shown in Lau (1980):

$$Y_{it} = A_{i0}F(A_{iKH}(t)K_{it}^{\lambda}H_{it}^{1-\lambda}, A_{iL}L_{it}) \quad (6.1)$$

where F(.) is a real-valued function of two variables and λ is, without loss of generality, a positive constant between zero and one. Tangible capital and human capital together form a composite capital variable that has the Cobb-Douglas form. Based on the results of our hypothesis testing, we estimate a restricted specification incorporating all the restrictions implied by the hypotheses that are not rejected. These results are presented in Table 7.1 below.

7. Empirical Results

The estimated final specification for the aggregate meta-production function is reported in Table 7.1. It is notable that the initial set of augmentation rates, c_{iK1}'s, for the G-5 economies are statistically significant both individually and as a group, whereas those for the four EANIEs and the four ASEAN developing economies are not statistically significant as respective groups. This is actually quite consistent with for example the empirical findings of Kim and Lau (1995, 1996) for developing economies in their early stages of industrialisation. However, we find that the second set of augmentation rates for the four EANIEs (after their respective break years), the c_{iK2}'s, are statistically significant as a group. In particular, the augmentation rates are individually statistically significant for South Korea and Taiwan, but not for Hong Kong and Singapore. We believe this may have to do with the relatively low level of investment in Research and Development (R&D) in Hong Kong and Singapore.

Table 7.1: Estimated Parameters for the Final Specification

Parameter		Estimate	t-statistic
A_K		0.344	1.455
A_L		0.455	1.460
B_{KK}		-0.061**	-1.972
B_{LL}		-0.041	-0.541
B_{KL}		0.069*	1.810
c_{iK1}	France	0.073***	3.108
	Germany	0.057***	3.183
	Japan	0.066***	2.725
	United Kingdom	0.040***	2.993
	United States	0.048***	2.794
	Hong Kong	0.053	1.275
	South Korea	0.023	1.014
	Singapore	0.063	1.604
	Taiwan	0.027	1.269
	Indonesia	0.009	0.380
	Malaysia	0.028	1.114
	The Philippines	0.008	0.641
	Thailand	0.035	1.413
c_{iK2}	Hong Kong	0.012	0.145
	South Korea	0.089**	2.043
	Singapore	0.071	1.006
	Taiwan	0.103***	3.143
λ		0.728***	3.587
Adjusted R-squared		0.700	
D.W.		1.675	
No. of Observations		588	

Notes: Augmentation rates for the oil break slowdown are estimated for the G5 economies for the period of 1974–1985 but are not reported here.
*indicates significance at the 10% level, ** at the 5% level, and *** at the 1% level.

8. The Variability of the Degree of Returns to Scale and the Rate of Technical Progress across Economies

(1) Estimated degrees of local returns to scale

For each economy and each year in the sample, the degree of local returns to scale can be calculated by using the values of the estimated parameters in Table 7.1. We take into account the fact that the human capital in our analysis is measured as the total years of education of the working age population. This implies that human capital is the product of the average schooling years and the number of persons in the working-age population. It is assumed that the labour force is a good proxy for the working-age population. Thus, an increase in the labour input will influence the output through two separate channels: the direct increase in labour (L), and the indirect increase in human capital (H). Assuming that the employment rate (ratio of employment to labour force) is relatively stable, an increase in employment will raise both the labour and also the human capital inputs at the same time. This consideration is reflected in the degree of local returns to scale formula. Given that the degree of local returns to scale (LRTS) is measured by the sum of output elasticities with respect to each of the inputs, it takes the following form.

(8.1) $LRTS = \frac{\partial lnY}{\partial lnK} + \frac{\partial lnY}{\partial lnL} + (\frac{\partial lnY}{\partial lnH} + \frac{\partial lnY}{\partial lnH}\frac{\partial lnH}{\partial lnL}) = \frac{\partial lnY}{\partial lnK} + \frac{\partial lnY}{\partial lnL} + \frac{\partial lnY}{\partial lnH} + \frac{\partial lnY}{\partial lnH},$

since $\frac{\partial lnH}{\partial lnL} = 1$.

