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“Do Higher Energy Prices Promote Productivity Gains?”

An investigation based on cost Malmquist indexes for 11 OECD economies from 1978-2007

Verfasser

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1 Introduction

"We cannot afford to delay further action to tackle climate change if the long-term target of limiting the global average temperature increase to 2°C [...] is to be achieved at reasonable cost" the International Energy Agency warned last year (International Energy Agency, 2011). Without new policies, the report continued, "we are on a [...] dangerous track, for a temperature increase of 6°C or more."

Containing global warming is among the most pressing issues on the global agenda, and saving energy to reduce greenhouse gas emissions has been assigned a central role in this quest. Energy savings shall mostly be achieved through improved 'energy efficiency'. According to the International Energy Agency (IEA) "global CO_2 emissions could be reduced by 7.6 gigatonnes by 2030" (International Energy Agency, 2012*a*) if the Agency's recommendations for energy saving policies were implemented globally. Moreover, a more 'efficient' use of energy is thought to "reduce the need for investment in energy infrastructure, cut fuel costs, increase competitiveness and improve consumer welfare." (International Energy Agency, 2012*a*)

In spite of the importance attributed to 'energy efficiency', the definition of this term remains blurred. In publications on energy saving in the industry sector (Tanaka, 2008), and the transport sector (Kojima and Ryan, 2010) the IEA relies on one-dimensional measures of 'efficiency', such as vehicle fuel consumption per distance travelled in the transport sector, or energy use per unit of output in the industry sector. In the economic literature, for example in Fried, Lovell and Schmidt (2008), such measures are considered measures of *productivity*, as they reflect the ratio of output to input. In contrast, *efficiency* relates to a comparison of observed values to optimal values of inputs and outputs. Moreover, one-dimensional measures fail to take into account that a reduction in energy use does not necessarily mean that productivity will increase overall, as energy savings might, for example, lead to increased labour or capital use. Consequently, an assessment of 'energy efficiency' needs to also include the use of other factors of production.

Numerous contributions to the economic literature investigate 'energy efficiency' in a total factor context. Emrouznejad, Parker and Tavares (2008) review the general literature on data envelopment analysis between 1978 and 2007, while Zhou, Ang and Poh (2008) survey the literature applying data envelopment analysis to energy and environmental studies up to 2007. More recent examples for energy and environmental studies are Kumar and Managi (2009), Zhou, Ang and Han (2010), and Chen and Yu (2012), who are all estimating total factor productivity indexes from panel data, either through data envelopment analysis (DEA) or stochastic frontier analysis (SFA).

In this thesis I adopt a similar approach and estimate cost Malmquist productivity indexes for 11 OECD economies from 1978 - 2007 to investigate some issues related to the policy objective of raising ‘energy efficiency’. Through the analysis of long-term trends in productivity I try to assess whether ‘efficiency gains’ on a scale implied by the IEA are realistically achievable. In contrast to Kumar and Managi, Zhou, Ang and Han, and Chen and Yu, I do not investigate productivity of the total economy, but of the industry and the transport sector.

Moreover, I also examine the impact of factor prices and output variations on estimated productivity indexes, as an often stated policy suggestion to promote energy savings is to increase the (relative) price of energy. The energy price increase is thought to account for negative externalities of energy consumption (e.g. its contribution to global warming), and often complemented by the suggestion to lower taxes on labour to limit companies’ additional cost from higher energy prices and to generate positive employment effects. To the best of my knowledge, the contribution by Kumar and Managi (2009), which relies on SFA, is the only paper in the literature that investigates the link between energy prices and ‘energy efficiency’ (or technical change to be more precise) within the framework of productivity analysis. To refine their analysis Kumar and Managi also estimate bias in technical change. In contrast to this, I estimate a cost Malmquist index of productivity that allows to identify the contribution of allocative (price) effects to productivity change. To the best of my knowledge, this is a novel approach that has not been taken before. In addition, I also analyse the impact of the business cycle on productivity estimates. As Shestalova (2003) points out, output fluctuations during the business cycle can have considerable impact on estimated Malmquist index components. However, such potential distortions are typically neglected in the literature applying productivity analysis techniques to energy and environmental topics.

The following section provides an overview over the employed methods of efficiency measurement and establishes the theoretical foundations of estimating the cost Malmquist index. Section 3 describes the used data and provides details on the procedure for estimating the cost Malmquist index. Section 4 presents obtained results and discusses the impact of factor price changes and output fluctuations on productivity growth. Section 5 draws conclusions of the findings.

2 Measurement of Productive Efficiency

Pioneering work in the field of efficiency measurement was undertaken by Koopmans (1951), who provided a formal definition of efficiency and by Debreu (1951), who developed a distance-based measure of efficiency depending on prices in optimum. Farrell built on these ideas in his seminal 1957 paper on "The Measurement of Productive Efficiency". A formal definition of efficiency is

Definition Let $x = (x_1, x_2, \dots x_n) \in \Re_+^N$ be a vector of inputs used to produce a vector of outputs $y = (y_1, y_2, \dots y_m) \in \Re_+^M$ and $T = \{(x, y) : x \text{ can produce } y\}$ be the set of all input-output combinations that are technologically feasible, i.e. y can be produced using x.
Then the feasible combination $(y, x) \in T$ is technically efficient if, and only if, $(y', x') \notin T$ for $(y', -x') \geq (y, -x)$

This definition can be interpreted in an output-oriented way, meaning that production is efficient "if an increase in any output requires a reduction in at least one other output or an increase in at least one input". Alternatively, efficiency can be defined from an input-perspective, such that efficient production would entail "a reduction in any input requires an increase in at least one other input or a reduction in at least one output." (Fried, Lovell and Schmidt, 2008, p.20).

In order to analyse the relation between factor prices and efficiency, this thesis focuses on input-oriented measures of efficiency. Therefore, it is useful to express technology T, which was defined above over inputs x and outputs y, also in input-space. The input requirement set

$$L(y) = \{x : (y, x) \in T\}$$

contains all input bundles x which can produce y given technology T. The input requirement set is bounded by the input isoquant

$$I(y) = \{x : x \in L(y), \lambda x \notin L(y) \text{ for } \lambda < 1\}$$

which is the locus of all technically efficient input bundles. The input isoquant $I(y)$ depends on the output bundle y and characterises technology T.

Farrell (1957) suggested using data from observed inputs and outputs to estimate the isoquant $I(Y)$. Figure 1 illustrates the proposed methodology, albeit only in two dimensions for the purposes of simplicity. The amount of the input x_1 used to produce one unit of the single output y is plotted against the amount of input

x_2 used per unit of output on the horizontal axis. Each point in this input space represents the observed input mix of a *decision making unit* (DMU).

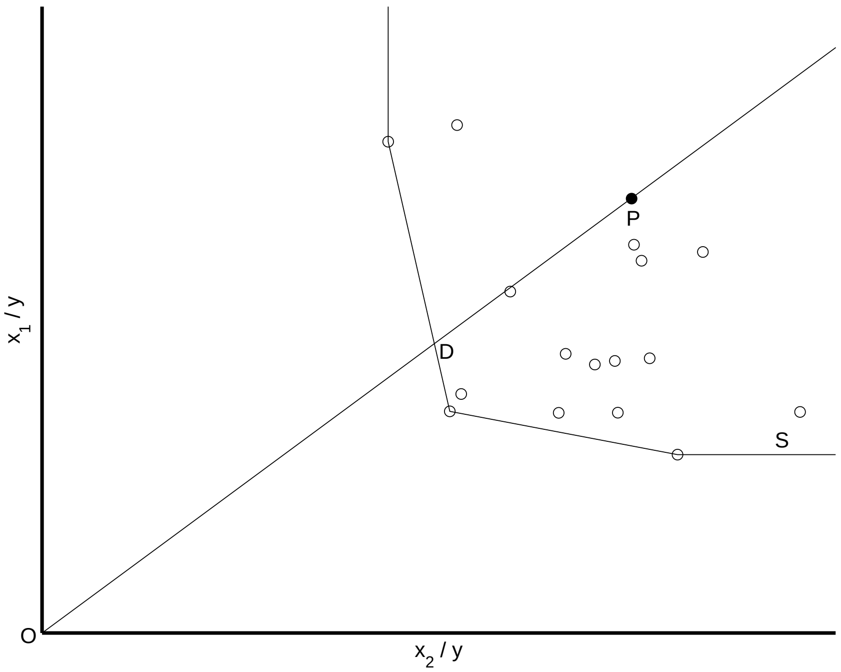

Figure 1: Technical Efficiency

Following Farrell (1957) the input isoquant bounding the input requirement set is estimated by connecting the points which are closest to the origin and the points $(0, \infty)$ and $(\infty, 0)$, which are added to produce the line segments parallel to both axes, with line segments, meaning that there are no other points between the input isoquant and the origin. By construction, the estimated isoquant S is convex to the origin and non-increasing. Convexity implies that any linear combination of observed input mixes per unit of output is also achievable, while a non-increasing isoquant implies that increased use of all factors does not result in reduced output.

As Farrell points out, this estimate of the input isoquant is "the most conservative (or pessimistic) estimate of it. That is to say, S is the least exacting standard of efficiency that is consistent with the observed points and satisfies these two assumptions [of convexity and negative slope]." (Farrell, 1957, p. 255)

Using the estimated isoquant S, and assuming that the technology it represents is available to all decision making units in the sample, the efficiency of each DMU can be related to the distance of the observed input-output combination from the isoquant S. Farrell's proposed input-oriented measure of efficiency equals the smallest factor ϑ by which the input bundle x can be multiplied so that y can still be produced as an input-oriented measure of efficiency. This measure of efficiency is the reciprocal of the Shephard (1953) input distance function, which is defined as

$$D_i(y,x) = \sup_{\theta}\{\theta : (x/\theta) \in L(y) \text{ for } \theta > 0\} \tag{2.1}$$

The input distance function D_i is equal to the largest number θ by which the input bundle X can be divided such that y is still feasible, i.e. $x \in L(y)$. Division by θ amounts to an equiproportional reduction of all inputs until factors are used efficiently. In effect, x/θ (or $x \cdot \vartheta$) projects x onto the input isoquant S, the locus of efficient factor use. Consequently, a value of $\theta = 1$ indicates technical efficiency, as inputs cannot be reduced any further within the technologically feasible limits given by $L(y)$.

Graphically, Farrell's measure of efficiency corresponds to the distance DP in figure 1. Efficiency is measured along the ray through P and the origin, along which all factors are used in constant proportions, and equals OD/OP. Thus, multiplying the factors used at P with Farrell's measure of efficiency projects P to the point D on the input isoquant S. Point D also equals the weighted average of the inputs and outputs of two observed efficient DMUs that define the corresponding section of the input isoquant. Hence, the essence of the methodology is to compare the efficiency of the DMU to be evaluated with a fully efficient hypothetical DMU that uses the factors of production in the same proportions. The hypothetical DMU is constructed from observed DMUs, which are also referred to as the 'peers' of the DMU to be evaluated.

Farrell's methodology requires DMUs to be comparable, ideally using the same inputs to produce the same outputs. Otherwise, the estimated input isoquant S might not represent actual technology, leading to a bias in estimated efficiency scores. Differences in the quality of inputs, for example, might give high efficiency scores to a DMU that uses a lower number of high-quality inputs in production. Similar problems arise when the input isoquant S is estimated from data measured in monetary value, as the underlying inputs and outputs are not necessarily comparable. In effect, S would not only depend on a specific technology, but on a mix of technologies. In this case, a change in the technology mix might be identified as an efficiency gain.

2.1 Malmquist Productivity Index

The Malmquist-Productivity-Index, introduced by Caves, Christensen and Diewert (1982), extends Farrell's method of efficiency measurement to investigate changes in productivity over time. In addition, a decomposition of the Malmquist-index enables the identification of the different sources of productivity changes.

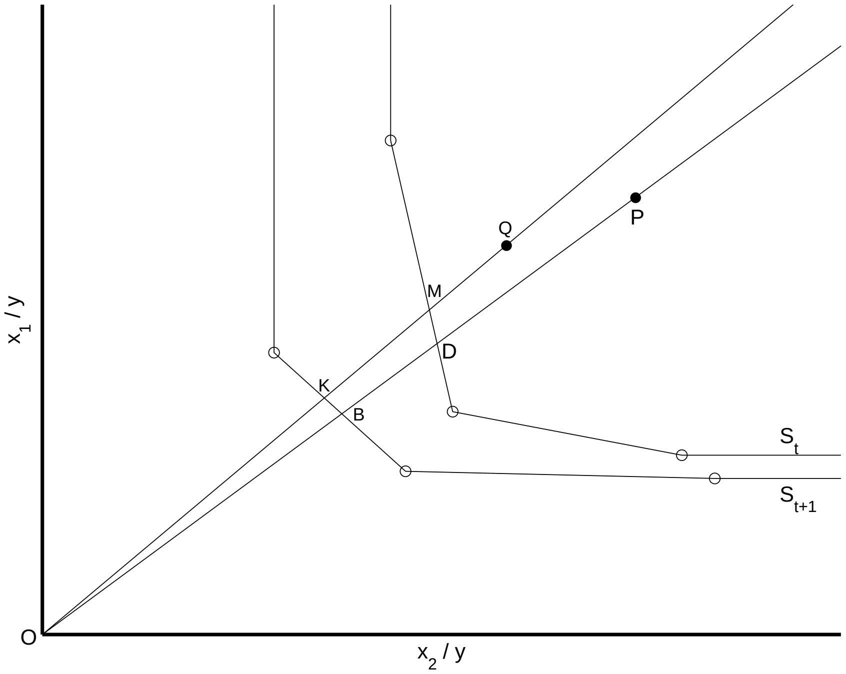

Figure 2: Malmquist Productivity Index

To evaluate whether productivity increased from period t to $t+1$, the change in Farrell's efficiency measure can be used. In figure 2 this amounts to comparing the distance from $P = x_t/y_t$ to the input isoquant S^t to the distance from $Q = x_{t+1}/y_{t+1}$ to the isoquant S^t. Both distances are measured along the rays through the observed input-output combinations and the origin, i.e. along the rays through OP and OQ. Illustrated graphically, the input-oriented Malmquist index relative to the isoquant S^t, denoted M_t^I corresponds to $(OQ/OM)/(OP/OD)$. In terms of input distance functions, the input-oriented Malmquist index is

$$M_I^t = \frac{D_I^t(x^{t+1}, y^{t+1})}{D_I^t(x^t, y^t)}$$

where $D_I^t(x^t, y^t)$ is the input distance function at time t, while $D_I^t(x^{t+1}, y^{t+1})$ is the distance from the observed input-output combination at time $t+1$ to the input isoquant at time t.

