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Dynamic Industry Productivity Measures: The case of thermal electricity generation by South Korean plants 2001-2008 and in Chinese regions 2000-2014*

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Dynamic Industry Productivity Measures: The case of thermal electricity generation by South Korean plants 2001-2008 and in Chinese regions 2000-2014*

by

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Abstract: A framework for applied production theory should focus on the crucial features of the industry to be studied. First of all, to be useful for a dynamic study, a distinction has to be made between the theoretical production possibilities before investment takes place and the actual empirical production possibilities in the short run after investment has taken place. Then there is the distinction between production possibilities at the micro level of a plant or even division within a plant, and the aggregate production possibilities for the industry as a whole. Entry and exit of plants, and embodied technological change at the micro or plant level drive the dynamics. South Korean thermal plants using bituminous coal are studied for the period 2001-2008. The requirement of plant level data has severely restricted the use of the approach. However, the paper shows that such production function concepts can be applied to coal-fired electricity generation aggregated to the Chinese province level and still get valuable structural information for policy analysis. Development in Total Variable Factor Productivity (TVFP) and bias of technical change are estimated and illuminated using figures for isoquant maps, capacity regions in input coefficient space and average- and marginal cost functions both for the plant level in South Korea and for the aggregated province level in China.

Keywords: Thermal electricity generation; Short-run production function; Dynamic structural change; Total Variable Factor Productivity measure; Factor bias

JEL classifications: C43; C61; D24

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1. Introduction

The structure of an industry responds to changes in technology, in costs and in current profitability and future prospects of profitability. In order to understand structural change it is important to base analyses on a relevant modelling of the production technologies of the industries in question. The typical textbook production theory, assuming substitution possibilities both ex ante and ex post, may not be so well suited for understanding structural change within industries characterised by embodied technical change and the significant presence of capital equipment that represents sunk cost. Examples of industries fitting this description are process industries such as chemicals, aluminium, steel, pulp and paper, cement, and thermal electricity generation (see Førsund and Hjalmarsson (1987) for applications).

One early contribution to understanding industrial structural change is Salter (1960). The dynamic structural analysis of Salter (1960) can be founded on an operational production theory for firms. Such a production theory was presented in Johansen (1972).

A framework for applied production theory should focus on the crucial features of the industry to be studied. First, to be useful for a dynamic study, a distinction has to be made between the theoretical production possibilities before investment takes place and the actual empirical production possibilities in the short run after investment has taken place. This is the case of embodied technology of capital equipment. Then there is the distinction between production possibilities at the micro level of a plant or even division within a plant, and the aggregate production possibilities for the industry as a whole. The dynamics of the industry is driven by entry and exits of micro units; plants or capital equipment within plants, and embodied technological change at the micro or plant level. To capture these features of different production possibilities before and after investments, and the aggregation of micro units into an industry (or macro) level, four specific production function concepts are introduced for each of these aspects in Johansen (1972, Chapter 2); the ex ante micro production function, the ex post micro production function, the short-run industry production function and the long-run (steady state) industry production function. This last one will not be used in this study and is based on no further technology change in the long run.

The aggregation to the industry short-run function was a novel approach in the literature based on linear programming (Johansen 1972, Subsection 2.4). An inspiration was Houthakker (1955-56) that introduced a Pareto distribution for the input coefficients of the micro units and derived a Cobb-Douglas short-run industry function. In the literature an industry function is often based on aggregation of micro-level data to the industry level (Diewert and Fox 2008), or scaling up an average production function, thus losing all micro heterogeneity.

Structural change is by nature a bottom-up process, having a plant or even a production department as primary units reflecting concrete technical change. The entry and exit of technologies at this basic micro level will then have impacts at more aggregate levels, like multi-plant firms and industries. The application of the approach at a real micro level has faced the difficulty of getting relevant data, and few examples of use of the approach are found in the literature (Johansen 1972 (oil tankers); Førsund and Hjalmarsson 1983 (cement kilns); Førsund and Jansen 1983 (aluminium plants); Førsund and Hjalmarsson 1988 (pulp plants, blast furnaces)[2]; Førsund et al. 1996 (breweries); Førsund et al. 2011 (thermal electricity plants)). It is a challenge to make use of the structural change approach at an aggregation level with complex links to the underlying changes at the micro level.

However, vintage models have been formulated at the macro level (Johansen, 1959; Solow, 1960). In continuous time, the capacity created during a time interval Δt represents a vintage. But the link to the real-life micro level is then absent. A novel question investigated both theoretically and empirically in the paper is if an aggregated industry at a regional level can serve as a micro unit. The individual plants within a region are aggregated to this regional level, and then this aggregate is the “micro” unit of production.

Two datasets are explored; yearly data on the plant level for South Korean thermal electricity generating plants for the period 2001-2008, and yearly data for aggregated thermal electricity plants to the province level in China for the period 2000-2014.

Concerning a short-run function at the province level, it may be questioned what can be learned at such an aggregate level. Aggregation of all coal-fired electricity plants to the province level constitutes the data at hand. A province is then considered as the production

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[2] The empirical studies extended with further explanation of the modelling approach are also found in Førsund and Hjalmarsson (1987).

unit applying the production function approach of Johansen (1972). It is obvious that the driving forces of the underlying structural change within a province cannot be captured at this aggregated level, but we can find diverging developments comparing provinces caused by the unobserved structural change at the real micro level. We will argue and demonstrate that the micro production function tools of Johansen (1972) applied at the province level can indeed give valuable insights into productivity change, and structural differences between provinces.

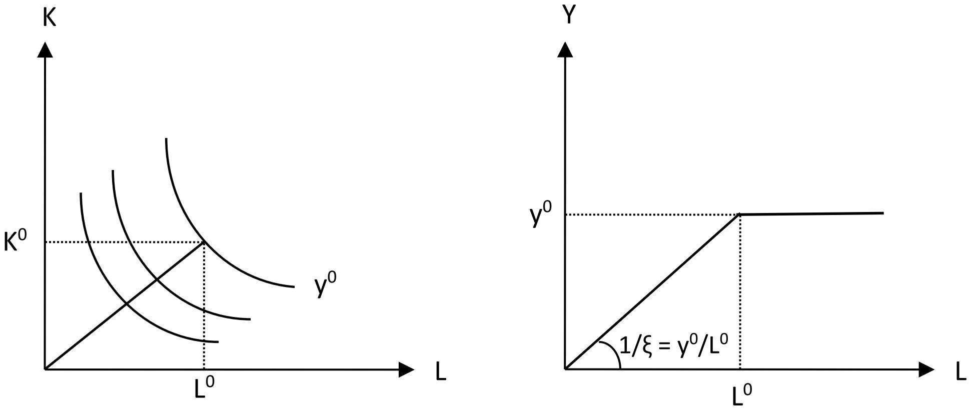
The plan of the paper is as follows. Section 2 reviews the vintage model and the construction of the short-run industry function. Section 3 presents the data for a selected sample of South Korean plants. The empirical results are shown by using illustrations and tables for productivity change and factor bias. Section 4 presents the data for Chinese provinces and the empirical results for productivity growth and factor bias. Section 5 concludes.

2. The methodology

Because the Johansen (1972) approach is not so well known, an exposition of the short-run industry model is given (see also Førsund and Hjalmarsson 1987; Førsund and Vislie 2016). For a number of manufacturing industries there is a crucial difference at the micro level between substitution possibilities *ex ante* (before an investment is made) when capital is to be invested and ex post when capital is committed. A stylised assumption is that substitution between all factors of production including capital is possible *ex ante*, as in a standard neoclassical production function, while the input coefficients of variable factors of production are frozen to given values after the investment is made. Capital with its embodied technology characteristics is sunk and has no independent role except as defining the output capacity of the unit. Figure 1 shows the design of the *ex ante* and *ex post* micro production functions; ξ is the input coefficient, y output, K is capital and L is labour.