(8.2) $\frac{\partial lnY}{\partial lnK} = A_K\lambda + B_{KK}\lambda^2 lnK + B_{KL}\lambda lnL + B_{KK}\lambda(1-\lambda)lnH + B_{KK}\lambda^2\ln(1+c_{iK})t;$

(8.3) $\frac{\partial lnY}{\partial lnL} = A_L + B_{LL}lnL + B_{KL}\lambda lnK + B_{KL}(1-\lambda)lnH + B_{KL}\lambda\ln(1+c_{iK})t;$ and

(8.4) $\frac{\partial lnY}{\partial lnH} = A_K(1-\lambda) + (1-\lambda)^2 B_{KK}lnH + B_{KK}\lambda(1-\lambda)lnK + B_{KL}(1-\lambda)lnL + B_{KK}\lambda(1-\lambda)\ln(1+c_{iK})t.$

Thus, (8.5)

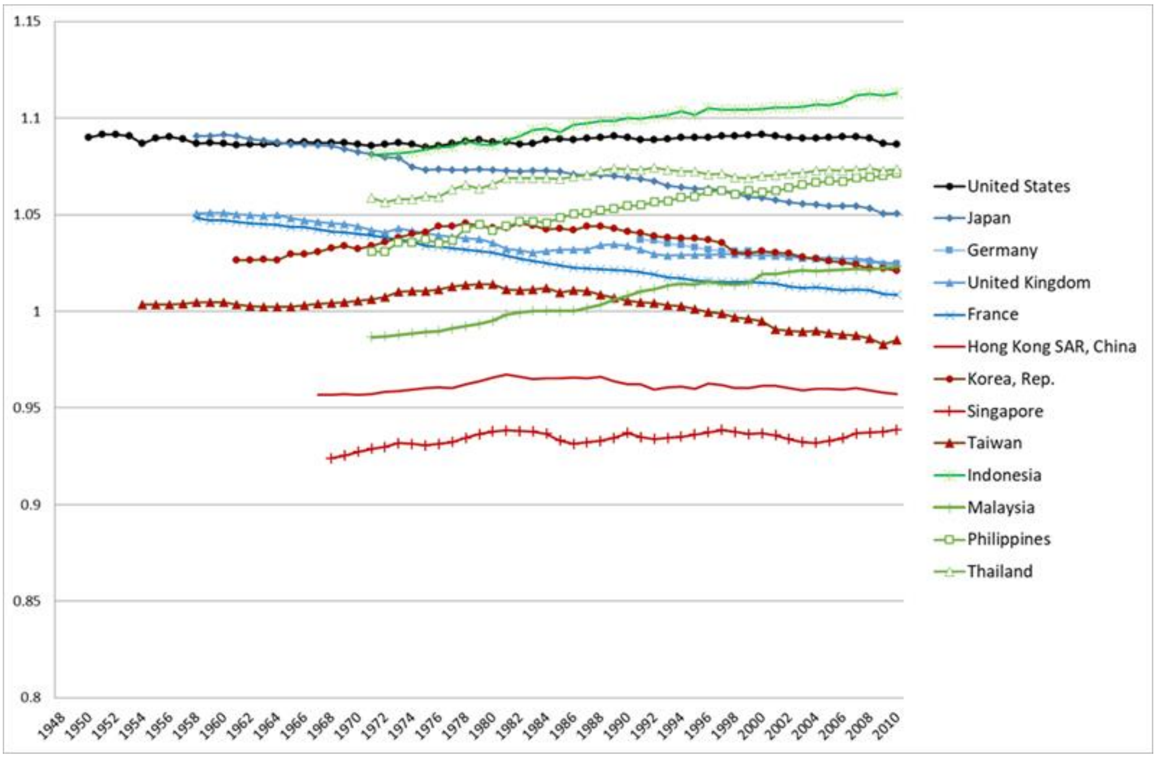
$$\begin{aligned} LRTS = \; & A_K\lambda + B_{KK}\lambda^2 lnK + B_{KL}\lambda lnL + B_{KK}\lambda(1-\lambda)lnH + B_{KK}\lambda^2\ln(1+c_{iK})t \\ & + A_L + B_{LL}lnL + B_{KL}\lambda lnK + B_{KL}(1-\lambda)lnH + B_{KL}\lambda\ln(1+c_{iK})t \\ & + 2\{A_K(1-\lambda) + (1-\lambda)^2 B_{KK}lnH + B_{KK}\lambda(1-\lambda)lnK + B_{KL}(1-\lambda)lnL \\ & \quad + B_{KK}\lambda(1-\lambda)\ln(1+c_{iK})t\}. \end{aligned}$$