However, the Malmquist index could also be calculated relative to S^{t+1}, the input isoquant at time $t+1$. Graphically, this corresponds to $(OQ/OK)/(OP/OB)$, while in terms of input distance functions this is equal to

$$M_I^{t+1} = \frac{D_I^{t+1}(x^{t+1}, y^{t+1})}{D_I^{t+1}(x^t, y^t)}$$

As the choice between both indices would be arbitrary, Färe et al. (1989) use the geometric average of both indices, so that the input-oriented Malmquist index becomes

$$M_I = \left(\frac{D_I^t(x^{t+1}, y^{t+1})}{D_I^t(x^t, y^t)} \frac{D_I^{t+1}(x^{t+1}, y^{t+1})}{D_I^{t+1}(x^t, y^t)} \right)^{1/2} \tag{2.2}$$

The Malmquist index measures productivity gains solely on the basis of technological change. If the index has a reading below 1 productivity has improved, while a reading above 1 implies a reduction in productivity. As the Malmquist index is a geometric average of a ratio of input distance functions it *approximately* reflects the equiproportional reduction in inputs over time. The less the input mix changes from period to period, the better the approximation will be.

Further insight into the nature of progress in productivity can be gained by a decomposition of the Malmquist index. Productivity change can be caused by technical change, i.e. improvement in available technology, or by the adoption of superior technology already in existence. Technical change should be captured by the shift of the input isoquant over time. The distance by which the input isoquant shifts is measured along the rays through the origin and observed input uses. In figure 2, the measure of technical change is equal to $((OK/OM)(OB/OD))^{1/2}$. Expressed by input distance functions, technical change (TC) is equal to

$$TC = \left(\frac{D_I^t(x^{t+1}, y^{t+1})}{D_I^{t+1}(x^{t+1}, y^{t+1})} \frac{D_I^t(x^t, y^t)}{D_I^{t+1}(x^t, y^t)} \right)^{1/2} \tag{2.3}$$

Readings of TC below 1 indicate technical progress, while readings above 1 signal technical regress. A reading equal to 1 implies no technical change.

In general, the productivity of a DMU does not necessarily progress in line with technical change. A DMU might adopt new technologies later, falling behind technical change. It might also catch up relative to efficient technology by replacing inefficient technologies with efficient ones. In effect, productivity progresses at a faster pace than reflected by technical change. Such differences in the evolution of productivity across DMUs are captured by the technical efficiency change (TEC) index component which captures technical catching up. Referring to figure 2, catching up with technology would be measured by $(OQ/OK)/(OP/OD)$. Written in input distance functions, this is equal to

$$TEC = \frac{D_I^{t+1}(x^{t+1}, y^{t+1})}{D_I^t(x^t, y^t)} \tag{2.4}$$

If the distance from the observed input use to the corresponding input isoquant declines over time, TEC will be below 1, signalling productivity gains that are outpacing technical change, i.e. the DMU in question is catching up with its peers. A reading of 1 indicates productivity change at the speed of technical change, while a reading above 1 means that the productivity of the respective DMU is improving slower than technology, i.e. it is falling behind its peers.

Both index components are connected multiplicatively, so that their product yields the input-oriented Malmquist index M^I.

$$\begin{aligned} TC \cdot TEC &= \left(\frac{D_I^t(x^{t+1}, y^{t+1})}{D_I^{t+1}(x^{t+1}, y^{t+1})} \frac{D_I^t(x^t, y^t)}{D_I^{t+1}(x^t, y^t)} \frac{(D_I^{t+1}(x^{t+1}, y^{t+1}))^2}{(D_I^t(x^t, y^t))^2} \right)^{1/2} = \\ &= \left(\frac{D_I^t(x^{t+1}, y^{t+1})}{1} \frac{1}{D_I^{t+1}(x^t, y^t)} \frac{D_I^{t+1}(x^{t+1}, y^{t+1})}{D_I^t(x^t, y^t)} \right)^{1/2} = M^I \end{aligned}$$

The Malmquist index measures progress in technical productivity with minimal assumptions regarding technology. The method is non-parametric as it does not impose any particular functional form on technology a priori. Moreover, the (input-oriented) Malmquist-index relates only to minimal input use, not to the choice of inputs, making it a robust measure of efficiency. Finally, estimation of the productivity index requires data only for used inputs and produced outputs, but does not need any information about prices.

2.2 Allocative Efficiency and the Cost Malmquist Index

When price data is available, the Malmquist index can be extended in order to assess progress in technical efficiency as well as progress in *allocative efficiency.* In effect, the scope of the Malmquist index, which focuses on technical efficiency in the sense of using minimal amounts of inputs, is extended by a measure of the optimal choice of inputs.

To illustrate, consider figure 3, which depicts the observed input-output combination P, the input isoquant S, and the isocost line

$$IC(y, w) = \{x : wx = \bar{C}\} \tag{2.5}$$

where w is the vector of input prices and x the vector of inputs. Thus, wx is the cost of using input bundle x. The isocost line is the locus of all input combinations that result in the same cost. The closer the isocost line is to the origin, the lower the associated cost. The slope of the isocost line reflects relative input prices.

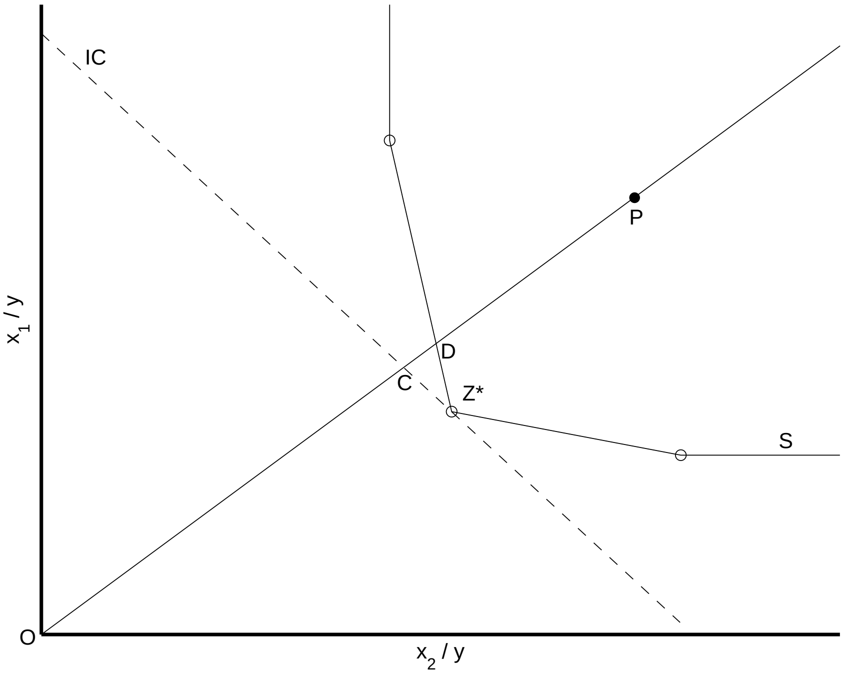

Figure 3: Allocative Efficiency

Production at the point of tangency of the input isoquant and the isocost line, Z^*, is technically efficient and also cost minimising. Any other input combination on the input isoquant would be technically efficient, but come at a higher cost of production. Any other input combination on the isocost line would come at the same cost, but would be technically infeasible.

The distance between the projection of the observed input-output combination onto the input isoquant (point D) and the isocost line IC is CD. It measures potential cost reduction, if the input mix was to be changed so that it would be consistent with cost minimisation. If the input mix used by a DMU is cost minimising, the DMU is said to be *allocatively efficient*.

Formally, the fact that the cost of production is nowhere lower than at the point of tangency of the isocost line and the input isoquant can be conceptualised by the inequality

$$C(y, w) \leq \frac{wx}{D_i(y, x)} \tag{2.6}$$

where wx are the actual cost of production, $D_i(y, x)$ is the input distance function as defined in equation (2.1), and $C(y, w)$ is the cost function

$$C(y, w) = \inf\{wx : x \in L(y) \text{ for } w > 0\} \tag{2.7}$$

representing the minimal cost of producing y when input prices are given by w and technology is given by the input requirement set $L(y)$.

In (2.6), the division of wx by $D_i(y, x)$ projects x onto the input isoquant (as $D_i(y, x)$ is equal to the highest number by which x can be divided such that y can still be produced). As the isocost line representing minimum cost is a lower bound to the input isoquant, actual production costs wx at any technically feasible input combination can be no lower than minimum cost.

If production is not cost efficient, this can either be because the input-mix is not reflecting input prices, or because inputs are used excessively, or both. Excessive input use would be captured by the reciprocal of the input distance function on the right-hand side of (2.6). To capture allocative efficiency, i.e. the alignment of the input mix with input prices, the term AE is introduced such that (2.6) holds with equality:

$$C(y, w) = \frac{wx}{D_i(y, x)} AE$$

This can be rearranged to give

$$AE = \frac{C(y, w) D_i(y, x)}{wx}$$

which measures allocative efficiency as the potential reduction in cost from changing the input mix when production is technically efficient. To illustrate, consider technically efficient production using the input mix at point D (the projection of P on S) in figure 3. The corresponding cost of producing output level y is indicated by an isocost line parallel to IC through D (not shown in the figure). As the cost associated with an isocost line declines, the isocost line moves closer to the origin. The lowest possible cost of producing y is indicated by the isocost line IC through Z^*. Consequently, the potential cost reduction when producing at Z^* instead of at D is given by the distance of both isocost lines OC/OD. This complements Farrell's measure of technical efficiency, which indicates the potential reduction in input use such that technical efficiency is achieved while the input mix is held constant. Together, both measures form an overall measure of cost efficiency, CE.

$$CE = AE \cdot TE = \frac{C(y,w)D_i(y,x)}{wx} \cdot \frac{1}{D_i(y,x)} = \frac{C(y,w)}{wx} \tag{2.8}$$

Similar to the measure of technical and allocative efficiency, the measure of cost efficiency CE is equal to the smallest number by which cost can be multiplied such that output y can still be produced given input prices w.

Based on this concept of allocative efficiency, which was already laid out in Farrell (1957), Maniadakis and Thanassoulis (2004) have defined an index of cost efficiency analogous to the Malmquist index. The so-called cost Malmquist index

$$CM^t = \frac{C^t(y^t,w^t)}{w^t x^t} \Big/ \frac{C^t(y^{t+1},w^t)}{w^t x^{t+1}}$$

measures the change in productivity from t to period $t+1$ by projecting observed inputs onto the isocost line at time t. In figure 4 this corresponds to $(OQ/OL)/(OP/OC)$. Alternatively, observed input combinations can be projected onto the isocost line in period $t+1$, which in figure 4 corresponds to $(OQ/OJ)/(OP/OA)$. In terms of cost functions, this is equal to

$$CM^{t+1} = \frac{C^{t+1}(y^t,w^{t+1})}{w^{t+1} x^t} \Big/ \frac{C^{t+1}(y^{t+1},w^{t+1})}{w^{t+1} x^{t+1}}$$

As there is no sensible way to discriminate between the two indices Maniadakis and Thanassoulis (2004) follow the convention of the Malmquist index and define the cost Malmquist index as the geometric average of CM_t and CM_{t+1}. The cost Malmquist index is then defined as

$$CM = \left(\frac{C^t(y^t,w^t)/w^t x^t}{C^t(y^{t+1},w^t)/w^t x^{t+1}} \frac{C^{t+1}(y^t,w^{t+1})/w^{t+1} x^t}{C^{t+1}(y^{t+1},w^{t+1})/w^{t+1} x^{t+1}} \right)^{1/2} \tag{2.9}$$