The short-run *ex post* production function for a unit j with fixed variable input coefficients can in general be expressed by a limitational (or Leontief) production function:

$$y_j(t,v) = \min\left[\frac{x_{1j}(t,v)}{\xi_{1j}(v)},\ldots,\frac{x_{nj}(t,v)}{\xi_{nj}(v)},\bar{y}_j(v)\right],\ t \geq v\,,\ j = 1,\ldots,N \tag{1}$$



a) Ex ante

b) Ex post

Figure 1. *The ex ante and the ex post micro production functions*
Source: Førsund and Vislie (2016)

Here $\bar{y}_j(\nu)$ is the production capacity of unit *j* corresponding to the *ex ante* choice of mix of capital and variable factors (as in Panel a) in Fig. 1). The input of type *i* for unit *j* is x_{ij}, the input coefficient of factor *i* for unit *j* is ξ_{ij}, and y_j is the production of unit *j*. It is assumed that the input coefficients are independent of rate of capacity utilisation, and identical to the values observed new at time *v*, i.e. it is assumed that the input coefficients stay fixed over time. Due to the nature of the data to be used time is treated as discrete.

Assuming single output production the efficient requirement of factors for the given production y_j^0 is

$$y_j^0(t,\nu)\xi_{ij}(\nu) = x_{ij}^0(t,\nu)\ ,\ i = 1,...,n,\ \ t \geq \nu, y_j^0(t,\nu) \leq \bar{y}_j(\nu) \qquad (2)$$

The definition of an input coefficient follows as illustrated in Fig. 1, Panel b). It is assumed that the input coefficients are independent of rate of capacity utilisation, and identical to the values observed new at time *v*.

Simplifying by dropping the index *v* for the vintage and *t* for current time for convenience we can set up the following optimisation problem for optimal utilisation of the individual units in the short run for a given period:

$$\text{Max } Y = \sum_{j=1}^{N} y_j$$
subject to
$$\sum_{j=1}^{N} \xi_{ij} y_j \le \bar{X}_i \,, i = 1,\dots,n \qquad (3a)$$
$$y_j \le \bar{y}_j \,, j = 1,\dots,N$$

Y is the aggregated output over the units and $\bar{X}_i$ the given total level of input i. The constraints follows from the short-run micro functions (2). The Lagrangian for the problem is

$$L = \sum_{j=1}^{N} y_j - \sum_{i=1}^{n} \lambda_i (\sum_{j=1}^{N} \xi_{ij} y_j - \bar{X}_i) - \sum_{j=1}^{N} \gamma_j (y_j - \bar{y}_j) \qquad (4)$$

The necessary first-order conditions are

$$\frac{\partial L}{\partial y_j} = 1 - \sum_{i=1}^{n} \lambda_i \xi_{ij} - \gamma_j \le 0 \, (= 0 \text{ for } y_j > 0)$$
$$\lambda_i \ge 0 \, (= 0 \text{ for } \sum_{j=1}^{N} \xi_{ij} y_j < \bar{X}_i) \qquad (5)$$
$$\gamma_j \ge 0 \, (= 0 \text{ for } y_j < \bar{y}_j)$$

Notice that the shadow price λ_i for input of type i measures the change in the objective function by a unit increase in the total input restriction, i.e., it has the interpretation of the marginal productivity of an input. In optimum the marginal productivity for a type of input must be the same for all units employing the same type of input (as if all units face the same input prices). Thus, the short-run industry function is a *normative* function showing the maximal industry output, and not a *positive* description of an observed state. An optimal solution implies that a micro unit may be in one of three states: fully utilised, partly utilised, or not used at all:

a) Fully utilised units: $1 - \sum_{i=1}^{n} \lambda_i \xi_{ij} = \gamma_j \ge 0$

b) Partly utilised units: $1 - \sum_{i=1}^{n} \lambda_i \xi_{ij} = 0$ (6)

c) Units not in use: $1 - \sum_{i=1}^{n} \lambda_i \xi_{ij} \le 0$

The common expression on the left-hand sides in (6) can be given an economic interpretation. The measurement unit of the shadow price is output per unit of input i, and the input coefficient is measured as input of type *i* per unit of output of micro unit *j*. The whole expression can be interpreted as the unit quasi-rent deflated with a common output price for the case of all marginal productivities of the micro units being the same. The measurement unit for a factor price deflated by the output price is just output per unit of input, i.e. the same unit as for productivity. In the case of a fully utilised unit, the quasi-rent will typically be positive, a partly utilised unit will have zero quasi-rent, and an inactive unit will typically face a negative quasi-rent if production is undertaken. Assuming we have a unique optimal solution, the endogenous variables can in general be written as functions of the exogenous variables:

$$\begin{aligned} y_j &= F_j(\bar{X}_1,...,\bar{X}_n,\bar{y}_1,..,\bar{y}_N,\xi_{11},...,\xi_{n1},...,\xi_{1N},...,\xi_{nN})\,(j=1,...,N) \Rightarrow \\ Y &= F^*(\bar{X}_1,...,\bar{X}_n,\bar{y}_1,..,\bar{y}_N,\xi_{11},...,\xi_{n1},...,\xi_{1N},...,\xi_{nN}) = F(X_1,...,X_n) \end{aligned} \qquad (7)$$

In the last equation in (7), we have aggregated the outputs of the micro unit and suppressed capacities and fixed input coefficients as arguments, as well as considering a parametric variation in the given total inputs. The relation *F*(.) is the short-run industry production function. Notice that capital has no role as an argument in the function. The output capacities of the micro units are arguments in the function, but these capacities are fixed in the short run, and therefore for notational convenience included in the functional form as is the case for the input coefficients. The function can in principle be described by the fundamental production function concepts like marginal productivities and scale elasticities (Førsund and Hjalmarsson 1983; Førsund and Jansen 1983).

The short-run industry function (7) does not have an analytical form, i.e., it is a non-parametric representation of the production possibilities that may be portrayed numerically in tables over inputs and output, marginal productivities and scale elasticities. One way of visualising the production function is to construct an isoquant map within the region of substitution. The use of isoquants is the key to derive measures of structural change, such as productivity change and input biases. Although there are no substitution possibilities in the micro short-run function (1) or (2), differences between fixed input coefficients give substitution possibilities in the aggregate industry short-run function.

The short-run industry function is here not estimated in the traditional econometric sense using data *Y* and $\bar{X}_i$ (*i*=1,…,*n*) on industry level. In order to solve problem (3a) data for capacities $\bar{y}_j(j=1,...,N)$ must be available. The input coefficients ξ_{ij} appearing in problem (3a) are usually not available and have to be estimated from data on production and input use. The simplest way to do this is to use the observations for a time period *t* and calculate

$$\xi_{ij}(t) = x_{ij}(t) / y_j(t) \;\; (i = 1,...,n,\; j = 1,...,N),\; y_j(t) \leq \bar{y}_j \,. \tag{8a}$$

The assumption is then that the input coefficient is independent of capacity utilisation as stated above, and that inputs are applied efficiently, i.e., at minimum values for producing y_j. A calculation of input coefficients assumed to be fixed for period *t* can be done without knowing when the unit was constructed, as assumed in (1). The vintage will then be defined as if being from period *t*. Using (8a) for calculation will accommodate the case that the micro unit may consist of several pieces of equipment and that the unit may be modernised by substituting some of the pieces with more productive equipment reducing the input coefficient for the unit. For units that existed for earlier periods updating the input coefficients for each period also opens up for disembodied technical. This depends on the aggregation level of the unit, i.e. a single piece of equipment up to the plant level. It is, of course, somewhat arbitrary to define the key technology characteristics based on the period concept behind the data at hand, e.g., a year. Entry and exit may take place at any time within a period, as well as new technology being available or disembodied technical change occurring.

The use of the short-run industry function to reveal structural change

In order to visualise our concepts a case of two variable inputs will be adapted. This may not be as restrictive as may be feared. The three groups of variable inputs are materials, energy and labour, but materials may often be applied in fixed proportions to output and can therefore be left out of the analysis focusing on the consequences of substitution between inputs. In the case of e.g. smelting of aluminium there is a fixed relationship, given by chemical laws, between the amount of aluminium oxide and aluminium produced by the electrolytic process. Technical change can reduce the amount of electricity and labour per unit of aluminium, but not the amount of aluminium oxide per unit of aluminium.