We note that for all economies, the formula for LRTS is the same except for the effect of the t variable (time) which varies across economies. In the case of South Korea, the LRTS takes the form: (8.6)

$$\text{LRTS} = 0.8926 - 0.0063lnK - 0.0023lnH + 0.0468lnL - 0.0001 * t.$$

We estimate the degree of local returns to scale for each country using the estimated parameters of the meta-production function in Table 7.1. The estimated LRTS's are presented in Figure 8-1. It is notable that the returns to scale for the G-5 economies are slightly above one and they all have a moderate downward trend. As for the four EANIEs, the returns to scale are very different and have different trends. South Korea's returns to scale are slightly above one with an initially rising and then falling trend after the 1980s. As for Taiwan, its returns to scale began around one and increased slightly up to 1980s and then turned to a declining trend afterwards, falling to slightly below one. As for Hong Kong and Singapore, their degrees of returns to scales are below one and do not have any trend. This may have been due to the fact that neither economy has had much manufacturing industry, especially capital-intensive heavy manufacturing industry. As for the four ASEAN developing economies, their degrees of returns to scale are above one and have a rising trend, which is reminiscent of the initial industrialisation phases of South Korea and Taiwan.

Figure 8-1: Estimated Degrees of Local Returns to Scale: G-5 and 8 East Asian Economies



Note: Authors' calculations based on the parameter estimates from Table 7.1.

(2) Biases in local returns to scale

From equation (8.6), we can see that the local returns to scale are neither constant nor neutral. The returns decrease with higher levels of tangible capital and human capital, and increase with higher levels of labour, other things being equal. If returns to scale were neutral, then a proportional increase in all inputs should not cause any change in the degree of local returns to scale. An increase of 1 percent in all the inputs in say the South Korean economy will cause an increase in the local returns to scale of 0.0004, whereas a 1 percent increase in the labour input alone will cause an increase in the local returns to scale of 0.0005.

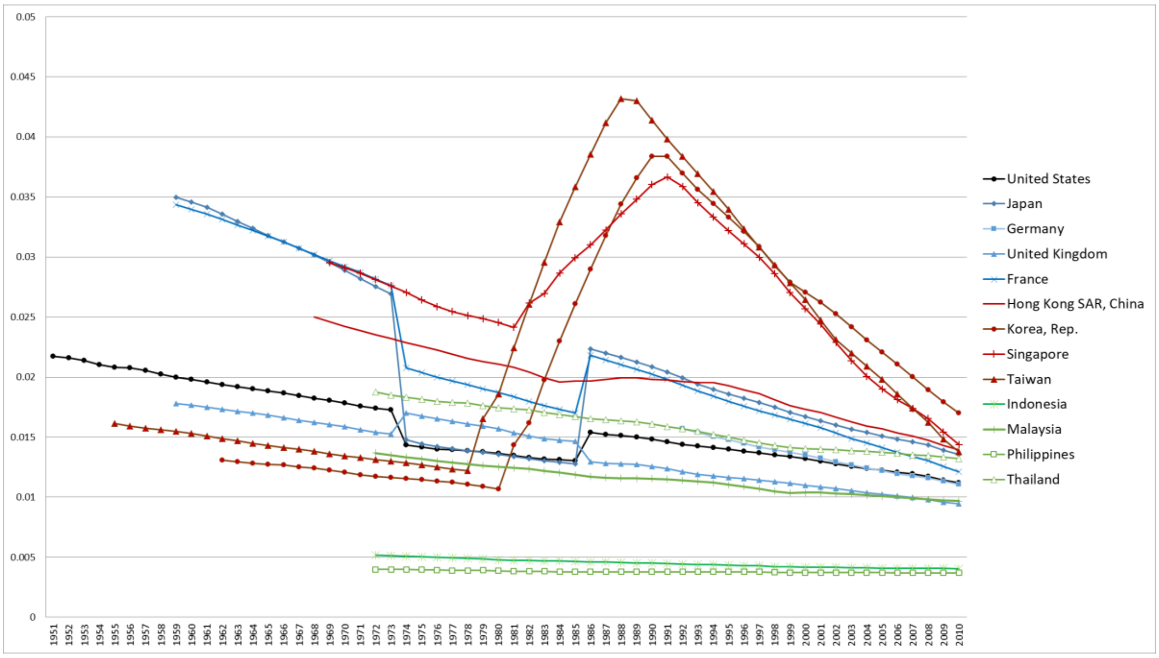
(3) Estimated rates of technical progress