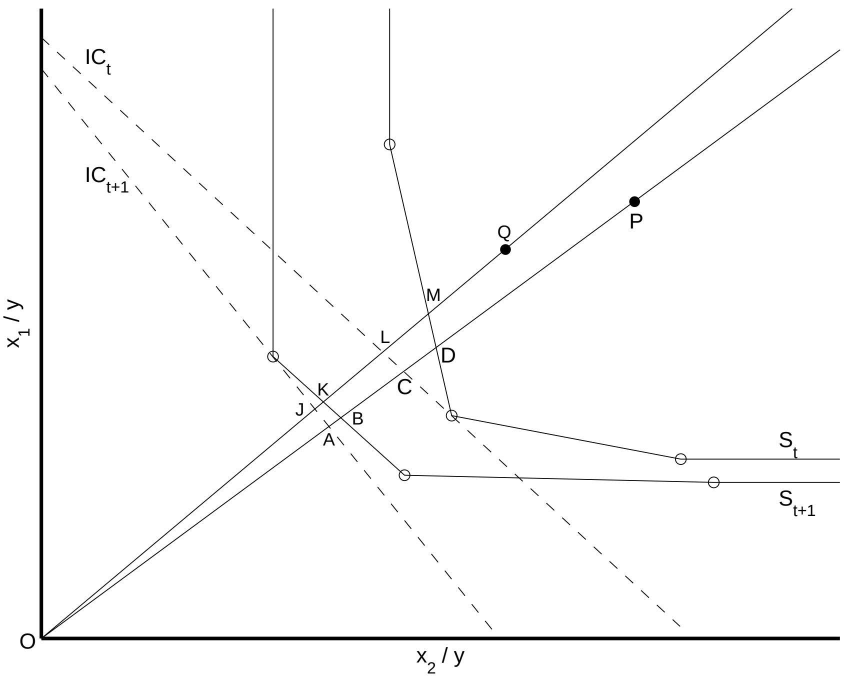

Figure 4: Cost Malmquist Index

The cost Malmquist index can be broken up into a technical component and an allocative component. The technical component is simply the Malmquist index, as described in section 2.1. The allocative component is

$$AE = \left(\frac{C^t(y^t, w^t)D^t(y^t, x^t)/w^t x^t}{C^t(y^{t+1}, w^t)D^t(y^{t+1}, x^{t+1})/w^t x^{t+1}} \right. \\ \left. \frac{C^{t+1}(y^t, w^{t+1})D^{t+1}(y^t, x^t)/w^{t+1} x^t}{C^{t+1}(y^{t+1}, w^{t+1})D^{t+1}(y^{t+1}, x^{t+1})/w^{t+1} x^{t+1}} \right)^{1/2}$$

and, following Maniadakis and Thanassoulis (2004), can be further decomposed into *allocative efficiency change* (AEC) and a *price effect* (PE), such that

$$AEC = \frac{C^t(y^t, w^t)D^t(y^t, x^t)/w^t x^t}{C^{t+1}(y^{t+1}, w^{t+1})D^{t+1}(y^{t+1}, x^{t+1})/w^{t+1} x^{t+1}} \qquad (2.10)$$

is a measure of the individual DMU's adjustment to the price-optimal input mix. If the potential cost reduction from bringing the input mix in line with the cost minimising allocation of inputs, in figure 4 measured as OD/OC for time t and OK/OJ for time $t + 1$, declines over time, the AEC index component will be smaller than 1, indicating improvement in the 'allocative productivity' of the evaluated DMU.

As potential cost reduction is measured relative to the input isoquant which is determined by the DMU's peers, a reading of AEC below 1 also implies that the DMU is adjusting to relative input prices faster than its peers. This overall effect is captured by the *price effect* PE

$$PE = \left(\frac{C^{t+1}(y^{t+1}, w^{t+1}) D^{t+1}(y^{t+1}, x^{t+1})}{w^{t+1} x^{t+1}} \frac{w^t x^{t+1}}{C^t(y^{t+1}, w^t) D^t(y^{t+1}, x^{t+1})} \right. \\ \left. \frac{C^{t+1}(y^t, w^{t+1}) D^{t+1}(y^t, x^t)}{w^{t+1} x^t} \frac{w^t x^t}{C^t(y^t, w^t) D^t(y^t, x^t)} \right)^{1/2} \tag{2.11}$$

which is the geometric average of the ratio of potential cost reduction at $t+1$ to the potential cost reduction at t along both rays of equiproportional input combinations, i.e. when input mix is kept constant. This broader measure reflects the allocative productivity gains due to the adjustment of technology to relative factor prices. If, for example, the relative price of one factor increases markedly, technical change might be biased towards reducing the use of this particular factor of production. This would be identified as price effect. In figure 4 the price effect corresponds to $[(OM/OL)/(OK/OJ)\,(OD/OC)/(OB/OA)]^{1/2}$.

In total, the cost Malmquist index can be decomposed such that $CM = TC \cdot TEC \cdot AEC \cdot PE$. The index components TC and TEC measure technical efficiency, and their product is equal to the Malmquist productivity index. AEC and PE measure allocative efficiency, such that $AE = PE \cdot AEC$.

Like the Malmquist index, the cost Malmquist index is a non-parametric measure of productivity, which requires only minimal assumptions on technology. However, assessing allocative efficiency is possible only when price information is available, leading to stronger data requirements.

3 Data and Method

3.1 Data

A huge strand of the literature on the measurement of productive efficiency uses international cross-sections to estimate typically economy-wide energy efficiency within the framework presented in section 2.1.

Following this strand of the literature, I use data on a sample of 11 countries for the years 1978-2007 to estimate a cost Malmquist index. However, my analysis focuses on the industry and transport sectors, as these two sectors account for the bulk of energy use in OECD economies. The sectoral analysis reduces potential bias due to differing sector size across economies. However, differing composition of sectors across economies could still distort estimated productivity indexes if specific industries that have a particularly high (or low) factor intensity make up a particularly large (or small) share of the sector under consideration.

Real gross output serves as the output variable, while hours worked, real fixed capital stock and energy consumption are the input variables. Factor prices are also used in the estimation. The countries covered are Austria, Denmark, Finland, Germany, Italy, Japan, the Netherlands, Spain, Sweden, the United Kingdom, and the United States. Together, these eleven countries account for 70.9% of OECD total final energy consumption.

Data for output, hours worked, the capital stock, and respective prices was obtained from the EU KLEMS database, which breaks down national accounts sector-by-sector and covers the years 1970-2007. In the database monetary variables are measured in the currency circulating in 2007, so that Euro area countries' output, for example, is denominated in Euro even in the years before the introduction of the single currency. For a description of the EU KLEMS database providing further details see O'Mahony and Timmer (2009).

- To obtain *real gross output* in Euros of the year 2005, the gross output at current prices in national currency (GO) was deflated by the gross output price index (GO_P) to obtain gross output at constant prices of the year 2005. Series not denominated in Euros were converted to Euros by application of the respective exchange rate of the year 2005 obtained from the AMECO database.
- *Hours worked* by people engaged in the relevant sector (H_EMP) are reported in million hours per year.
- The *real hourly price of labour* in Euros of the year 2005 was calculated by deflating the nominal labour compensation (LAB) by the gross output price

index (GO_P).[1] Real labour compensation was then divided by the number of hours worked (H_EMP) and converted to Euros (if required), using 2005 exchange rates from the AMECO database.

- The *real fixed capital stock* (K_GFCF) is reported in millions of national currency at constant prices of 1995. To convert the base year to 2005, the price index of gross fixed capital formation (Ip_GFCF) was used. If required, the value of the real capital stock was converted to Euros using exchange rates of the year 2005 as obtained from the AMECO database.

- The *real price of capital* in Euros of the year 2005 was obtained by deflating the compensation of capital (CAP) in millions of national currency by the gross output price index (GO_P), so that it is denoted in constant prices of 2005. The real capital compensation was then divided by the real fixed capital stock (K_GFCF) to determine the real price of capital. Finally, exchange rates from the AMECO database were used to convert to Euros where required.

EU KLEMS data was complemented by data taken from the International Energy Agency's (IEA) 'Extended Energy Balances of OECD Economies' and the same agency's publication on 'Energy Prices and Taxes'. The extended energy balances provide a detailed break-down of energy production, trade and consumption by country, sector and energy source for the years 1970-2009.

- *Total final energy consumption* from all energy sources, measured in Terajoules (TJ, 10^{12} Joules), is obtained from the 'Extended Energy Balances of OECD Economies'.

- The *real price of energy in the industry sector* in Euros of the year 2005 was calculated by applying the index of real energy end-use prices for the industry sector as reported in the IEA's publication on 'Energy Prices and Taxes' to a consumption-weighted average of end use prices for petroleum fuels, coal, natural gas, and electricity in the industry sector in the year 2009. End use prices reported in US dollars per tonne of oil equivalent were converted to Euros by application of the Euro–Dollar exchange rate from the AMECO database. Following the IEA's conventions, the resulting price in Euros per tonne of oil equivalent was transformed to Euros per Terajoule assuming an energy content of 41.868 GJ per tonne of oil equivalent.

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[1] Using a consumer price index would be preferable. However, harmonized consumer price indices are available only after 1988 for most countries included in the sample.

- The *real price of energy in the transport sector* in Euros of the year 2005 was approximated by calculating a weighted average of end-user prices for each of the years 1978-2007, where weights equal the share of each energy source in total final consumption in the transport sector. Nominal prices were converted to constant prices of the year 2005 by applying the US GDP (total output) deflator from the EU KLEMS database. The resulting prices were converted to Euros using the exchange rate of the year 2005.

Variable	Unit	Mean	Median	Std Dev	Max	Min
Output	Mrd €	1041.3	476.0	1296.4	5492.2	55.5
Labour	Mrd h	14.66	7.29	17.94	62.21	0.94
Capital	Mrd €	669.1	292.2	912.9	3610.9	28.0
Energy	TJ	2306.8	809.9	3660.0	16455.5	100.5
Labour Intensity	min/€	0.840	0.814	0.257	1.476	0.375
Capital Intensity	€/€	0.614	0.622	0.162	1.048	0.267
Energy Intensity	MJ/€	2.222	1.789	1.032	5.274	0.969
Labour Price	€/h	20.36	20.27	4.86	31.13	4.92
Capital Price	€/€	0.208	0.198	0.056	0.379	0.101
Energy Price	€/MJ	0.011	0.011	0.003	0.024	0.005

Table 1: Descriptive Statistics – Industry Sector

Variable	Unit	Mean	Median	Std Dev	Max	Min
Output	Mrd €	109.0	57.2	119.9	556.1	7.7
Labour	Mrd h	2.23	1.15	2.54	9.20	0.21
Capital	Mrd €	173.56	81.19	218.60	973.58	16.03
Energy	TJ	2914.6	945.8	6051.4	26324.6	109.5
Labour Intensity	min/€	1.165	1.083	0.403	2.469	0.358
Capital Intensity	€/€	1.695	1.429	0.735	3.670	0.738
Energy Intensity	MJ/€	16.833	13.035	13.577	71.805	4.797
Labour Price	€/h	19.82	19.49	5.01	37.58	5.92
Capital Price	€/€	0.082	0.084	0.032	0.146	0.002
Energy Price	€/MJ	0.026	0.026	0.006	0.044	0.010

Table 2: Descriptive Statistics – Transport Sector

Descriptive statistics for the data series (pooled for all countries and years) are provided in tables 1 and 2. Variables in levels are disperse as the size of the analysed economies differs considerably. Normalising input variables by the level of output eliminates these effects and reduces dispersion considerably and is also closer to the input-oriented measures of efficiency that will be estimated. Compared to the industry sector, factor intensity in the transport sector is high, and exhibits more variation across countries. Energy intensity is markedly higher in the transport sector than in the industry sector. This divergence is also due to the fact that energy consumption in the transport sector includes private driving, which does not enter the sector's output. As a consequence, the sector's energy intensity is overestimated. Moreover, this also leads to increased variation between different countries' transport sectors, as energy intensity will depend on the respective size of commercial transportation (which enters the output measure) relative to private transportation (which does not enter the output measure). This is a likely explanation for the fact that average energy intensity in the United States transport sector is around 60 MJ/€, almost five times as high as the average of all other countries.

Further variation in factor intensity is due to differing composition of sectors. Change in the sector composition may lead to biased productivity estimates. If, for example, a country's industry sector is predominantly made up of heavy, energy intense industries, but over time the sector composition changes so that light, less energy intense industries hold a bigger share, the sector's total energy intensity will decrease, although no technical change took place.