In the case of more than two inputs, being necessary to model two-dimensional illustrations, it may still be possible by cutting a multidimensional production function with a two-dimensional plane. The problem (3a) is a linear programming problem that we assume yields the unique solution (7) for the short-run function. However, we get numerical solutions. An isoquant is a relation between the inputs for a given level of output, i.e. the relation Y^0

$= F(X_1, X_2)$ implicitly defines an isoquant for output level Y^0. Although the micro units have fixed input coefficients ex post, differences in coefficients give substitution possibilities at the industry level.[3]

In order to establish productivity- and bias measures it is convenient to move from the general relationship $Y^0 = F(X_1, \dots, X_n)$ to a cost-function representation. Assuming input prices $q_1, \dots, q_n$ we have the following industry cost minimisation problem

$$\text{Min } C = \sum_{i=1}^{n} q_i X_i$$

subject to

$$\sum_{j=1}^{N} \xi_{ij} y_j \le X_i, i = 1, \dots, n \qquad (9)$$

$$y_j \le \bar{y}_j, j = 1, \dots, N$$

$$\sum_{j=1}^{N} y_j \ge Y^0$$

The choice of industry output level is restricted by $Y^0 \le \sum_{j=1}^{N} \bar{y}_j$. The Lagrangian function is (writing the minimisation problem (9) as a maximisation problem for convenience, changing the sign of the input expenditure)

$$L = -\sum_{i=1}^{n} q_i X_i - \sum_{i=1}^{n} \alpha_i \left(\sum_{j=1}^{N} \xi_{ij} y_j - X_i\right) - \sum_{j=1}^{N} \beta_j (y_j - \bar{y}_j) - \mu\left(-\sum_{j=1}^{N} y_j + Y^0\right) \qquad (10)$$

The necessary first-order conditions are

$$\begin{aligned}
&\frac{\partial L}{\partial X_i} = -q_i + \alpha_i \le 0 \, (= 0 \text{ for } X_i > 0) \\
&\frac{\partial L}{\partial y_j} = -\sum_{i=1}^{n} \alpha_i \xi_{ij} - \beta_j + \mu \le 0 \, (= 0 \text{ for } y_j > 0) \\
&\alpha_i \ge 0 \, (= 0 \text{ for } \sum_{j=1}^{N} \xi_{ij} y_j < X_i) \qquad (11) \\
&\beta_j \ge 0 \, (= 0 \text{ for } y_j < \bar{y}_j) \\
&\mu \ge 0 \, (= 0 \text{ for } \sum_{j=1}^{N} y_j > Y^0)
\end{aligned}$$

The shadow price α_i on the input constraint for the industry has the interpretation of the increase in industry cost of increasing input i marginally. The first condition in (11) tells

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[3] It is shown in Førsund and Hjalmarsson (1987) in detail that the isoquant may be constructed geometrically.

us that the shadow price on the input will be set equal to the exogenous input price. From the second condition in (11) we see that in case of positive output - but less than the capacity - of unit *j* implying positive input i, a unit j will be partially utilised if its unit cost is equal to the shadow price μ on the constraint for total output, $\sum_{i=1}^{n} q_i \xi_{ij} = \mu \, (j = 1, ..., N)$ (assuming that the shadow price β_j on unit *j*'s capacity constraint is zero). This shadow price is equal to the cost of increasing output marginally, i.e., the short-run industry marginal cost. A unit that is fully utilised to its capacity will have a unit cost lower than the industry marginal cost in the typical case of a positive shadow price on its capacity. A unit that has a greater unit cost than the industry marginal cost will not be utilised.

The algorithm for construction isoquants starts with establishing the substitution region. We will only model the production possibilities for non-negative marginal productivities.[4] The first units to be utilised must be the cheapest units to operate given the input prices. If we assume that one input price is zero, then the first unit to be utilised in the direction of the axis of the input with the zero price will be the unit with the lowest input coefficient for the input in question. Units ranked by increasing value of the input coefficient form the full border of the substitution region toward the axis of the input with zero shadow price, i.e. units are entered in the order of decreasing partial efficiency. Given the value of the industry output, we therefore know where to start an isoquant on the border of the substitution region in any of the input dimensions.

In the case of two inputs the isoquant will be piecewise linear, and may be constructed by using the convexity condition on isoquants. If we start from the upper border (arbitrary choice) of the substitution region in a two input space, then the first segment of the isoquant in the interior must be a combination of the starting unit and the unit forming the steepest angle of the segment (in case of starting from the lower border it will be the flattest segment). Moving along the isoquant the capacity of the border unit will be utilised less and less, and the capacity of the second unit on the isoquant will be more and more utilised. We come to a kink in the linear segment when the capacity utilisation of the starting unit becomes zero or the capacity of the second unit is exhausted. The next unit to be activated is found by selecting the unit that forms the steepest angel with the unit partially utilised

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[4] Hildenbrand (1981) extends the isoquants to the uneconomic region, in contrast to the approach favoured by Farrell (1957), arguing that this region is not of interest to businessmen.

at the firs corner point. The procedure continues in the same way until the lower border is reached (for a detailed explanation see Førsund and Hjalmarsson 1983; 1987).

Using aggregated micro units

Concerning data the situation may be that it is not possible to get plant level data, but only data for a more aggregate level. An example may be that only data on a regional level are available for a specific type of production. The data come in the form

$$y_r = \sum_{j=1}^{Nr} y_{jr},\ \bar{y}_r = \sum_{j=1}^{Nr} \bar{y}_{jr},\ x_{ir} = \sum_{j=1}^{Nr} x_{ijr},\ \ r = 1,\dots,R,\ i = 1,\dots,n\,.$$

There are N_r units within each aggregated unit *r* and these units sum up to the total number micro units, $\sum_r N_r = N$. The aggregated data replace the micro level data in all equations (1) - (7) above. The input coefficient for an aggregated unit *r* will be constructed as:

$$\xi_{ir}(\nu) = \frac{x_{ir}(t,\nu)}{y_r(\nu)} = \frac{\sum_{j=1}^{N} x_{ijr}(t,\nu)}{\sum_{j=1}^{N} y_{jr}(\nu)},\ i = 1,\dots,n,\ r = 1,\dots,R,\ t \geq \nu \tag{8b}$$

We see from the last expression that the input coefficients for an aggregated unit are the input coefficient for constructed average micro units. Thus, the input coefficients for the aggregated units will lie between the coefficients for the most efficient micro units and the most inefficient ones and thus reduce heterogeneity. Over time, the change in the aggregate input coefficients will reflect the underlying changes of all micro units.

The optimisation problem for defining the macro production function for aggregated units reads

$$\begin{aligned}
&\text{Max } Y = \sum_{r=1}^{R} y_r \\
&\text{subject to} \\
&\sum_{r=1}^{R} \xi_{ir} y_r \leq \bar{X}_i\,, i = 1,\dots,n \\
&y_r \leq \bar{y}_r\,,\ r = 1,\dots,R
\end{aligned} \tag{3b}$$

The solution to the problem will be identical to equations (5) - (6) above replacing micro unit index *j* with the aggregated unit index *r*.

Total variable factor productivity (TVFP)

In an industry comprising heterogeneous micro units the calculation of productivity change must reflect the heterogeneity; a single figure that is often presented is not so informative. We follow the approach of Salter (1960) and focus on the cost changes for specific isoquants with the same output over time. Choosing representative isoquants will reflect the heterogeneity of the data.

In order to calculate the productivity change we will follow an expansion path within the substitution region based on using the observed input prices of coal and labour in the last years of the two datasets we will use. The productivity index will then be of a Paasche type with prices locked to the end period.[5] The index of *Total Variable Factor Productivity* (TVFP) is calculated in the standard way as the ratio of weighted outputs over weighted inputs using prices as weights:

$$TVFP = \frac{pY^0}{q_1 x_1 + ... + q_n x_n} \tag{12}$$

Here q_i $(i = 1,\ldots, n)$ are the input prices, while p is the price for output and Y^0 is the given isoquant value. The productivity level is calculated for a given period. The TVFP change between period t_1 and t_2 is then calculated as[6]

$$\Delta TVFP(t_1, t_2) = \frac{q_1 x_1(t_1) + ... + q_2 x_n(t_1)}{q_1 x_1(t_2) + ... + q_2 x_n(t_2)},\ t_1 < t_2, Y = Y^0 \tag{13}$$

The common output term cancels out. A number greater (smaller) than one means that productivity has increased (decreased) over time, i.e. cost has decreased (increased).