Rates of technical progress for each economy can be calculated using the estimated parameters of the production function in Table 7.1. The formula is given in the following equation:

(8.7) $$\frac{\partial lnY}{\partial t} = A_K\lambda\ln(1+c_{iK}) + B_{KK}\ln(1+c_{iK})^2 t + B_{KK}\lambda\ln(1+c_{iK})lnK + B_{LK}\ln(1+c_{iK})lnL + B_{KK}(1-\lambda)\ln(1+c_{iK})lnH.$$

As we have seen in the regression results positive jumps in the augmentation rates have been identified for the four EANIEs in the 1980s. The jumps in the rates of technical progress were relatively more dramatic for South Korea, Singapore and Taiwan, whereas it was relatively mild for Hong Kong.[19] The rates of technical progress for the former three economies have even risen above those of the G-5. (See Figure 8-2 below.) After reaching the peak in the late 1980s, the rates of technical progress for all of these economies have steadily declined throughout the 2000s. As for the four ASEAN developing economies, the estimated rates of technical progress are relatively lower than those of the four EANIEs. It is interesting to note that amongst these economies, the rates of technical progress for Malaysia and Thailand are higher than those for Indonesia and Philippines, probably reflecting the relative progress in the growth of manufacturing industries.

Figure 8-2: Estimated Rates of Technical Progress: G-5 and 8 East Asian Economies



Note: Authors' calculation based on the parameter estimates from Table 7.1.

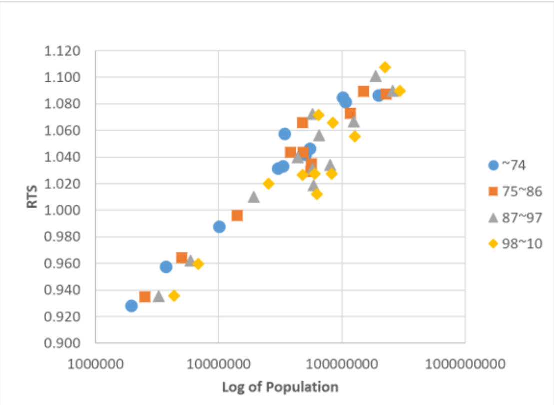
[19] The rise in the rate of technical progress is smooth because we have assumed that the transition in the augmentation rates takes ten years as discussed earlier. This assumption is reflected in the final specification.

(4) Determinants of the degrees of returns to scale

Within our framework, we have been able to identify and estimate the degree of returns to scale for each economy separately from its rate of technical progress for each sub-period of our analysis. The estimated degrees of returns to scale vary significantly across economies. We conjecture that the degree of returns to scale in each economy may be correlated with the size of its domestic market. In Panel A of Figure 8-3, we divide our period of analysis into 4 distinct sub-periods and plot the degree of returns to scale against the logarithm of the population for each economy.[20] The values for each economy are calculated as the average values for each sub-period. We observe that the degrees of local returns to scale are highly correlated with the size of population which may reflect the size of the market of the respective economy. In Panel B of Figure 8-3, we plot the local returns to scale against the share of industry value-added in GDP. Although the relationship is not as strong as that between the degree of returns to scale and population, a positive relationship may be discerned. As economies of scale may be related to the use of tangible capital, it is more likely to occur in industry. This also implies that the composition of the industrial sector may also be a significant determining factor of the degree of returns to scale.