3.2 Estimation of the Cost Malmquist Index

The non-parametric estimation of the cost Malmquist index requires computation of input distance functions, cost functions and actual cost. Actual cost is $w^t x^t = \sum_n w_n^t x_n^t$. The term $w^{t+1} x^t$ is the cost of using today's inputs at next period's prices while $w^{t+1} x^{t+1}$ is cost in period $t+1$ and computed analogously to $w^t x^t$. The non-parametric estimation of input distance functions relies on techniques of data envelopment analysis (DEA) introduced by Charnes, Cooper and Rhodes (1978). Following Charnes, Cooper and Rhodes, the reciprocal of the input distance functions can be estimated by the linear programs (3.1) to (3.3).

$$
\begin{aligned}
&\left(D^t(y^t, x^t)\right)^{-1} = \min_{z_k,\,\theta} \theta \\
&\text{subject to} \\
&\sum_{k=1}^{J} z_k\, y_{km}^t \geq y_{jm}^t\,,\ \forall j, m \\
&\sum_{k=1}^{J} z_k\, x_{kn}^t \leq \theta\, x_{jn}^t\,,\ \forall j, n \\
&z_k \geq 0
\end{aligned}
\tag{3.1}
$$

$$
\begin{aligned}
&\left(D^t(y^{t+1}, x^{t+1})\right)^{-1} = \min_{z_k,\,\theta} \theta \\
&\text{subject to} \\
&\sum_{k=1}^{J} z_k\, y_{km}^t \geq y_{jm}^{t+1}\,,\ \forall j, m \\
&\sum_{k=1}^{J} z_k\, x_{kn}^t \leq \theta\, x_{jn}^{t+1}\,,\ \forall j, n \\
&z_k \geq 0
\end{aligned}
\tag{3.2}
$$

$$\begin{aligned}&\left(D^{t+1}(y^t,x^t)\right)^{-1} = \min_{z_k,\,\theta} \theta \\ &\text{subject to} \\ &\sum_{k=1}^{J} z_k\, y_{km}^{t+1} \geq y_{jm}^{t}\,,\ \forall j, m \\ &\sum_{k=1}^{J} z_k\, x_{kn}^{t+1} \leq \theta\, x_{jn}^{t}\,,\ \forall j, n \\ &z_k \geq 0\end{aligned} \tag{3.3}$$

In each period of time $t = 1, \ldots, T$, there are $j = 1, \ldots, J$ decision making units, including the decision making unit $k = 1, \ldots, J$, whose productivity is to be evaluated. Each DMU uses $n = 1, \ldots, N$ inputs x to produce $m = 1, \ldots, M$ outputs y. The variable z_k serves to construct the weighted average of observed inputs and outputs of the DMUs to which the DMU to be evaluated is compared. It will be larger than zero only for the peers of the evaluated DMU. The variable θ is the smallest number by which observed inputs can be multiplied, such that the observed output level is still feasible, i.e. it is Farrell's measure of efficiency.

To assess allocative efficiency, cost functions need to be computed. This is accomplished by the linear programs (3.4) to (3.6). Again, z_k is an intensity variable used to form the weighted average of observed inputs and outputs. The variable x_n reflects the cost-minimising input required to produce the observed output level.

$$\begin{aligned}&C^t(y^t,w^t) = \min_{z_k,\,x_n} \sum_{n=1}^{N} w_n^t x_n \\ &\text{subject to} \\ &\sum_{k=1}^{J} z_k y_{km}^{t} \geq y_{m}^{t}\,, \forall m \\ &\sum_{k=1}^{J} z_k x_{kn}^{t} \leq x_n\,, \forall n \\ &z_k \geq 0\,, \quad x_n \geq 0\end{aligned} \tag{3.4}$$

$$\begin{aligned}&C^t(y^{t+1},w^t) = \min_{z_k,\,x_n} \sum_{n=1}^{N} w_n^t x_n \\ &\text{subject to} \\ &\sum_{k=1}^{J} z_k y_{km}^{t} \geq y_{m}^{t+1}\,, \forall m \\ &\sum_{k=1}^{J} z_k x_{kn}^{t} \leq x_n\,, \forall n \\ &z_k \geq 0\,, \quad x_n \geq 0\end{aligned} \tag{3.5}$$

$$
\begin{aligned}
&C^{t+1}(y^t, w^{t+1}) = \min_{z_k,\, x_n} \sum_{n=1}^{N} w_n^{t+1} x_n \\
&\text{subject to} \\
&\sum_{k=1}^{J} z_k y_{km}^{t+1} \geq y_m^t \,, \forall m \\
&\sum_{k=1}^{J} z_k x_{kn}^{t+1} \leq x_n \,, \forall n \\
&z_k \geq 0 \,, \quad x_n \geq 0
\end{aligned}
\tag{3.6}
$$

The LP models (3.1) to (3.6) were stated and solved with the General Algebraic Modeling System (GAMS). The results were used to calculate the cost Malmquist index (2.9) and its components (2.3), (2.4), (2.10), and (2.11). The respective code is provided in appendix C.

4 Results and Discussion

4.1 Aggregate Productivity Growth

The methodology presented in section 3.2 was applied to data for the industry and transport sectors of the eleven OECD economies described in section 3.1. The resulting country-specific cost Malmquist productivity indexes can be decomposed into four components measuring technical change (TC), technical efficiency change (TEC), allocative efficiency change (AEC) and the price effect (PE). Table 3 provides descriptive statistics for each productivity index component and both sectors in aggregate over eleven countries.

The estimated productivity indexes account for capital, labour, and energy as factors of production, i.e. they extend beyond a one-dimensional measure of ‘energy efficiency’. As the used productivity indexes are based on radial measures of productivity that reflect equiproportional change in all factors, the results are valid for each single factor of production and may also be interpreted in an energy-context.[2] In the following I often interpret results from a total factor perspective to allow for maximum generality, but make frequent references to implications for energy consumption.

	TEC	**AEC**	**TC**	**PE**
Geo Mean	1.000	0.994	0.988	1.000
Median	1.000	1.000	0.986	0.998
StDev	0.030	0.033	0.029	0.034
Max	1.112	1.157	1.090	1.147
Min	0.871	0.879	0.913	0.888

(a) Industry Sector

	TEC	**AEC**	**TC**	**PE**
Geo Mean	1.005	1.002	0.986	0.990
Median	1.000	1.000	0.990	0.995
StDev	0.043	0.039	0.044	0.038
Max	1.161	1.227	1.129	1.163
Min	0.861	0.869	0.868	0.800

(b) Transport Sector

Table 3: Descriptive Statistics of Cost Malmquist Index Components

In aggregate, technical productivity gains, brought about by technical change, account for the largest part of overall progress in productivity.

In the industry sector, technical change (TC) between 1978 and 2007 led on average to an equiproportional reduction in factor intensity of approximately 1.2% per year, making it the most important source of productivity gains in the sector. This is also visible in figure 5, which depicts cumulated changes in productivity and output growth since 1978, two countervailing determinants of factor demand.

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[2] Minor divergences between actual and index-implied factor intensities can arise from the the convention to use the geometric average of Malmquist indexes for two consecutive periods as productivity index.

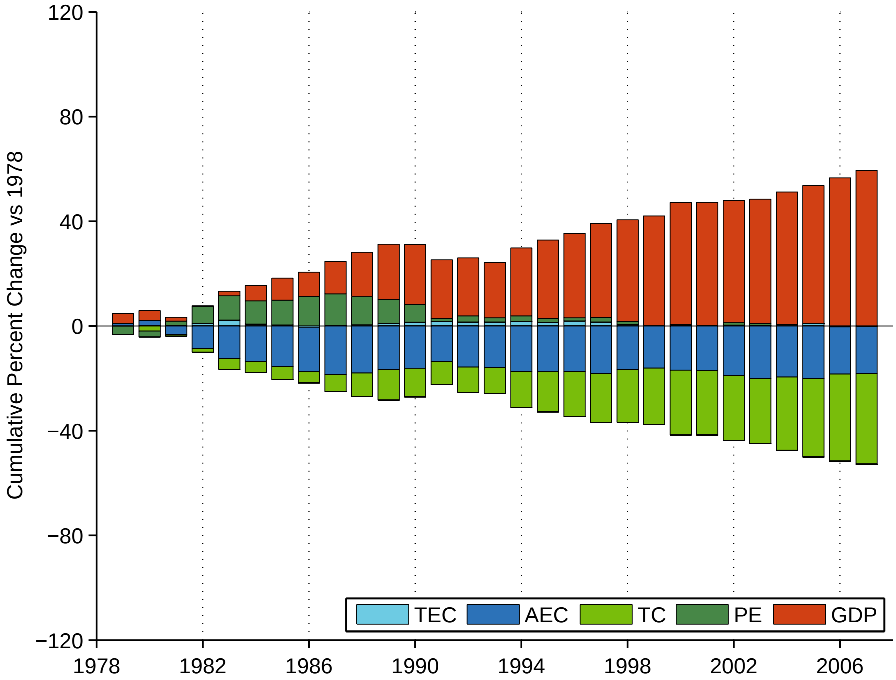

Figure 5: Cumulative Productivity & Output Growth, Industry Sector

Up until the mid 1990s, technical change progressed at an average growth rate of 0.9% per year, but accelerated to almost 1.6% per annum in later years. Technical efficiency change (TEC) was, on average, neutral and not a persistent source of productivity gains, as during half of the observed years technical efficiency change was either stagnating or regressing. The input isoquant in the industry sector is set by Sweden, Italy, Finland (from 1978 to 1986), and Denmark (since 1981).

In the transport sector, overall productivity rose by around 1.7% per year on average between 1978 and 2007. Technical change (TC), led by Denmark, the Netherlands (from 1978 to 1999), and Sweden (since 1987), accounted for more than half of this, increasing productivity on average by 1.4% per year. However, some of the gains due to technical change were offset by regress in technical efficiency change (TEC). In aggregate, regress in countries such as Germany, Japan, and the United Kingdom, reduced productivity by 0.5% per year, lowering total technical productivity gains to 0.9% per year on average. The lag effect is particularly pronounced from the mid 1990s onwards, when average regress in technical efficiency change increased from 0.1% per year in 1978 to 1995 to 1.1% per year during the years from 1996 to 2007. Figure 6 shows developments in transport sector productivity and output.

These findings are broadly in line with results from Chen and Yu (2012), who estimate technical progress (i.e. technical change and technical efficiency change) in

OECD countries at 1.16% per year. This estimate for the total economy is based on data for GDP, labour use, energy consumption, and the capital stock of 99 countries from 1991-2003. Technical change is estimated at 0.83% per year and accounts for almost three quarters of total technical progress. This puts technical efficiency change at 0.36% per year, which is considerably higher than implied by my estimates. Potentially this difference is due to the larger cross-section in Chen and Yu. Due to the comparatively small sample size underlying my estimates, some efficient countries might be excluded from my sample. This could lead to a misidentification of technical change, as countries that would not be efficient in the larger sample, might appear efficient in the smaller peer group. In effect, productivity changes in the countries wrongly identified as efficient, would inflate estimated technical change. While this problem would affect the decomposition of technical progress into technical change and technical efficiency change, the overall estimate of technical progress should remain unaffected.

In an earlier study Kumar (2006) estimates economy-wide Malmquist productivity indexes for 41 countries over the period 1971 to 1992 by applying data envelopment analysis to data on GDP, the capital stock, the labour force and commercial energy use. The study finds technical productivity gains of 0.95% per year in a subset of eleven OECD countries. Technical change is found to improve productivity on average by 0.35% per year, while catching-up effects account for the remaining 0.6% per annum. The low estimate of technical change is somewhat surprising and cannot be confirmed by my findings. In addition to differences in the decomposition of technical progress, Kumar also obtains lower estimates of overall technical progress than in this thesis and by Chen and Yu (2012). The divergence might be due to the differences in the time periods underlying the estimates. While Kumar's sample ends in 1992, I find an acceleration in technical change from the mid 1990s onwards. This would also be in line with higher technical change found by Chen and Yu, who base their estimates on data from 1991 through 2003.

In total, the estimated average technical progress between 0.9% and 1.2% per year found in my analysis seems to be well in line with the literature. Even though technical progress might have accelerated at some time during the 1990s, technical progress of 1.2% to 1.5% would still be too slow to meaningfully reduce total final energy consumption (and in consequence CO_2 emissions) if the economy is assumed to expand at a rate of 2.5%, which is equal to the average growth rate of the eleven countries in my data sample. Assuming CO_2 emissions grow in line with energy consumption, price-induced productivity gains or a shift from carbon-intense energy sources to carbon-neutral sources of energy would have to reduce CO_2 emissions at least by 1.0% per year to stabilize emissions at the current level.

Price-induced changes in allocative efficiency are estimated to have improved overall productivity in the industry sector on average by 0.6% per year, accounting for one third of overall productivity gains. In aggregate, these productivity gains were realised through factor substitution at the level of individual economies (AEC), in particular during the early 1980s, when energy prices rose to unprecedented highs in the wake of the oil price shock following the Iranian revolution. The aggregate price effect (PE) led to a productivity regress during that period. However, the effects did not persist and vanished during the 1990s.

In the transport sector, relative price changes have in aggregate, led to overall productivity gains of 0.8% per year. The increased allocative productivity is entirely due to the price effect (PE), which progressed at an average rate of 1.0% per year. However, regress in allocative efficiency change in individual economies at an annual average rate of 0.2% reduced the improvement in overall productivity. The regress in allocative efficiency change accelerated around the turn of the Millennium. Between 1978 and 1999 allocative efficiency progressed on average by 0.3%, but regressed by 1.5% per year from 2000-2007. The United States and Italy are estimated to have fallen the widest behind global improvements in price efficiency. Nevertheless, total allocative effects have improved productivity even in these two economies. Overall, price effects account for almost one half of total productivity gains in the transport sector, highlighting the importance of changes in relative factor prices.

To the best of my knowledge, allocative efficiency across countries has previously not been assessed in the literature related to productivity measurement in the tradition of Farrell (1957). Hence, respective results can not be discussed in the context of previous studies.

Improvements in allocative efficiency are estimated to have led to productivity gains between 0.6% and 0.8% on average. Although allocative efficiency is an important source of productivity gains, the average magnitude of price-induced effects observed during the thirty years from 1978 to 2007 is below 1.0%, which would be required to keep CO_2 emissions stable. Moreover, the relative price of energy would have to increase persistently in order to induce energy-saving allocative efficiency gains in the long term.[3] Strongly and persistently rising energy prices seem politically infeasible and might also have adverse effects on economic growth. Strongly rising energy prices are likely to also have drastic effects on the poor as energy

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[3] Once factor use is aligned with relative factor prices allocative efficiency can not be improved any further. Hence, the relative price of energy would have to rise continuously to induce persistent energy-reducing allocative efficiency gains.