It is standard in productivity studies to include capital as a factor in measures of total factor productivity (TFP). Capital is then measured in a technical unit, i.e. capital is regarded as a volume variable. There are many difficulties involved coming up with a technical measure. Usually the cost of capital in fixed prices is used as a measure. However, with embodied technology implying sunk cost, the capacity is the technical variable. It does not make much sense to measure the productivity of capacity as a factor together with standard inputs. Instead, we are entering the discussion of measures of technical change. One may distinguish

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[5] Using the base period prices the productivity index will be of the Laspeyres type.

[6] Salter (1960) called this measure a measure of technical advance and illustrated it in the input coefficient space underlining technical change as the driver. Salter used labour and capital as inputs, and studied "best practice productivity movements" (Chapter III) using ex ante functions in our terminology.

between a measure of productivity of variable resources utilising capacity, and a measure of the return to the financial capital of investing in fixed capacity.

We are studying a short-run industry function and then capital in the form of capacity is a fixed factor. Variable inputs like labour and energy have alternative uses in the economy, they can be reallocated, while capital in the form of capacity is by definition sunk. Whether investment is worthwhile or not is better measured by the expected or realised rate of return.

Bias measures

Technical change of an ex ante function takes place when less inputs are needed producing the same output, or more output is produced using the same capital equipment (the Horndal effect). Investing in capacity embodying new technology and retiring old capacity constitute the drivers of productivity at the industry level. Technical change is seldom neutral, but shows bias in the relative use of inputs. Salter (1960) introduced a measure of the bias of technical change in the case of two inputs as the change in input ratios over time:

$$B(x_1, x_2, t_1, t_2) = (\frac{x_1}{x_2})t_2 / (\frac{x_1}{x_2})t_1,\ t_2 > t_1, Y = Y^0,\ q_1, q_2 \text{ given}, x_1, x_2 \text{ on the expansion path} \quad (14)$$

The inputs are found at the cost minimising corner point on the expansion path using factor prices q_1 and q_2 for isoquant Y^0. If $B > 1$ the we have a biased change of input x_1 over time because it increases more relative to x_2 (i.e., x_1 using or x_2 saving), and biased change for input x_2 if $B < 1$ (i.e., x_2 using or x_1 saving).[7]

The terms capital widening and capital deepening are used in connection with factor bias as defined above when capital is assumed to be a variable input. Capital deepening is defined as increasing capital per unit of labour over time, and capital widening is defined as a proportional development of labour and capital when both are increasing over time. If we have a reasonable good measure of capital volume, we can also apply such measures to the aggregated level, i.e. the total use of inputs including capital at the aggregated level. However, such a measure does not give us any insight to the dynamic process of technical change at the micro level under our assumptions of the vintage model.

3. South Korean thermal electricity plants

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[7] These results can also be expresses by input coefficients because the isoquant values are the same.

Data

An extensive set of physical and economic plant data for a sample of electricity-producing plants using various types of primary energy - nuclear (36% in 2008), hydro (1.3% in 2008), oil (3% in 2016), gas (25% in 2016), coal (total thermal 63% in 2008) - for the period 2001 – 2008 had previously been collected by Professor Almas Heshmati and associates at Sogang University, Seoul. In order to have homogenous thermal technologies only the six plants using bituminous coal were included in the sample.[8] Thus, natural gas and oil (3% in 2016) are not included. The six coal-fired plants represent a small sample of total generation based on coal.

The variables used constructing the short-run function are the output total generation of electricity during a year, input of bituminous coal in Kcal and labour in number of employees. In addition the generation capacity is used assessing the change over time relative to production. Electricity is consumed in continuous time, and demand varies according to day/night, working days and holidays, and seasons over the year. Some plants are only activated when there is a peak load, and others produce continuously near capacity (except for planned maintenance and unplanned stoppage). The last plants are called base load plants. The average utilisation rate has been 11.4 % with a rather small standard deviation of 2.8 percentage points. This indicates that all plants have been used as peak-load plants. Instead of trying to figure out individual utilisation rates of installed power capacity we have found it better to use the observed output each year as capacity. This implies that we are not considering a reallocation of inputs in order to increase production (as in e.g. Førsund and Jansen (1983) studying aluminium plants), but will concentrate on measuring productivity change and factor bias. The data are set out in Table 1. One unit has the max values for output

Table 1. *Data on output and inputs for Korean thermal plants*

Year	Output, TWh				Bituminous coal, Kcalx10^6				Labour, no. of employees			
	Mean	St.dev.	Min	Max	Mean	St.dev.	Min	Max	Mean	St.dev.	Min	Max
2001	3.83	3.31	0.04	9.62	7.53	5.76	0.11	16.86	302	158	156	588
2002	4.45	3.96	0.10	10.79	8.56	6.80	0.24	18.59	339	244	156	819
2003	4.38	3.99	0.06	10.95	8.42	6.81	0.15	18.72	345	241	173	819
2004	4.94	4.26	0.10	11.58	9.57	7.46	0.26	20.67	334	234	180	797
2005	4.65	3.74	0.11	10.75	8.97	6.39	0.27	18.98	319	241	81	777
2006	5.34	4.36	0.18	12.18	10.14	7.36	0.43	12.18	330	230	127	773
2007	5.95	4.90	0.06	12.80	11.31	8.40	0.06	12.80	327	240	89	778
2008	5.67	4.48	0.02	11.71	10.82	4.48	0.06	11.71	340	262	87	834

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[8] One unit with unreliable data had to be eliminated.

and inputs, and the smallest input coefficients, for every year. Another unit has the min values for output and input, and the highest input coefficients for every year. The capacity has been growing with an average rate of 11.4 % with a standard deviation of 19.9 percentage points. The smallest plant has a negative growth of 32.5 %, but all the other plants has positive growth.

Substitution region and isoquants

The short-run functions for three of the eight years, 2001, 2004 and 2008, are shown in Fig.2

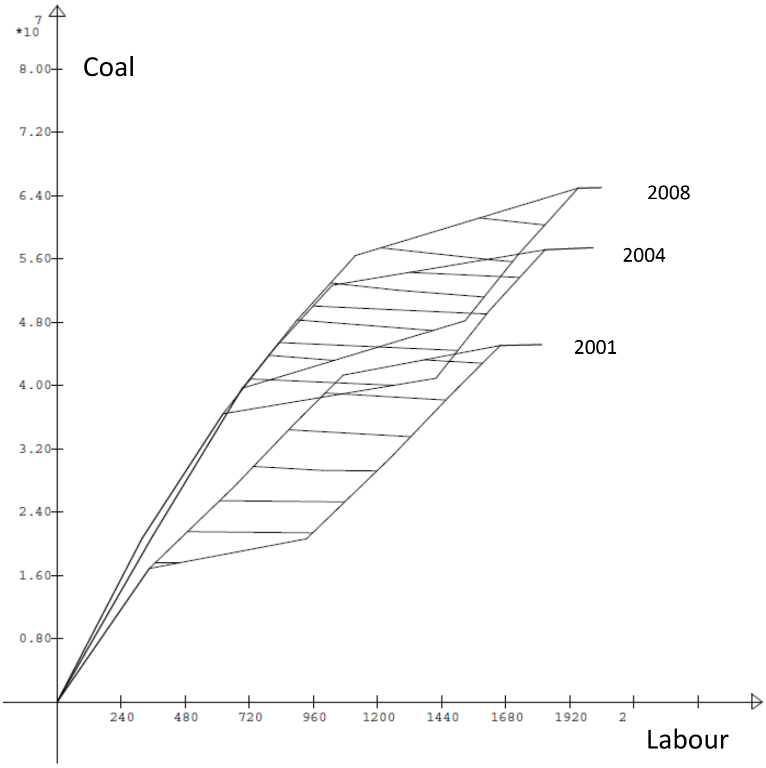

Figure 2. *Substitution regions and isoquants for Korean plants*

in the same diagram to give an impression of the shift in the function. The isoquants are spaced by TWh. All functions start from the origin with straight lines. This is because one best practice (BP) plant (the largest one) has the smallest input coefficients for both inputs in 2001, and two BP plants (largest and second largest) come first and second in 2004 and 2008 for both inputs (see Table 2). There are four isoquants points on the line representing the first part of the short-run production function in 2001. There are seven isoquants portraying substitution possibilities in 2001, four in 2004 and 10 isoquant points, and six (the last isoquant is difficult to see and is almost a point) and 11 isoquant points in 2008. We see from the end points of the substitution regions that there has been an increase