Figure 8-3: The Determinants of the Degree of Returns to Scale: Population and Share of Industry Value-Added in GDP

A. Population



B. Share of Industry Value-Added

Note: Authors' calculation based on the parameter estimates from Table 7.1.

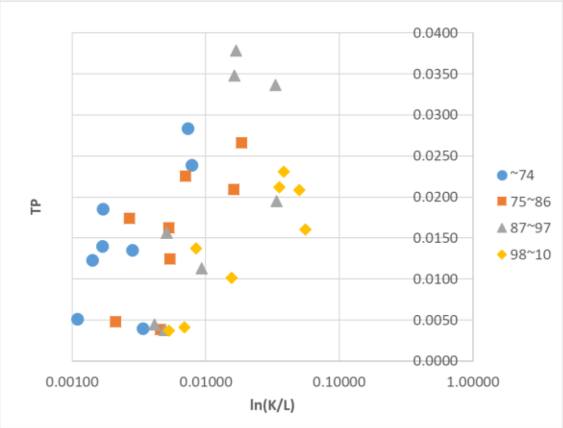
[20] The four distinct sub-periods are chosen to reflect the global shocks: pre~1974, 1974~1986, 1987~1997, and 1998~2010.

(5) Determinants of the rates of technical progress

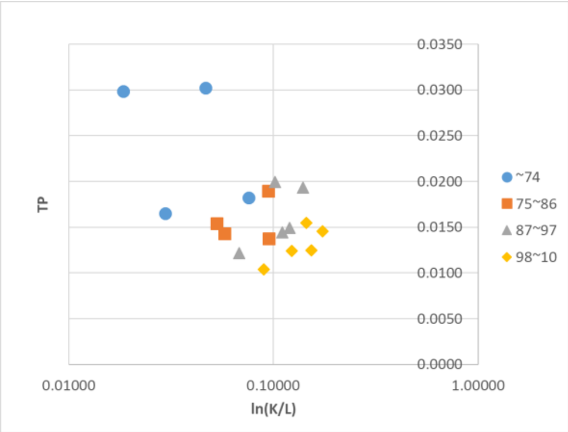
The rates of technical progress of individual East Asian economies are found to depend on their tangible capital intensities whereas those of the G-5 economies do not. (See the Panels A and B in Figure 8.4 below.) We believe this is due to the relative maturation of the developed G-5 economies, in which the tertiary (service) sector, rather than the secondary (manufacturing) sector, has become the most dominant.

Figure 8-4: The Determinants of the Rate of Technical Progress: Tangible Capital Intensities

A. 8 East Asian Economies



B. G-5 Economies



Note: Authors' calculations based on the parameter estimates from Table 7.1.

9. Concluding Remarks

We have shown how economies of scale may be distinguished from technical progress and how both may be simultaneously identified in the empirical analysis of aggregate economic growth by applying the meta-production function model to time series macroeconomic data of a sample of economies. The meta-production function model does not require the assumption of identical aggregate production functions for all economies; they only need to be similar after suitable economy- and commodity-specific time-varying transformations of the quantities of the measured inputs and outputs. Moreover, these latter similarity assumptions can and are explicitly tested. In our empirical implementation, the validity of the meta-production function model cannot be statistically rejected.

The hypothesis of constant returns to scale of the aggregate production function in tangible capital, human capital and labour is decisively rejected for our sample of economies. The individual economy-specific biases of returns to scale and technical progress are also identified. It is found that the degree of returns to scale of an individual economy depends on the size of its domestic market, represented by the size of its population, and the share of industry value-added in its GDP. It is also found that technical progress is simultaneously purely capital-augmenting and purely human-capital-augmenting, resulting in a composite capital that is a Cobb-Douglas aggregate of tangible capital and human capital. In addition, the rates of technical progress of individual East Asian economies are found to depend on their tangible capital intensities.

It is important to distinguish between economies of scale and technical progress, not only because they can confound each other, but also because they have different implications for economic policy. For example, the degree of returns to scale depends on the size of an economy which cannot be easily changed, whereas technical progress (or growth of total factor productivity) depends on cumulative investments in Research and Development (R&D) which can be affected by appropriate government policy.

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