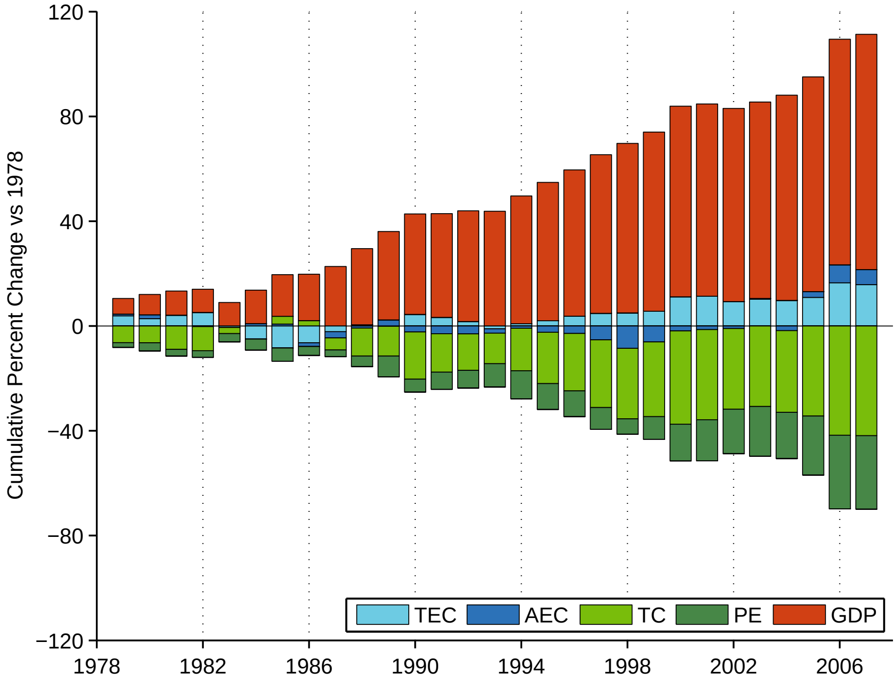


Figure 6: Cumulative Productivity & Output Growth, Transport Sector

requirements, for example for heating in winter, are to quite some extent vital. However, Hicks (1966) argued that a relative price increase, for example of energy, affects productivity not only through an allocative effect, but also induces innovation to reduce factor use through technical progress. This induced innovation would amplify the effect of energy price increases and make respective policies more effective. Hence, I commence with an analysis of the relation between factor prices, output fluctuations and progress in technical productivity.

4.2 A Non-Parametric Assessment of Dependency

Simar and Wilson (2007) show that estimated productivity indexes exhibit complex serial correlation that arises in part due to the assessment of productivity relative to the input isoquant, which itself is estimated from the data. Changes to DMUs defining the frontier will thus affect productivity estimates of many, if not all other DMUs. According to Simar and Wilson, widely used censored or OLS regressions on productivity indexes cannot easily be corrected for this complex serial correlation. Instead, the authors propose to use bootstrap procedures to allow for valid inference. The construction of such a bootstrap is beyond the scope of this work and left for future research. Instead, chi-plots introduced by Fisher and Switzer (1985) can be used to visualise the dependence structure of variables. However, the method delivers only a graphical assessment of dependence and does not quantify the impact or the relative importance of variates.

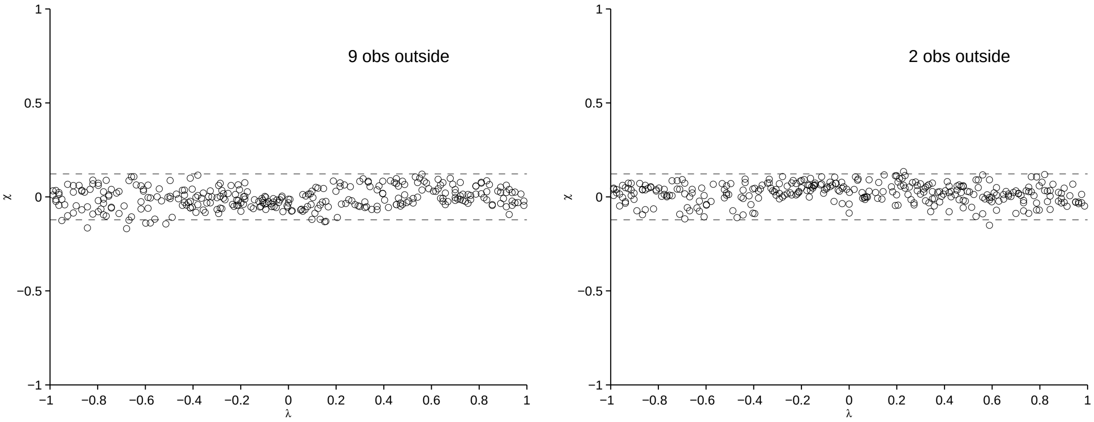
The chi-plots plot a measure of distance from the sample center, λ, against χ, a measure of the degree to which the empirical distribution function fails to factorize into a product of marginal distribution functions. For independent variates, one would expect the points on the chi-plot to be uniformly scattered along the λ-axis, with most of the points inside the 99% probability region. Details on the construction of these plots are provided in appendix D.

4.2.1 Technical progress and factor prices

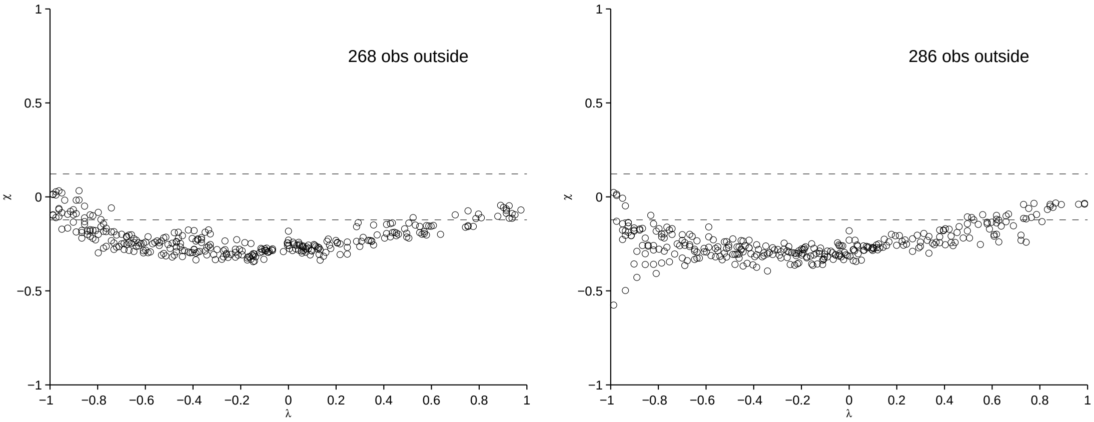
In the following analysis overall technical progress ($TC \cdot TEC$) is used as dependent variable, as this helps to avoid issues potentially arising when difference in the sectoral composition across countries distorts estimated index components. In general, the Malmquist index reflects changes in productivity. This renders level-effects irrelevant, except for the decomposition of technical progress into technical change and technical efficiency change, which relies on technical change in the identified peer economies. If one sector of an economy is wrongly identified as efficient (for example because an industry with particular low energy consumption makes up a huge part of the sector) this results in distorted estimates for technical change of the affected DMU and all DMUs whose productivity is assessed relative to the distorted DMU. However, estimates of technical efficiency change would be reduced by the same amount, making estimates of overall technical progress relatively robust to such adverse effects.

Inspecting the chi-plots for labour prices in the industry and the transport sector in figure 7, points appear evenly scattered across the 99% probability region. In the industry sector chi-plot nine observations, or 2.8% of the sample lie outside the region, which is slightly more than the three observations expected to be outside the interval for $n = 11 \cdot 29 = 319$. Nevertheless, dependence between technical progress and the price of labour seems at most mild, also in the transport sector, where two observations are located outside the 99% probability area.

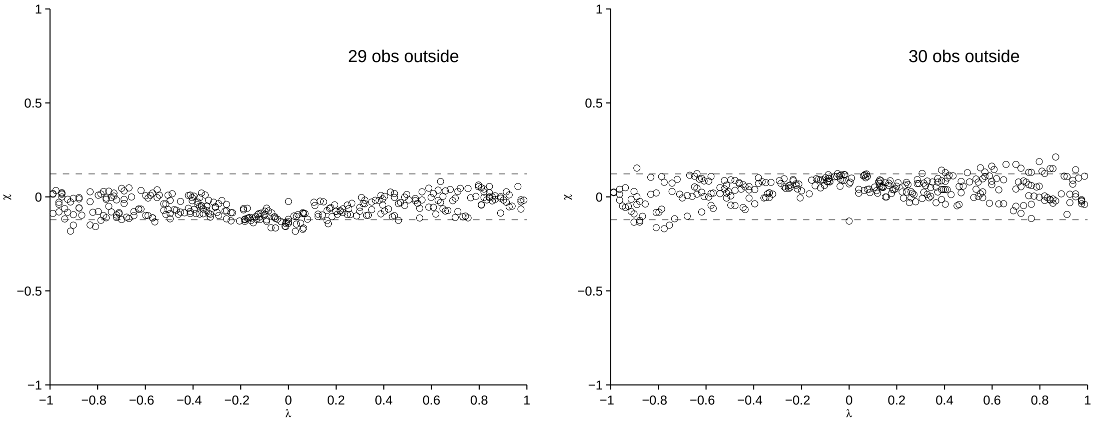
In case of capital prices, the chi-plots 7c and 7d reveal a U-shaped relation, with 268 and 286 observations, or 84% and 89.7% of the sample outside the 99% probability region. This suggests strong dependency between technical progress and capital prices. The U-shape is skewed to the right, indicating that technical productivity is progressing more often than regressing. Technical progress and the price of capital are negatively associated, as points on the chi-plots are almost entirely below the $\chi = 0$ line. This is in line with expectations as higher factor prices should provide incentive to lower factor use.



(a) Labour Price, Industry Sector (b) Labour Price, Transport Sector



(c) Capital Price, Industry Sector (d) Capital Price, Transport Sector



(e) Energy Price, Industry Sector (f) Energy Price, Transport Sector

Figure 7: Chi-Plots of Technical Progress and Factor Prices

Chi-plots relating technical progress to energy prices are evenly scattered at the end of the λ-interval in both sectors. In the industry sector, scatter tends to decline, moving towards the lower bound of the 99% probability region as λ approaches zero. In total 29 observations, an amount equal to 9% of the sample lie outside the 99%

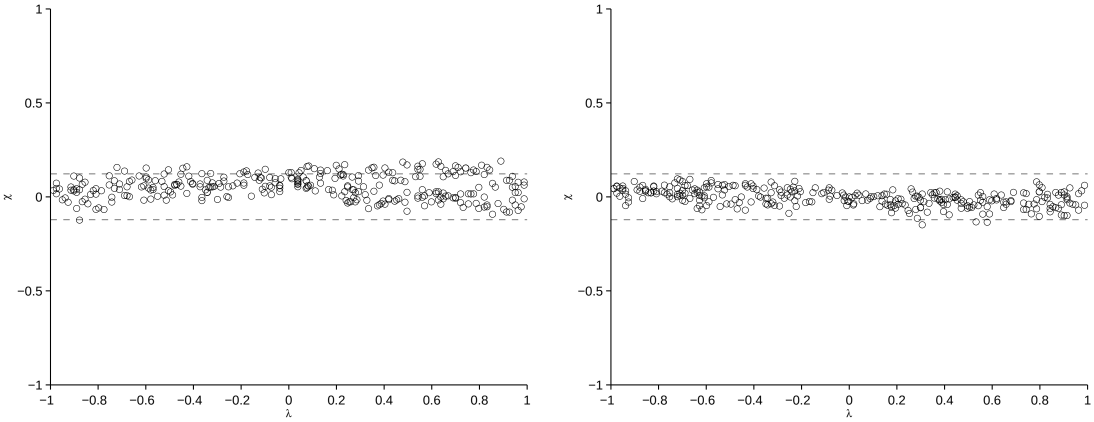
probability region, pointing at low to moderate dependence between energy prices and technical progress in the industry sector. In the transport sector, points tend to approach the upper limit of the 99% probability area as λ goes to zero. This hints at a slight positive association between energy prices and technical progress in the transport sector. This is in contrast to slight negative association between energy prices and technical progress suggested by figure 7e for the industry sector. With 30 observations outside the 99% probability region, dependence between energy prices and technical progress in the transport sector is only mild.