Table 2. *Ranking units' input coefficients for labour (L/Y) and coal (Co/Y)*

2001				2004				2008			
Unit	L/Y*10^{-5}	Unit	Co/Y	Unit	L/Y*10^{-5}	Unit	Co/Y	Unit	L/Y*10^{-5}	Unit	Co/Y
42	3.6	42	1.8	42	2.7	42	1.8	42	3.0	42	1.8
34	6.0	55	1.9	34	3.6	34	1.9	34	3.2	34	1.8
10	6.6	34	2.0	10	5.4	55	1.9	10	5.3	55	1.9
54	6.9	10	2.3	54	6.3	10	2.3	54	6.2	10	2.2
55	30	54	2.3	55	33	54	2.3	55	18	54	2.3
44	380	44	2.7	44	176	44	2.5	44	356	44	2.5

in use of inputs over time; 44 % for coal and 12% for labour, but for 2004 to 2008 only 1.5 % for labour. The last isoquants represent 22, 28 and 34 TWh, respectively, for 2001, 2004 and 2008. The upward shift of the substitution regions show an increase in coal use. The slope of the isoquants is influenced by the measuring units used. The isoquants look fairly straight, and, in fact, of the seven isoquants for 2001 only two isoquants have one interior corner point, while of the four isoquants for 2004 two isoquants have interior corner points, and four of the six isoquants for 2008 have corner points and only two isoquants are straight lines. The end straight lines of the substitution regions consist mainly of the input use of the smallest and most inefficient unit 44 (see Table 2).

Capacity region

Transforming the border of the substitution region and isoquants to the input coefficient space reveals the position of the efficiency frontier of the short-run production function. In Fig. 2 the three years 2001, 2004 and 2008 are put together. The capacity regions have been shrinking and moving towards the coal coefficient axis. In 2001 there is a single starting unit (42) with the smallest input coefficients for both inputs, therefore the spear-like shape, while for 2004 and 2008 the number two unit (34) in both dimensions as to small input coefficients, makes the straight short starting line.

Productivity change

In order to calculate productivity change in the fashion of Salter it is most convenient to calculate the cost curve based on the expansion path for the chosen end period average prices

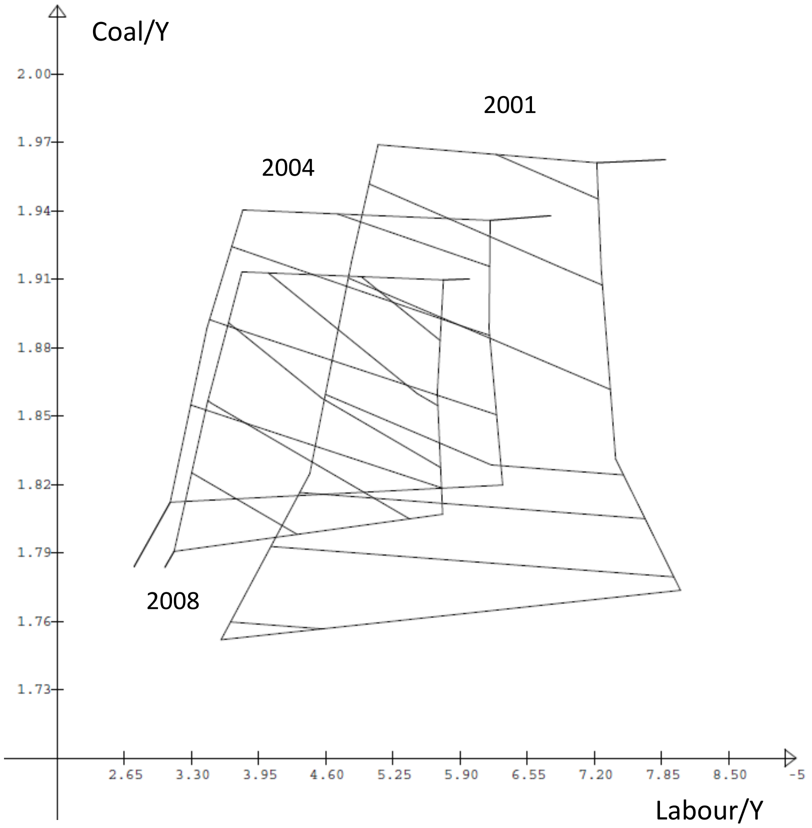

Figure 3. *Capacity regions with isoquants for Korean plants*

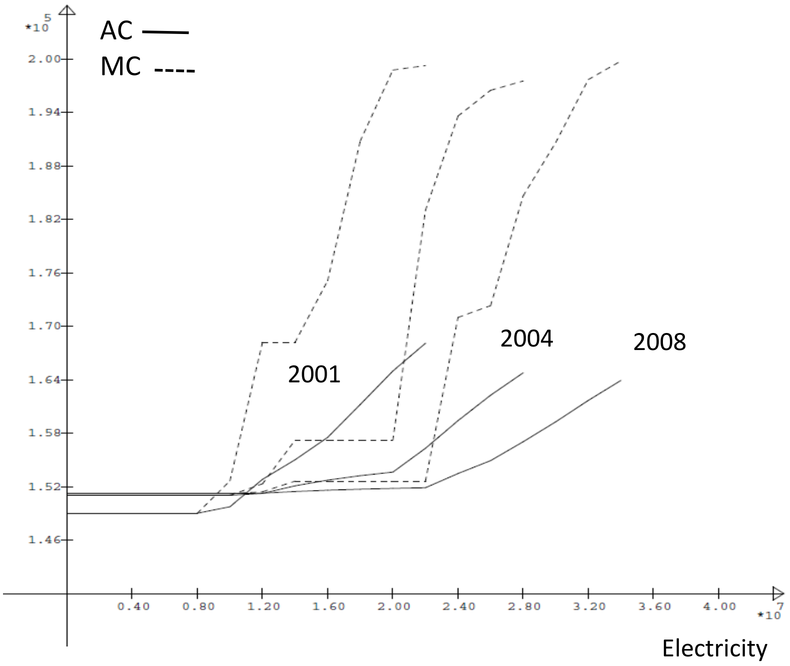

Figure 4. *Average (-) and marginal (--) variable costs 2001, 2004, 2008*
Average input prices 2008

of labour and coal. For the Korean plants the expansion path happens to follow the upper border towards the coal axis in Fig. 2. (For the Chinese province data we will see an interior expansion path.) The minimum cost at each point on the isoquants can then be directly used to calculate the productivity change numbers (13). The cost functions for the three chosen years are set out in Fig. 4. As is evident from the capacity regions in Fig. 3 when we know the location of the expansion path, is that the cost at the BP part of the capacity regions the average cost for constant prices is lowest in the first year 2001. For the years 2004 and 2008 the BP cost (based on units 42 and 34) is about the same, and the average cost curves are flatter than for 2001. Looking at the marginal cost curves we see that in 2001 marginal cost increase when the BP capacity is used up, and the gap is widening substantially. This pattern is about the same for 2004, but for 2008 the marginal cost curve keeps close to the average curve for almost 2/3 of the production. The shape of the top part of the marginal cost curves are quite similar, and they end at about the same level due to the labour coefficients of units 55 and 44 seen in Table 2.

The productivity change results are set out in Table 3. The choice of isoquant levels is

Table 3. *Productivity change for Korean plants*

Years	Output levels in TWh					
	2	8	14	20	22	28
2001-2004	0.99	0.99	0.99	1.07	1.08	
2004-2008	1.00	1.00	1.00	1.01	1.05	1.05
2001-2008	0.99	0.99	1.00	1.09	1.11	

comprising both points on BP lines and WP isoquants for the years 2001 and 2004. However, the WP levels for 2008 do not have a match among levels in 2004 and 2001.

We see from Fig. 3 and Table 2 that it is the low coal coefficient for unit 42 that contributes to the lowest BP average cost in 2001 and results in a negative change in productivity for the three first output levels for 2001 to 2004, and the two first levels for 2001 to 2008. However, for the two highest output levels the productivity change is positive both for 2001 to 2004, and 2001 to 2008, the latter being on a level of 10%.

Factor bias

Appplying the Salter bias measure (14) the results are set out in Table 4. A suitable number of isoquants is chosen covering BP units and WP units for 2001 and 2004, but no WP units for 2008 due to the increase in output over time. The results are somewhat mixed and uneven. For the period 2001-2004 we have labour saving for all output levels, but the numbers differ with the maximum labour saving for the second to the last isoquant. In the period 2004 to 2008 we have labour saving for all isoquant levels except for the 20 TWh isoquant for having coal saving. For the period 2001 to 2008 all the isoquant levels have labour saving with the two last isoquants having the highest savings of around 100 %.

Table 4. *Factor bias for Korean plants*

Years	Output levels in TWh					
	2	8	14	20	22	28
2001-2004	1.37	1.33	1.49	2.24	1.18	
2004-2008	1.11	1.11	0.93	1.02	1.80	1.03
2001-2008	1.20	1.20	1.39	2.19	1.98	

4. Thermal electricity generation at a Chinese province level

Data

The raw data is taken from the China Electricity Yearbook for each of the years 2000 to 2014 and contains data at the province level[9] for coal consumption (measured in **t**ons of **c**oal **e**quivalent, tce) for coal-fired electricity generation, total electricity produced, capacity and total number of employees. Table 5 provides the descriptive statistics of these data in selected years during our study period. The national average of coal consumption and capacity increased with a factor of about 3.34 and 3.85, respectively, while the staff decreased about 24 per cent from 2000 to 2014 in China. Over the same timespan the generated

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[9] Quality has been checked and electricity output has been somewhat adjusted. However, there may be potential problems with labour data whether only labour working at coal-fired plants is recorded or labour employed at other types of plants is also included.

Table 5. *Summary of input and output data in selected years for China's provinces coal-fired electricity generating industry*

Year		**Coal** 10^6tce	**Electricity** TWh	**Power capacity** GWh	**Staff** 10^3 persons
2000	Mean	13.05	36.22	7.92	29.54
	St. Dev.	9.78	29.50	5.89	16.63
	Max	34.94	103.86	23.01	63.32
	Min	0.86	2.61	0.84	4.17
2005	Mean	25.67	66.19	13.05	28.35
	St. Dev.	20.24	52.83	11.13	15.96
	Max	75.09	192.58	42.51	60.78
	Min	1.74	5.56	0.89	4.00
2010	Mean	37.43	110.83	23.55	25.90
	St. Dev.	28.48	85.78	17.41	15.65
	Max	100.63	316.63	60.02	62.16
	Min	3.47	9.72	1.93	3.43
2014	Mean	43.56	140.15	30.51	22.42
	St. Dev.	34.41	107.35	21.47	12.62
	Max	139.99	406.25	77.27	48.07
	Min	4.11	12.99	2.42	3.16

tce: ton of standard coal

electricity increased with a factor of 3.82, slightly less than the production.

Change in generation capacity over time gives interesting information about net investment and possibilities for embodied technical change. The relative strong increase in capacity should have resulted in rapid technical change. The productivity calculations will reveal the pace. At the plant level units may be utilised as peak units activated a limited time when demand peaks, or base load units running all the time at full capacity (except when maintenance is done and unanticipated stoppage occur). Then some capacity less than full may be utilised for a third group of plants. However, at a province level it makes most sense to operate with actual total production as output and not consider the unobserved underlying plant generation capacities and their utilisation.

The 30 Chinese provinces are listed in Table 6.

Table 6. *Provinces of China*

Beijing	Liaoning	Zhejiang	Henan	Hainan	Shaanxi
Tanjin	Jilin	Anhui	Hubei	Chongqing	Gansu
Hubei	Heilongjiang	Fujian	Hunan	Sichuan	Qinghai
Shandong	Shanghai	Jiangxi	Guangdong	Guizhou	Ningxia
Inner Mongolia	Jiangsu	Shanxi	Guangxi	Yunnan	Xinjiang

The average province utilisation rate was 48 % with a small standard deviation of 0.017. As explained in Section 3 we do not consider reallocation of among regions, but focus on measuring productivity change and variable factor bias.

Using provinces as micro units strengthen the logic of using observed output each year as capacity. There is no reallocation of inputs between provinces and no normative merit order in play constructing the short-run industry function. Is to identify efficient provinces The purpose of the analysis is to reveal the structure of differences in efficiency of provinces in production, and to calculate productivity change and factor bias characterising the nature of technical change using the heterogeneity of provinces.

The heterogeneity of the input coefficient structure is shown in Table 7 for the five smallest partial coefficients and the five largest ones for each of the three years. The difference in labour coefficients between BP and WP units is most striking for all years, but we see a reduction over time of both coal and labour coefficients. Shanghai is the only province being among the five BP units in all three periods (two periods with both input coefficients in the BP group), while Hainan is among the BP provinces with the five smallest coal coefficients the three years, Jiangsu and Shanxi with labour coefficients for the three years, and Beijing for two years with

Table 7. *Partial best practice (BP) and worst practice (WP) Chinese provinces*

Panel (a) year 2000

Partial BP provinces				**Partial WP provinces**			
Province	**Coal/Y**	**Province**	**L/Y**	**Province**	**Coal/Y**	**Province**	**L/Y**
Chongqing	2.34	Shanghai	12.48	Jiangxi	4.43	Qinghai	189.89
Shandong	2.37	Jiangsu	36.76	Heilongjiang	4.43	Hunan	224.40
Ningxia	2.85	Shanxi	42.11	Guizhou	4.48	Yunnan	236.22
Shanghai	2.95	Tianjin	42.56	Yunnan	5.08	Sichuan	275.16
Hainan	3.13	Zhejiang	54.20	Sichuan	5.46	Guangxi	289.96

Panel (b) year 2007

Partial BP provinces				**Partial WP provinces**			
Province	**Coal/Y**	**Province**	**L/Y**	**Province**	**Coal/Y**	**Province**	**L/Y**
Hainan	2.47	Shanghai	9.63	Inner Mongolia	4.27	Jiangxi	66.23
Beijing	3.04	Jiangsu	12.28	Guangxi	4.53	Guangxi	75.47
Fujian	3.08	Inner Mongolia	14.92	Jilin	5.03	Beijing	81.66
Guangdong	3.11	Shanxi	15.95	Yunnan	5.17	Heilongjiang	86.25
Tianjin	3.32	Ningxia	17.69	Sichuan	5.51	Sichuan	118.30

Panel (c) year 2014

Partial BP provinces				**Partial WP provinces**			
Province	**Coal/Y**	**Province**	**L/Y**	**Province**	**Coal/Y**	**Province**	**L/Y**
Beijing	1.25	Ningxia	6.05	Liaoning	3.67	Hunan	37.37
Zhejiang	2.54	Jiangsu	6.25	Heilongjiang	3.77	Beijing	41.67
Guangxi	2.59	Shanghai	6.66	Yunnan	3.96	Yunnan	46.53
Shanghai	2.61	Shanxi	7.63	Inner Mongolia	8.24	Heilongjiang	48.83
Hainan	2.69	Xinjiang	7.82	Jilin	35.80	Sichuan	66.49

low coal coefficient. The BP plants in 2007 are all different in the two coefficient columns underlying the heterogeneity.

Among the five provinces with the largest input coefficients we have Sichuan with both coefficients for years 2000 and 2007 and all three years for the labour coefficient in the WP group. Yunnan has both coefficients in the WP group for year 2000, and the coal coefficient for three years. Jilin is in the WP group for coal coefficients for the two years 2007 and 2014. Somewhat surprising Beijing is in the WP group for the labour coefficient the two years 2007 and 2014. We note some outliers in the WP group.

Substitution region and isoquants

Figure 5 shows the substitution region and a selection of isoquants with a constant increase of 200 TWh in output for 2000, 2007 and 2014 together. Labour is measured along the vertical axis and coal along the horizontal axis. The substitution regions are rather narrow compared with a textbook illustration and non-convex. This reflects the observed limited range of variable input mix between regions and the inherent accumulating averaging process behind the philosophy of the short-run function. The substitution regions grow fatter over time due to increasing heterogeneity of input coefficients. The isoquants show the greatest relative variability in labour (but this is depending on the measuring units). The isoquant are all piecewise linear (cf. the linear program used to solve problem (3b)), but this is not always so easy to see from the figure.