4.2.2 Productivity and the business cycle

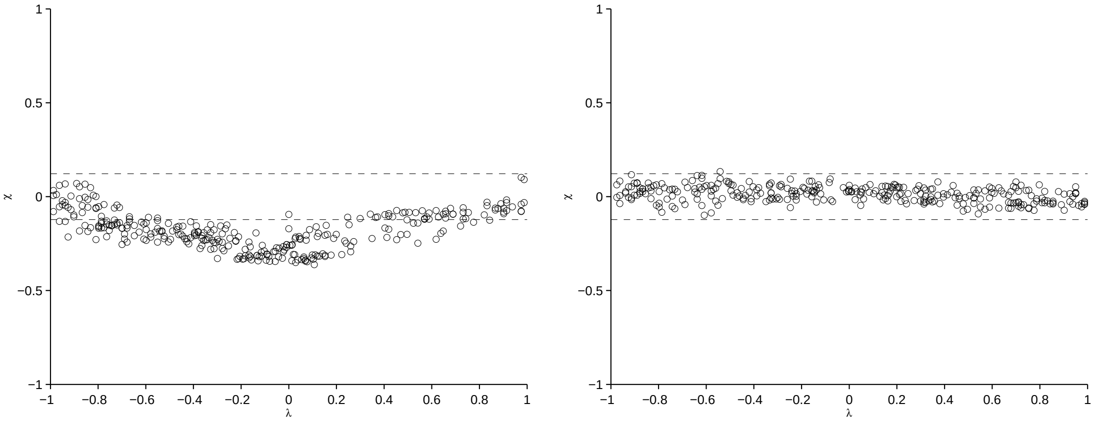
Inspecting plots of productivity change and output growth for individual countries, some components of the cost Malmquist index seemed to fluctuate with output. This confirms findings by Shestalova (2003), who proposed to estimate a sequential Malmquist index that excludes regress in technical change to eliminate distortions of the index components due to output fluctuations over the business cycle. According to Shestalova the correlation between standard Malmquist index components and sequential Malmquist index components can be as low as 0.3, highlighting the potential severity of such distortions. Figures 8 and 9 provide chi-plots of each cost Malmquist index component against output growth.

The chi-plots for the industry sector are depicted in figure 8. Technical efficiency change seems to be mildly dependent on output growth, as 57 observations, or 17.9% of the sample are outside of the 99% probability range. The majority of points lies above $\chi = 0$, suggesting mild positive association between technical efficiency change and output growth.

The chi-plot for technical change and output growth indicates a strong, negative association of technical change and output growth. Of the 319 observations in the sample, 220 lie outside the 99% probability interval. This corresponds to 69% of the sample. Moreover, the vast majority of points are below $\chi = 0$, hinting at a particularly strong negative association. This implies slow productivity gains, or even productivity regress in times of recession, while productivity growth due to technical change rebounds in line with increasing output. A potential explanation is ‘creative destruction’ in times of recession, as the most inefficient companies should be the most likely to go out of business. In aggregate, the sector becomes more efficient, leading to stronger productivity gains when output growth returns. However, the finding might also be explained by firms not reducing factor use equiproportionally to the decline in output during recessions, for example because firms’ management wants to avoid the cost of firing staff in recession and hiring once output expands



(a) Technical Efficiency Change (TEC) (b) Allocative Efficiency Change (AEC)

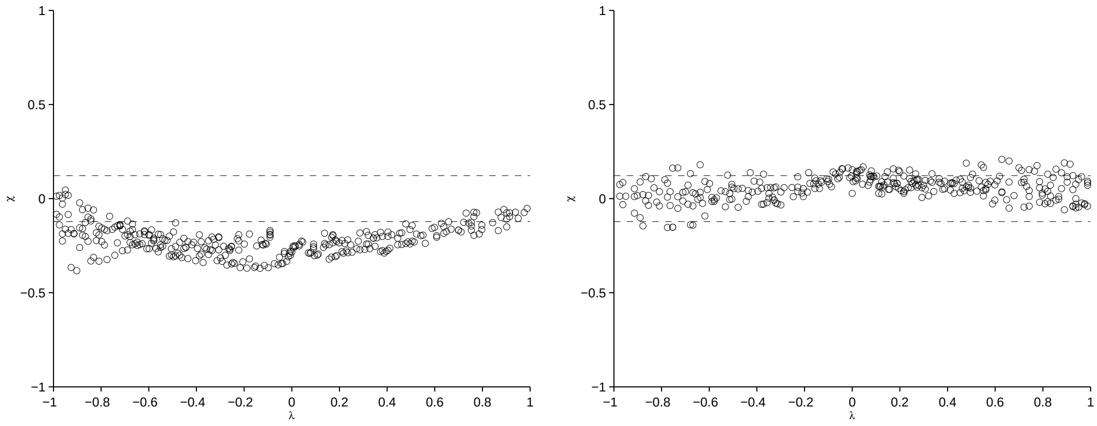


(c) Technical Change (TC) (d) Price Effect (PE)

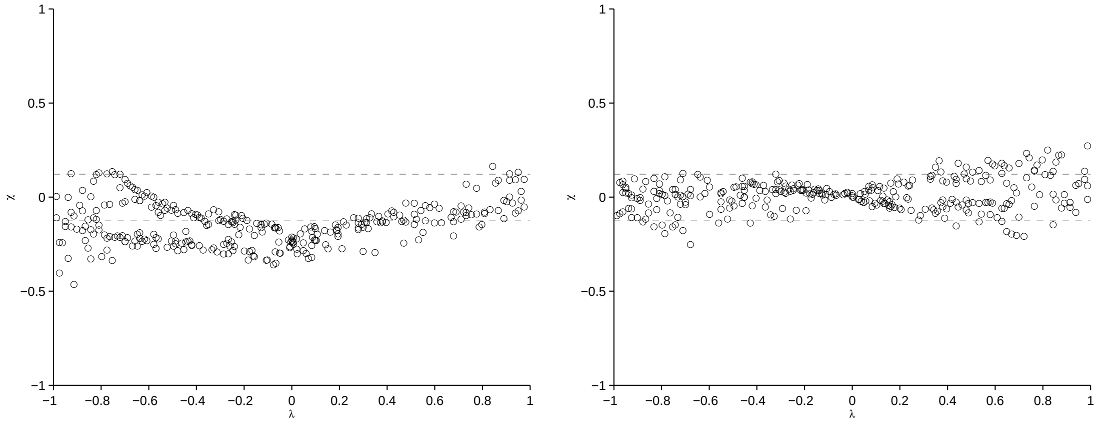
Figure 8: Chi-Plots of Productivity Change & Output Growth, Industry Sector

again. In this case, the used measure of technical change would decline during recessions as technically efficient DMUs reduce their factor use disproportionately to the decline in output, leading to a slowdown or even regress of technical change. Following recessions, technical change would accelerate again in line with expanding output, even though the underlying technology remained unchanged.

Allocative productivity seems to be independent of variations in output. Points in figures 8b and 8d are scattered evenly within the 99% probability interval, and do not exhibit any strong pattern. Points on the chi-plot for allocative efficiency change in the industry sector might be declining slightly as λ increases. Yet, the three observations outside the 99% probability range are fully in line with expectations and do not suggest any dependence between output growth and allocative efficiency change. The same also holds true for the chi-plot 8d, where one point outside the 99% confidence range does not indicate any association between output growth and the price effect. These findings are in line with expectations, and confirm the validity of



(a) Technical Efficiency Change (TEC) (b) Allocative Efficiency Change (AEC)



(c) Technical Change (TC) (d) Price Effect (PE)

Figure 9: Chi-Plots of Productivity Change & Output Growth, Transport Sector

the cost Malmquist decomposition, as allocative efficiency should reflect substitution effects and be entirely driven by changes in relative prices, not by level-effects caused by output fluctuations.

Chi-plots for the transport sector are shown in figure 9. The U-shape in the chi-plots for technical efficiency change and technical change point to negative association between output growth and the components of the technical productivity index. Moreover, on both plots the bulk of observations (281 for TEC and 196 for TC) is outside the 99% probability interval, suggesting strong dependence of technical efficiency change and technical change on output growth. Points on the chi-plots for the allocative efficiency components AEC and PE are more evenly distributed within the 99% probability interval, although scatter seems to increase as the distance from the center of the data increases. With 16.3% and 15.7% of observations for AC and PE outside the 99% probability range, dependence between output growth and allocative efficiencies appears to be mild to moderate.

4.3 Regression Analysis of Factor Prices, Output Growth, and Technical Progress

While the chi-plots used in section 4.2 are useful to determine whether or not there is dependence between a pair of variables, they are, for example, not suitable to quantify the dependency. Therefore I estimate regressions of factor prices and output growth on technical progress, keeping in mind the problem of serial correlation of productivity estimates emphasised by Simar and Wilson (2007).

To linearise the problem, logarithmic differences of the capital price p_K, the labour price p_L, the energy price p_N, and output o are regressed on the logarithm of the TC and TEC components for each country. The corresponding regression model for each country j is

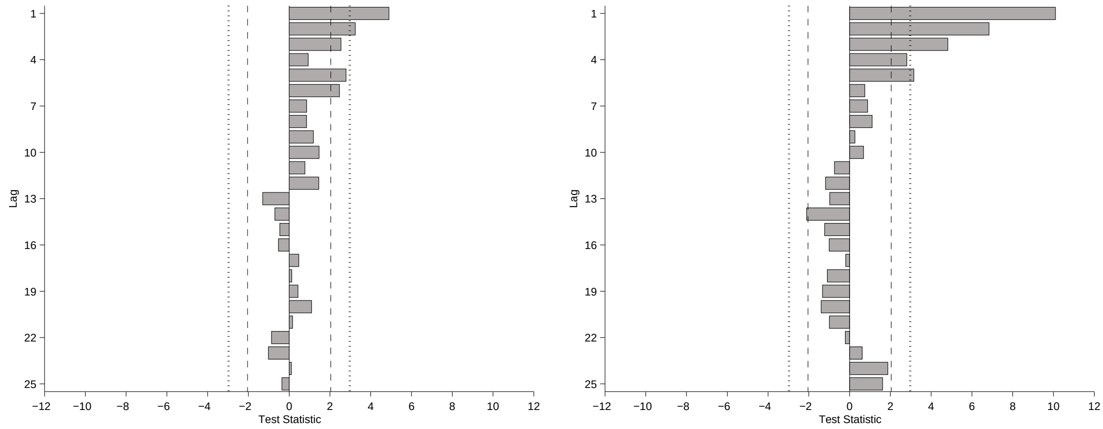
$$\begin{aligned}\ln(TC_j^t\ TEC_j^t) = \beta_0 + \beta_1 \Delta \ln(p_{Kj}^t) + \beta_2 \Delta \ln(p_{Lj}^t) + \\ + \beta_3 \Delta \ln(p_{Nj}^t) + \beta_4 \Delta \ln(o_j^t) + \varepsilon_j^t\end{aligned}$$

where Δ is the difference operator, such that $\Delta \ln(p_t) = \ln(p_t) - \ln(p_{t-1})$ equals the percentage change in price. The time and cross-sectional dimension of the data would suggest the use of panel regression analysis. However, residuals of pooled regressions exhibit significant serial correlation, which, according to Simar and Wilson (2007), is too complex to be corrected by conventional methods. As more sophisticated regression models would suffer from serial correlation as well, analysis was limited to country-specific and pooled regressions.

Figure 10 displays the test statistics of a test for the significance of Spearman rank correlations r_s of residuals ε^t and lagged residuals ε^{t-l} of pooled regressions for the industry and transport sector. According to Zar (1972), the t-distributed test statistic $t = r_s / \sqrt{(1 - r_s^2)/(n-2)}$ can be used to test for significance for $n > 100$. Dashed lines are 90% confidence bands, while dotted lines indicate the 99% confidence region.

Serial correlation of residuals from pooled regressions for the transport and the industry sector is positive and highly significant at nearby lags. Moreover, there is significant negative serial correlation at lags around 14 in the transport sector. Positive serial correlation at nearby lags will lead to inflated estimates of standard errors, leading for example to exaggerated estimates of statistical significance or goodness of fit. Hence, statistical inference is invalid.

Pooled regressions were broken up into country-specific regressions, which suffer from significant, though less pronounced serial correlation. The results of pooled and country-specific OLS regressions are reported in table 4 for the industry sector



(a) Industry Sector (b) Transport Sector

Figure 10: Rank Correlations of Residuals from Pooled Regressions

and in table 5 for the transport sector.

In the pooled regression for the industry sector, estimated coefficients for all factor prices are negative. This is in line with expectations, as higher factor prices should lead to productivity progress, not regression. The capital price is estimated to have had highly significant impact on technical progress, although significance might be overstated due to serially correlated residuals. The effect of capital prices on productivity is by far the greatest in magnitude, implying an acceleration of productivity growth by 0.09 percentage points for each percent increase in the capital price. Pooled regressions do not indicate any effect of labour or energy prices on industry sector productivity, as both estimated coefficient do not differ significantly from zero. Output growth has a highly significant impact on productivity. A one percentage point change in the output growth rate is estimated to have more than five times the effect of a one percentage point change in capital prices, highlighting the dominating effect of economic growth on productivity growth. The estimated coefficient is negative, implying productivity growth is strongest at the height of the business cycle.[4]

These findings were largely confirmed by country-specific regressions. Estimated coefficients for capital prices are negative in nine out of elven countries. However, changes in capital prices are estimated to increase the rate of technical change significantly only in two out of eleven countries. In the United States an increase of the capital price by one percent is estimated to lead to a 0.16 percent improvement in total factor productivity. This is almost twice the aggregate response to capital price

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[4] The causality might also be reverse, such that economic growth is highest when productivity growth is strongest.