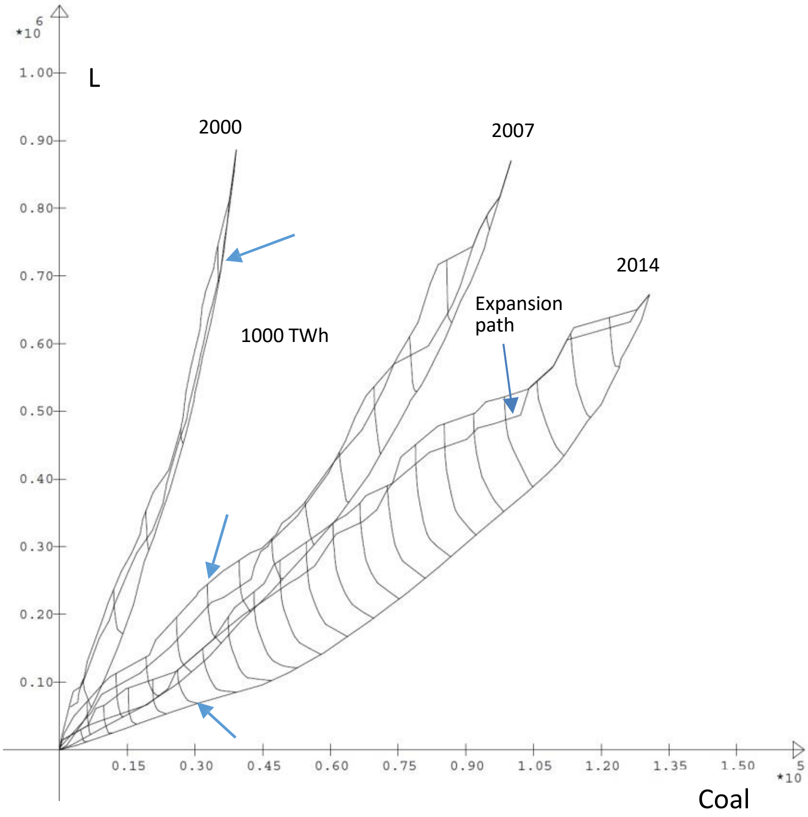

Figure 5. *Substitution regions and isoquants Chinese provinces for years 2000, 2007, 2014 with expansion path using 2014 average input prices*

The expansion path will in general go through corner points of isoquants and reflect the cost minimising inputs on a given isoquant. We see that the expansion path for the average 2014 prices are far from a straight line, and is closer to the labour-intensive part for the years 2007 and 2014.

The amount of output of electricity has increased substantially (see the increase in the number of isoquants) together with the use of coal, while the total use of labour has almost been the same between the two first years, but is even reduced the last year, as seen from the tip ends of the substitution regions. The last isoquant for year 2000 has the level of 1000 TWh, while the last isoquant for year 2007 has a level of 2600 TWh; an increase with a factor of 2.6. The last year 2014 ends with an isoquant of 4200 TWh, an increase from 2007 with a factor of 1.6, or 4.2 from year 2000. Notice that this increase is just utilising all units to observed output as full capacity instead of the potential capacity using installed power capacity. The technical change has obviously been labour saving and coal using. This will be illuminated calculating the bias measure below. Following the 1000 TWh isoquant in Fig. 2 the use of labour has decreased substantially from 2000 to 2007 while coal consumption stayed about the same, and also from 2007 to 2014 there is a reduction in use of labour, but now also a reduction in use of coal at this level of production. We notice a systematic shift towards the coal axis implying a relative increase in the use of coal.

We can connect the short-run function to the provinces by using information on which provinces are used to produce electricity at the various isoquant levels. The most efficient provinces in the use of the variable factors will be utilised first and the least efficient last along the borders. Then there may be combinations along isoquants. The active provinces we can term the best practice (BP) ones are set out in Table 8. Along the first isoquant of level 200 TWh the capacities of provinces for the first 200 TWh isoquant Beijing, Zhejian, Shanghai, Jiangsu and Ningxia, are used. This holds also for the next 400 TWh level, but Guangxi is added, while at the 600 TWh level Shanghai's capacity is exhausted and the provinces Jiangsu and Ningxia also come in. At the opposite end of nearing exhaustion of

Table 8. *Best Practice (BP) provinces forming the 200 TWh isoquant*

Year 2000					
Upper border sorted by increasing coal coefficients			**Lower border sorted by increasing labour coefficients**		
Province	**Coal/Y**	**Labour/Y**	**Province**	**Coal/Y**	**Labour/Y**
Chongqing	2.34	113.8	Shanghai	2.94	12.5
Shandong	2.37	63.0	Jiangsu	3.84	36.8
Ningxia	2.85	64.7	Shanxi (end)	3.61	42.1
Shanghai	2.94	12.5			
Hainan	3.13	151.4			
Tianjin (start)	3.15	42.6			

Year 2007					
Upper border sorted by increasing coal coefficients			**Lower border sorted by increasing labour coefficients**		
Province	**Coal/Y**	**Labour/Y**	**Province**	**Coal/Y**	**Labour/Y**
Hainan	2.47	48.1	Shanghai	3.61	9.63
Beijing	3.04	81.7	Jiangsu (end)	3.34	12.28
Fujian	3.08	36.4			
Guangdong (start)	3.11	23.1			

Year 2014					
Upper border sorted by increasing coal coefficients			**Lower border sorted by increasing labour coefficients**		
Province	**Coal/Y**	**Labour/Y**	**Province**	**Coal/Y**	**Labour/Y**
Beijing	1.25	41.67	Ningxia	3.48	6.05
Zhejiang (start)	2.54	9.57	Jiangsu (end)	2.72	6.25
Shanghai On isoquant	2.61	6.66			

the total province capacity the provinces Jilin and Yunnan are marginal at the last isoquant of 4200 TWh. In year 2000 the large difference in the labour coefficients between Chongqing and Shanghai is causing the extensive spanning of the efficiency frontier. Moving outwards the aggregation effect soon sets in "slimming" the capacity region. The only provinces being on the starting isoquant all years are Shanghai and Jiangsu. Hainan and Ningxia are BP units twice.

Capacity regions

In our case of a single output the structure of production and the change over time can be visualised transforming the substitution region and isoquants from the factor space into input coefficient space by dividing with the output levels (see Førsund and Hjalmarsson 1983; 1987). The borders of the substitution region in input space will be converted to borders showing the development of input coefficients in the capacity space, and isoquants in input space will be converted to showing the substitution between input coefficients. The capacity regions for the years 2000, 2007, and 2014 are shown in Figure 6.

The start of the capacity regions closest to the origin are based on single units and correspond to the concept of efficiency frontier (Førsund and Hjalmarsson 1974). The span of the convex efficiency frontier in year 2000 is caused due to the unit with the smallest coal coefficient having a large employment coefficient. The unit is Chongqing. The unit with

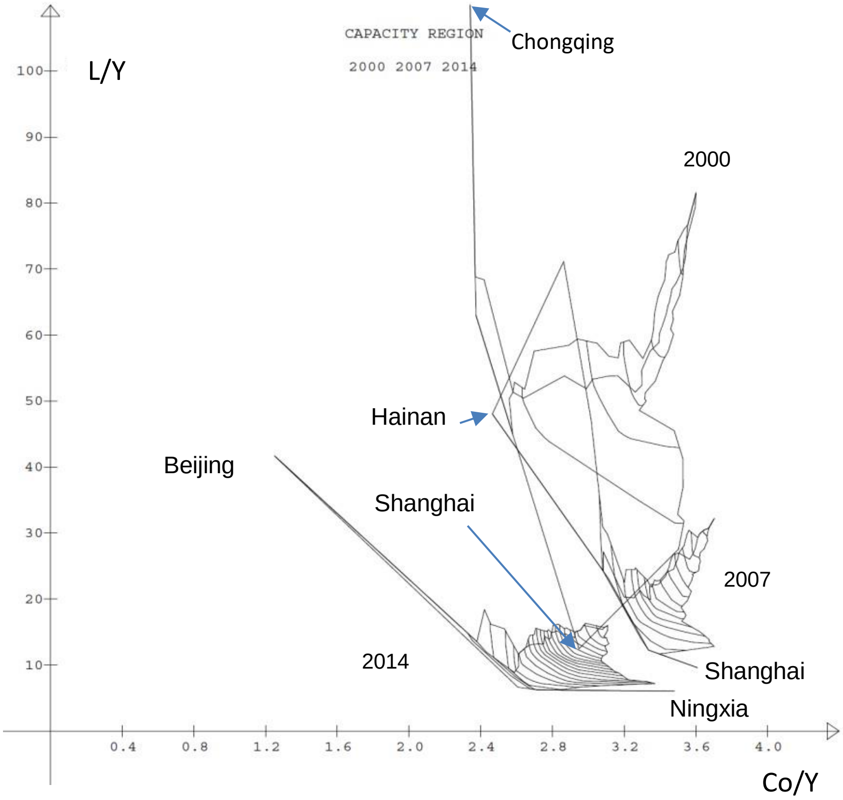

Figure 6. *Capacity regions for Chinese provinces 2000, 2007 and 2014*

the smallest labour coefficient but with a large coal coefficient starting the lower boundary is Shanghai. The efficiency frontiers the other two years also have large spans caused by the differences in input coefficient between the starting units; Hainan and Shanghai in 2007 and Beijing and Ningxia in 2014. The nature of the change over time is clearly revealed by plotting the capacity regions for 2000, 2007 and 2014 in the same diagram, as done in Figure 6. The productivity improvement is clearly illustrated by the marked shrinking of the main part of the capacity region. Comparing 2000 and 2007, and then 2014, we also see that the isoquant density increased markedly. There is a slight increase in the unit use of coal. From 2007 to 2014 both the input coefficients of coal and labour has decreased. Beijing represents an outlier with the smallest input coefficient for coal in 2014.

In year 2000 the large difference in the labour coefficients between Chongqing and Shanghai is causing the extensive spanning of the efficiency frontier. Moving outwards the aggregation effect soon sets in "slimming" the capacity region. The only provinces being on the starting isoquant all years are Shanghai and Jiangsu. Hainan and Ningxia are BP units twice.

Productivity change

Productivity change is calculated by identifying the input use at the expansion path based on the input prices of 2014. The results - based on Eq. (12) - on relative form are set out in Table 9. The productivity increases for the chosen isoquant levels are positive except for the 200 TWh isoquant where there is a decrease in productivity of about 6 % from 2000 to 2007. This is difficult to see from the isoquant- and capacity region figures. The productivity results will in general also depend on the choice of the expansion path and its location. For the periods 2000 to 2007, and 2000 to 2014 the productivity increase is greatest for the "worst practice" regions. For the period 2007 to 2014 the productivity gain is around 30 % for all chosen isoquant levels. When capacity expands, it will be with the most modern equipment. The capacity increased with a factor of 4.26 on the average for provinces with a standard deviation of 1.89.

Table 9. *Total Variable Factor Productivity (TVFP) change Chinese provinces*
2000 – 2014 measured by change in average costs
Average coal and labour prices 2014

Years	Output levels in TWh												
	200	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400	2600
2000-2007	0.94	1.05	1.10	1.13	1.20								
2007-2014	1.34	1.31	1.29	1.29	1.28	1.28	1.28	1.28	1.29	1.30	1.31	1.32	1.34
2000-2014	1.26	1.37	1.41	1.46	1.54								

The consequence of last feature is illustrated plotting the average and marginal cost function for 2000, 2007 and 2014 as done in Figure 7. The gap between average and marginal costs show the increased inefficiency of additional capacity taken into use compared with the average efficiency of the capacity in use. The average cost curve is much flatter for 2007 and 2014 than for 2000, indicating a more active replacement policy in regions previously lagging behind in technology. However, there is still a tail of high marginal cost regions in all periods. The superior technology of the "best practice" (BP) region in 2000 resulting in a reduction in productivity for BP regions for 2000 – 2007 shows up as the average cost curve for 2000 starting out lower than the average cost curve for 2007.

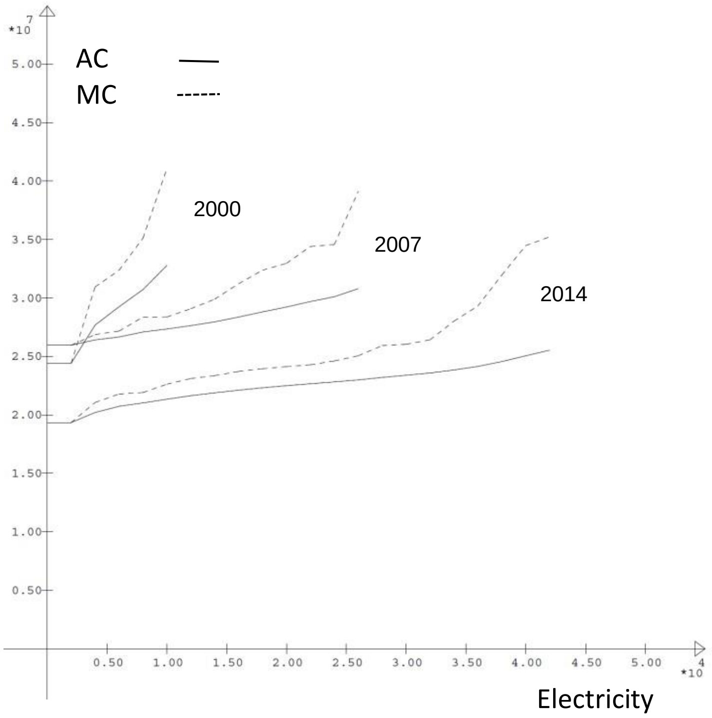

Figure 7. *Average (-) and marginal (--) variable costs 2000, 2007, 2014*
Average input prices 2014

Variable factor bias

We see from Figures 5 and 6 that there is a marked increase in the coal – labour ratio. Applying the approach of Salter (1960) to variable factors we can quantify the measure of factor bias by using the optimal factor ratios along an isocline[10], i.e., the expansion path corresponding to a given factor price ratio. The results are presented in Table 10 for the same output levels as in Table 9. Numbers greater than one show labour saving, i.e., the optimal coal ratio has increased from t_1 to t_2 relative to the labour ratio. The factor of increase for the frontier from 2000 to 2007 is 146 %, and at worst practice (WP) the strongest change for the last isoquant level is 206 %. (The relative factors given in the table can easily be transformed to percentage changes by subtracting 1.) The next period 2007 to 2014 also shows labour saving for all isoquant levels of 25 to 64 %.

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[10] Isocline is Frisch (1965) concept defined as a curve in input space with a constant ratio between the marginal productivity of the two factors)

Table 10. *Factor bias Chinese provinces.*
Change in the optimal coal/labour factor ratios for given factor prices

Years	Output levels in TWh												
	200	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400	2600
2000-2007	2.42	1.87	2.78	2.76	3.06								
2007-2014	1.24	1.65	1.70	1.76	1.44	1.28	1.64	1.36	1.45	1.51	1.45	1.49	1.58
2000-2014	3.01	3.80	4.33	4.86	4.39								

The period 2000 to 2014 with a substantial increase in total capacity show the strongest labour saving ranging from 201 to 386 %. The labour saving is increasing with output levels reflecting the importance of entering more modern capacity for the structure of the efficiency of provinces.

3. Conclusions

The Leif Johansen short-run industry function can yield very useful policy tools for understanding the dynamics of change of industries with embodied technologies and sunk cost of capital. However, the main normative aspect of the Johansen model of efficient use of the total resources available to the industry is not addressed. One reason is that electricity generating plants have different roles in providing supply to match the demand in continuous time. We have peak load, shoulder load and base load plants, so without knowing the role of the micro units a normative set-up is difficult. We have chosen to measure capacity as the observed production each year, thus all plants end up in the short-run industry function producing their observed amounts. The short-run industry function can then be used to calculate productivity change and factor bias, thus reflecting the heterogeneity at the micro level.

The sample of coal-fired electricity plants from South Korea may seem quite small with only six plants. But it turns out that the short-run industry function can be established in the standard way. Productivity change and factor bias for variable inputs vary with isoquant levels and choice of expansion path. This is the key to manage to take heterogeneity into consideration and identify the performance of individual micro units.

It is not easy to get plant level data. This may be the main reason for the Johansen model hardly being used or cited. A novel approach in the paper is to use aggregated units as micro units. The electricity production using coal is aggregated to the province level in the publicly available energy statistics for China. Of course, aggregation of real micro units means that heterogeneity is reduced, but enough remains to study productivity change and factor bias in the same way as if provinces are real micro units. Policy makers can identify efficient and inefficient provinces as to use of inputs, and get interesting information on province level of productivity change and the impact of factor bias reflecting underlying exit and entry of capital embodying technology.

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