	Const	**Capital**	**Labour**	**Energy**	**Output**	**R^2**
AUT	0.004	0.134	−0.490	−0.084	−0.771*	0.166
	(0.017)	(0.138)	(0.335)	(0.138)	(0.364)	
DNK	−0.021***	−0.014	0.307	0.002	−0.191	0.199
	(0.0061)	(0.0452)	(0.199)	(0.0428)	(0.152)	
ESP	0.0001	−0.076*	0.081	−0.035	−0.652***	0.895
	(0.0031)	(0.0328)	(0.0537)	(0.0439)	(0.0884)	
FIN	−0.002	−0.141	0.211	0.027	−0.579***	0.546
	(0.0099)	(0.069)	(0.27)	(0.0954)	(0.167)	
GBR	−0.014*	−0.081	0.092	−0.022	−0.163	0.134
	(0.0067)	(0.0948)	(0.0985)	(0.0598)	(0.207)	
GER	−0.012	−0.134	−0.025	−0.179*	−0.212	0.333
	(0.006)	(0.0827)	(0.04)	(0.0784)	(0.167)	
ITA	−0.005	−0.078	0.043	−0.021	−0.610***	0.628
	(0.0044)	(0.0797)	(0.101)	(0.0327)	(0.122)	
JPN	−0.001	−0.038	−0.105	−0.019	−0.311	0.134
	(0.0105)	(0.129)	(0.16)	(0.0833)	(0.265)	
NLD	0.017	−0.084	−0.231	0.243*	−0.779*	0.594
	(0.0102)	(0.0776)	(0.132)	(0.101)	(0.273)	
SWE	−0.001	0.038	−0.021	0.119	−0.729***	0.766
	(0.0035)	(0.056)	(0.0631)	(0.0643)	(0.115)	
USA	0.011***	−0.161***	0.032	−0.014	−0.682***	0.928
	(0.002)	(0.0405)	(0.0162)	(0.022)	(0.0798)	
Pooled	−0.001	−0.090***	−0.009	−0.012	−0.514***	0.385
	(0.0019)	(0.0212)	(0.0241)	(0.0197)	(0.0531)	

Table 4: Regressions of Factor Prices & Output on Technical Progress - Industry Sector

changes, which is estimated at 0.09 in the pooled regression. In Austria and Sweden responses to capital price changes are estimated to be positive, although not significantly different from zero. Energy prices are found to have a significant effect only in Germany and the Netherlands. In Germany, the energy price effect is strongly negative, implying an increase in productivity of almost 0.2% for each percentage point increase in the price of energy. In contrast, productivity in the Netherlands is estimated to regress by 0.24% for each percentage points increase in the energy price. This finding is counter-intuitive and in contrast to the estimated negative coefficients for most other countries and the pooled regression. However, with the exception of Germany, these negative coefficients are not significantly different from zero. Signs of estimated coefficients for labour prices differ widely, with negative coefficients for five out of eleven countries. However, all estimated coefficients are not significantly different from zero, implying no connection between productivity changes and the price of labour. The observed substantial cross-country variation continues in the estimated coefficients of determination. While for example almost 93% of the variation in technical progress in the United States can be explained by the changes in factor prices and output, less than 14% of the variation in technical progress in Japan or Great Britain is attributable to factor price and output changes. In the

	Const	**Capital**	**Labour**	**Energy**	**Output**	$\mathbf{R^2}$
AUT	0.010	-0.072	-0.408	-0.302^{***}	-0.584^{*}	0.414
	(0.015)	(0.0536)	(0.268)	(0.0962)	(0.275)	
DNK	0.012	0.022	-0.101	-0.055	-0.928^{***}	0.705
	(0.0072)	(0.0314)	(0.196)	(0.0948)	(0.141)	
ESP	-0.008	-0.125	0.324^{***}	-0.265^{***}	-0.291	0.601
	(0.0054)	(0.0908)	(0.0933)	(0.0585)	(0.161)	
FIN	0.015^{*}	-0.055^{***}	0.057	0.039	-0.744^{***}	0.826
	(0.0056)	(0.0179)	(0.125)	(0.040)	(0.0885)	
GBR	0.035^{***}	-0.014	0.004	0.025	-0.876^{***}	0.750
	(0.0052)	(0.0177)	(0.056)	(0.048)	(0.121)	
GER	0.006	-0.012	-0.018	-0.037	-0.358	0.262
	(0.0058)	(0.0234)	(0.049)	(0.0382)	(0.185)	
ITA	0.007^{*}	-0.121^{***}	-0.132	-0.102^{***}	-0.558^{***}	0.838
	(0.0033)	(0.0317)	(0.0765)	(0.0259)	(0.0845)	
JPN	0.029^{***}	-0.122^{*}	0.025	-0.0467	-0.704^{***}	0.511
	(0.0085)	(0.0539)	(0.0814)	(0.0554)	(0.208)	
NLD	0.017^{***}	-0.001	0.084^{*}	-0.043	-0.810^{***}	0.928
	(0.0026)	(0.0307)	(0.031)	(0.0226)	(0.0695)	
SWE	0.020^{***}	0.007	-0.084	0.052	-0.923^{***}	0.762
	(0.0055)	(0.0079)	(0.0736)	(0.0549)	(0.122)	
USA	0.011^{***}	-0.057	-0.019	0.047	-0.817^{***}	0.851
	(0.0036)	(0.0307)	(0.0356)	(0.0236)	(0.0982)	
Pooled	0.014^{***}	-0.009	0.005	-0.023	-0.736^{***}	0.536
	(0.0019)	(0.0062)	(0.0218)	(0.0152)	(0.0434)	

Table 5: Regressions of Factor Prices & Output on Technical Progress - Transport Sector

pooled regression, factor prices and output fluctuations explain about two fifth of the observed variation in technical progress.

Results for the transport sector also show considerable variation in explanatory power, although not as pronounced as in regressions for the industry sector. Almost 93% of the variation in technical progress in the Netherlands can be attributed to changes in factor prices and output. The explanatory power of regressions for Finland, Italy, and the United States also exceeds 0.8. On the other hand, only slightly more than 26% of the variation in German technical progress can be explained by output and factor price movements. In transport sector pooled regressions, coefficient estimates for capital and energy prices are negative, while the estimated labour price coefficient is positive. Yet, none of the factor price coefficients is significantly different from zero. In aggregate, transport sector productivity seems to be largely driven by output growth. The impact of output fluctuations is highly significant, and considerably higher than in the industry sector. Interestingly, the constant is also highly significant and positive. This could hint at 'exogenous' productivity regress in the transport sector. Alternatively, the constant might capture the contribution of some omitted variable, or wrongly estimated to be significant due to present serial correlation. Further investigation would require valid inference through a bootstrap as proposed by Simar and Wilson (2007).

Rising energy prices are significantly contributing to productivity gains only Austria, Spain and Italy. However, compared to results for the industry sector, energy prices seem to have a stronger effect in the transport sector. On the other hand, energy prices do not significantly affect technical progress in the transport sectors of large economies like the United States, Japan, Germany and the United Kingdom. Although capital prices do not have a significant effect on productivity in aggregate, productivity growth in Finland, Italy, and Japan is found to be significantly supported by rising capital prices. With the exception of Spain and the Netherlands labour prices were not found to have significant impact on technical change. For Spain, estimations would suggest a 0.3 percentage point regress in productivity for each percent that the price of labour increases. This finding is counter-intuitive, as it is unclear how increasing labour prices induce regress in technical change. However, the high significance of the labour price impact might be attributable to serial correlation that impairs inference. As serial correlation is present in all regressions, the results presented in table 4 and 5 should be interpreted cautiously.

Overall, results from the regressions confirm the findings in section 4.2, which were based on the analysis of chi-plots. Among factor prices, the price of capital seems to be most closely connected to productivity changes. However, the effect of factor price changes is dwarfed by the effect of output fluctuations, which is estimated to be almost six times as high in the industry sector and more than 30 times as high in the transport sector.

The findings are also in line with results from Kumar and Managi (2009), who, to the best of my knowledge, contributed the only study of energy price effects on productivity in the literature on productivity analysis. Their parametric stochastic frontier analysis is based on data on the capital stock, labour use, and energy consumption of 80 countries over the period 1971-2000, and also incorporates CO_2 and SO_2 emissions as undesired output. The price of oil is used to approximate global energy prices, while other factor prices are not taken into consideration. In this framework Kumar and Managi (2009) estimate technical change between 1971 and 2000 at around 0.9% per year in developed countries, which is in line with my findings. Technical change is found to progress at about half this rate in developing countries. With respect to price effects on technical change, Kumar and Managi find in aggregate no effect of energy prices on technical change. However, technical change, in particular in developed economies, is found to progress faster in times of high oil prices (and slower in times of low prices). In 1979 and 1980, price-induced technical change is estimated at around 1.2% per year in developed economies, while between 1986-1988 regress in technical change of up to about 1.4% per year was induced by plummeting oil prices. Kumar and Managi's finding of no significant energy price effect on technical progress in aggregate can be cautiously confirmed by my findings, in particular when output variations are taken into account. The finding appears to be relatively robust, as it seems independent of the underlying methodology and data. Kumar and Managi analyse the energy price effect at the total economy level, using benchmark oil prices as a proxy of energy prices, while I use country and sector-specific end-user prices of energy. For the eleven OECD countries included in my sample the correlation between the annual average spot price of European benchmark crude oil grade Brent and energy end-user prices is 0.17 for the transport sector and 0.41 for the industry sector over the years from 1987-2007. The relatively low correlations between benchmark crude oil prices and end-user energy prices are largely due to the effect of taxes and subsides on energy prices, but also due to the existence of alternative energy sources that serve as substitutes to oil and keep end-user prices more stable than oil prices.

Overall, the findings on the linkage between factor prices, output growth, and productivity are not very supportive for policies that seek to reduce energy consumption by raising energy prices. I find no significant impact of the energy price on technical progress, neither using chi-plots, nor in regression analysis. This suggests that increases in the energy price would affect energy consumption exclusively through their allocative effect. Hence, increasing energy prices up to a level where negative externalities are internalised would be a sensible policy to reduce overconsumption and restore economic efficiency. However, such policies are unlikely to reduce energy consumption permanently and on the required scale, as the main driver of energy consumption is economic growth which is unlikely to halt, while allocative adjustments come to a stand-still once factor use is aligned with relative factor prices.

Among factor prices, the price of capital seems to be most likely to prove effective in promoting technical progress. However, the impact of the capital price on technical progress is significant only in the industry sector, and its impact on productivity is relatively small, requiring increases of more than 10% to raise productivity by one percent. Moreover, the price of capital is positively related to productivity gains, implying that productivity grows fastest when capital prices are high. While high capital prices should provide an incentive to reduce factor use through increased productivity, the causality might also be reverse. Capital prices should be responsive to monetary policy, and Central Bankers typically raise key interest rates at the height of the business cycle while they lower rates in times of recession. However, business cycle effects should be controlled for by including output growth in the estimated regressions. Investigating the direction of causality, for example through Granger causality tests in a bootstrapped model, could shed further light on this issue. This is also relevant as causality running from economic growth to productivity growth might be caused by rigidities in factor demand, leading to less than proportional adjustments of factor demand to output fluctuations during the business cycle. In effect, productivity gains would be underestimated when output contracts, and overestimated when output expands. This could adversely affect efficiency and productivity estimates obtained from datasets that cover only a small number of years, and should be considered in respective studies.

In the estimated regressions, output growth is the most influential variable. However, policies aiming to reduce energy consumption through promoting economic growth would be counterproductive, as output growth is estimated to increase productivity less than proportional (as estimated coefficients are smaller than one in absolute values). In effect, energy consumption increases along with output.

5 Conclusions

Containing global warming induced by excessive emission of greenhouse gases is a major challenge to humanity. Emissions of CO_2 (a top contributor to global warming) are directly linked to the consumption of fossil fuels, which still make up around 80% of global energy consumption, according to the International Energy Agency (2011). Energy consumption, in turn, is strongly linked to economic growth. Over the past 30 years the industry and transport sector of the eleven economies under consideration expanded on average by around 2.5% per year. Generally greenhouse gas emissions should grow in line with energy consumption as long as the share of carbon-intense energy sources in total energy supply remains constant.

To limit global warming to 2°C the International Energy Agency (2011) estimates that global greenhouse gas emissions, which stood at 30.4 Gt in 2010, would have to be reduced to 21.6 Gt by 2035. This implies the need for annual reductions in greenhouse gas emissions of almost 1.4%, bringing the total required annual reduction in greenhouse gas emissions to approximately 3.9%.

Meeting the required emission reductions through energy savings will be challenging, given that technical progress is estimated at around 0.9% and 1.2% per year. Under these conditions greenhouse gas emissions would have to be reduced by between 2.7% and 3.0% per year to limit global warming to 2°C. In theory such reductions could be realised through improved allocative efficiency. However, achieving an annual emission reduction of at least 2.7% up to 2035 through allocative effects seems extremely difficult. Historically allocative efficiency gains raised productivity on average by around 0.6% to 0.8% per year, although much higher gains were achieved in some years. However, achieving higher and persistent productivity gains through allocative effects would require energy prices to increase substantially and also persistently, as allocative efficiency gains come to a stand-still once factor use is aligned with relative factor prices. My findings also imply that the effects of increasing energy prices can not be expected to be leveraged through their impact on technical progress, as the impact is, at best, small.

Realising emission reductions of at least 1.9% per year (after accounting for allocative efficiency gains) will require extraordinary efforts to accelerate innovation to promote productivity growth. However, even with significant efforts in this direction it remains questionable whether productivity growth can realistically be more than doubled for a prolonged period of time. Therefore, strong efforts to promote productivity growth should be complemented by a decisive shift away from CO_2-intense energy generation towards CO_2-neutral generation of energy. Otherwise we are likely to lose the fight to contain global warming.

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Appendices

A Abstract

Cost Malmquist productivity indexes proposed by Maniadakis and Thanassoulis (2004) are estimated for the industry and transport sector of eleven OECD countries from 1978-2007. Theoretical foundations of the productivity index and its decomposition into components capturing technical and allocative (price) efficiency are established. The cost Malmquist index and its components are estimated by data envelopment analysis. Technical progress is estimated at 1.2% in the industry sector and 0.9% in the transport sector. Allocative efficiency change is found to contribute on average 0.6 (industry sector) and 0.8 (transport sector) percentage points per year to productivity growth. A non-parametric investigation of the dependence of technical progress on factor prices using chi-plots (Fisher and Switzer, 1985) suggests significant dependence of technical progress on capital prices. Moreover, dependency is found between technical progress and output growth. A regression analysis is conducted to quantify the effects of factor prices and output growth on technical progress. Output growth is found to have the most pronounced effect, while controlling for output growth also reduces impact of factor prices. Overall, no significant effect of energy prices on technical progress is found. However, inference is hindered by complex serial correlation of the estimated productivity indexes (Simar and Wilson, 2007). A bootstrap to allow for valid inference is left to future research.

In total, results obtained in this thesis suggest that changes to factor prices (for example through increased taxation of energy) are unlikely to reduce energy consumption sufficiently to limit global warming to 2°C. Consequently, alternative policies to promote technical progress, but also to substitute carbon-intense with carbon-neutral sources of energy are required.

B Zusammenfassung

Angelehnt an Maniadakis and Thanassoulis (2004) wurden ‘Cost Malmquist’ Produktivitätsindices für den Industrie- und den Transportsektor von elf OECD-Ländern für die Jahre 1978-2007 geschätzt. Die theoretischen Grundlagen des Produktivitätsindex werden erläutert und der Index in Komponenten zur Messung des technischen Fortschritts und der allokativen Effizienz zerlegt. Die nichtparametrische Schätzung des Produktivitätsindexes beruht auf ‘Data Envelopment Analysis’.

Resultate der Schätzung legen nahe, dass technischer Fortschritt die Produktivität im Industriesektor im Mittel der Jahre 1978-2007 um 1.2% pro Jahr steigen ließ. Für den Transportsektor wird die jährliche Produktivitätssteigerung durch technischen Fortschritt auf 0.9% geschätzt. Durch Steigerungen der allokativen Effizienz wird die Produktivität nochmals um geschätzte 0.6 (Industriesektor) beziehungsweise 0.8 (Transportsektor) Prozentpunkte pro Jahr erhöht.

Der Zusammenhang zwischen technischem Fortschritt und Faktorpreisen und Wirtschafwachstum wurde mittels sogenannter Chi-Plots (Fisher and Switzer, 1985) untersucht. Die Analyse legt nahe, dass statistische Abhängigkeit sowohl zwischen Kapitalpreisen und technischem Fortschritt als auch zwischen Wirtschaftswachstum und technischem Fortschritt besteht. Zusätzlich wurde eine Regressionsanalyse durchgeführt, um die Auswirkungen von Faktorpreisänderungen und Wirtschaftswachstum auf den technischen Fortschritt quantifizieren zu können. Die Ergebnisse zeigen, dass Wirtschaftswachstum einen deutlichen, positiven Effekt auf den technischen Fortschritt hat. Faktorpreise haben eine deutlich geringere Auswirkung. Insbesondere ist der Effekt von Änderungen im Energiepreis auf den technischen Fortschritt gering und statistisch nicht signifikant. Bei der Beurteilung muss jedoch berücksichtigt werden, dass die komplexe serielle Korrelation der geschätzten Produktivitätsindices die Ergebnisse statistischer Tests ungültig macht. Zur Durchführung gültiger statistischer Tests schlagen Simar and Wilson (2007) einen Bootstrap der geschätzten Malmquistindices vor.

Insgesamt legen die Ergebnisse nahe, dass Änderungen in (relativen) Faktorpreisen unzureichend sind um den Energiekonsum soweit zu reduzieren, dass die globale Erwärmung auf 2°C begrenzt werden kann. Um dieses Ziel zu erreichen sollte etwa die höhere Besteuerung von Energie durch weitere Maßnahmen zur Innovationsförderung und zur Förderung von CO_2-neutralen Energiequellen ergänzt werden.

C GAMS code for Cost Malmquist Index

```
sets
dmu              decision making units – countries
* j = 1 ... J
                  / AUT  Austria
                    DNK  Denmark
                    FIN  Finland
                    GER  Germany
                    ITA  Italy
                    JPN  Japan
                    NDL  Netherlands
                    ESP  Spain
                    SWE  Sweden
                    GBR  Great Britain
                    USA  United States of America
                  /


time             years
* t = 1 ... T
                 / 1978*2007 /

in               inputs
* n = 1 ... N
                 /
                 CAP  capital
                 LAB  labour
                 NRG  energy
                 /

out              output
* m = 1 ... M
                 /
                 GDP  Real GDP in Euros of 2005
                 /

components / Ct–yt–wt, Ct–yt+1–wt, Ct+1–yt–wt+1, Dt–yt–xt, Dt–yt+1–xt
   +1, Dt+1–yt–xt, wt–xt, wt+1–xt, wt–xt+1 /

decomp / CM, TEC, AEC, TC, PE /
;

Alias(k, dmu);
```

```
Parameter
OutQuant(dmu,time,out)
InQuant(dmu,time,in)
Prices(dmu,time,in)
;

$libinclude xlimport OutQuant 'Data.xls' OutEx!B1:D331
$libinclude xlimport InQuant 'Data.xls' InEx!B1:F331
$libinclude xlimport Prices 'Data.xls' PriceEx!B1:F331

Variables
zeta
c
;

Positive Variables
za(dmu, time, k)
zb(dmu, time, k)
zc(dmu, time, k)
zd(dmu, time, k)
ze(dmu, time, k)
zf(dmu, time, k)
xd(dmu, time, in)
xe(dmu, time, in)
xf(dmu, time, in)
costd(dmu, time)
coste(dmu, time)
costf(dmu, time)
thetaa(dmu,time)
thetab(dmu,time)
thetac(dmu,time)
;

Equations
obja
con1a
con2a
objb
con1b
con2b
objc
con1c
con2c
objd
costcond
```

```
costcone
costconf
con1d
con2d
obje
con1e
con2e
objf
con1f
con2f
;

*---------------Distance Functions----------------------

*--------------------All Current-------------------------
obja..
         Sum((dmu, time), thetaa(dmu,time)) =E= zeta;

con1a(dmu,time,out)..
         Sum(k, za(dmu, time, k) * OutQuant(k, time, out)) =G=
                              OutQuant(dmu, time, out);

con2a(dmu,time,in)..
         Sum(k, za(dmu, time, k) *  InQuant(k, time, in))  =L= thetaa(
            dmu, time) * InQuant(dmu, time, in);

*--------------Current Tech, Next In & Out---------------
objb..
         Sum((dmu, time), thetab(dmu,time)) =E= zeta;

con1b(dmu,time,out)$(Ord(time) < Card(time))..
         Sum(k, zb(dmu, time, k) * OutQuant(k, time, out)) =G=
                              OutQuant(dmu, time+1, out);

con2b(dmu,time,in)$(Ord(time) < Card(time))..
         Sum(k, zb(dmu, time, k) *  InQuant(k, time, in))  =L= thetab(
            dmu, time) * InQuant(dmu, time+1, in);

*---------------Next Tech, Current In & Out--------------
objc..
         Sum((dmu, time), thetac(dmu,time)) =E= zeta;

con1c(dmu,time,out)$(Ord(time) < Card(time))..
         Sum(k, zc(dmu, time, k) * OutQuant(k, time+1, out)) =G=
                              OutQuant(dmu, time, out);
```

```
con2c(dmu,time,in)$(Ord(time) < Card(time))..
         Sum(k, zc(dmu, time, k) *  InQuant(k, time+1, in))  =L= thetac
            (dmu, time) * InQuant(dmu, time, in);


*-----------------------------Cost Functions-----------------------------

*------------------------------All Current-------------------------------
objd..
         Sum((dmu, time), costd(dmu, time) ) =E= c;

costcond(dmu, time)..
         costd(dmu, time) =E= Sum(in, prices(dmu,time,in) * xd(dmu,
            time, in));

con1d(dmu,time,out)..
         Sum(k, zd(dmu, time, k) * OutQuant(k, time, out)) =G= OutQuant
            (dmu, time, out);

con2d(dmu,time,in)..
         Sum(k, zd(dmu, time, k) *  InQuant(k, time, in))  =L= xd(dmu,
            time, in);


*-----------------------Current Cost, Next Out---------------------------
obje..
         Sum((dmu, time), coste(dmu, time)  ) =E= c;

costcone(dmu, time)..
         coste(dmu, time) =E= Sum(in, prices(dmu,time,in) * xe(dmu,time
            ,in));

con1e(dmu,time,out)$(Ord(time) < Card(time))..
         Sum(k, ze(dmu, time, k) * OutQuant(k, time, out)) =G= OutQuant
            (dmu, time+1, out);

con2e(dmu,time,in)$(Ord(time) < Card(time))..
         Sum(k, ze(dmu, time, k) *  InQuant(k, time, in))  =L= xe(dmu,
            time,in);

*-------------------------Next Cost, Current Out--------------------------
objf..
         Sum((dmu, time), costf(dmu, time)  ) =E= c;
```

```
costconf(dmu, time)..
         costf(dmu, time) =E= Sum(in, prices(dmu,time+1,in) * xf(dmu,
            time,in));

con1f(dmu,time,out)$(Ord(time) < Card(time))..
         Sum(k, zf(dmu, time, k) * OutQuant(k, time+1, out)) =G=
            OutQuant(dmu, time, out);

con2f(dmu,time,in)$(Ord(time) < Card(time))..
         Sum(k, zf(dmu, time, k) *  InQuant(k, time+1, in))  =L= xf(dmu
            ,time,in);


Model moda /obja, con1a, con2a  /;
Model modb /objb, con1b, con2b  /;
Model modc /objc, con1c, con2c  /;
Model modd /objd, con1d, con2d, costcond /;
Model mode /obje, con1e, con2e, costcone /;
Model modf /objf, con1f, con2f, costconf /;

Parameter results(dmu,time,components)

Solve moda using LP minimizing zeta;
results(dmu,time,’Dt-yt-xt’) = thetaa.L(dmu,time)**(-1);

Solve modb using LP minimizing zeta;
results(dmu,time,’Dt-yt+1-xt+1’)$(Ord(time) < Card(time)) = thetab.L(
   dmu,time)**(-1);

Solve modc using LP minimizing zeta;
results(dmu,time,’Dt+1-yt-xt’)$(Ord(time) < Card(time)) = thetac.L(dmu,
   time)**(-1);

Solve modd using LP minimizing c;
results(dmu,time,’Ct-yt-wt’) = costd.L(dmu,time);

Solve mode using LP minimizing c;
results(dmu,time,’Ct-yt+1-wt’)$(Ord(time) < Card(time)) = coste.L(dmu,
   time);

Solve modf using LP minimizing c;
results(dmu,time,’Ct+1-yt-wt+1’)$(Ord(time) < Card(time)) = costf.L(dmu
   ,time);
```

```
results(dmu,time,'wt-xt') = Sum(in, prices(dmu,time,in) * InQuant(dmu,
  time,in));
results(dmu,time,'wt+1-xt')$(Ord(time) < Card(time)) = Sum(in, prices(
  dmu,time+1,in) * InQuant(dmu,time,in));
results(dmu,time,'wt-xt+1')$(Ord(time) < Card(time)) = Sum(in, prices(
  dmu,time,in) * InQuant(dmu,time+1,in));

Parameter index(dmu,time,decomp);

index(dmu,time,'CM')$(Ord(time) < Card(time)) =
sqrt(
  results(dmu,time,'Ct-yt-wt') * results(dmu,time,'wt-xt+1') *
    results(dmu,time,'Ct+1-yt-wt+1') * results(dmu,time+1,'wt-xt')
 *
 ( results(dmu,time,'wt-xt') * results(dmu,time,'Ct-yt+1-wt') *
   results(dmu,time,'wt+1-xt') *  results(dmu,time+1,'Ct-yt-wt'))
   **(-1)
);

index(dmu,time,'TEC')$(Ord(time) < Card(time)) =
   results(dmu,time+1,'Dt-yt-xt') * results(dmu,time,'Dt-yt-xt')
     **(-1);

index(dmu,time,'AEC')$(Ord(time) < Card(time)) =
  results(dmu,time+1,'wt-xt') * results(dmu,time,'Ct-yt-wt') *
    results(dmu,time,'Dt-yt-xt')
 *
 ( results(dmu,time,'wt-xt')   * results(dmu,time+1,'Ct-yt-wt') *
   results(dmu,time+1,'Dt-yt-xt') )**(-1);

index(dmu,time,'TC')$(Ord(time) < Card(time)) =
sqrt(
  results(dmu,time,'Dt-yt+1-xt+1') * results(dmu,time,'Dt-yt-xt')
 *
 ( results(dmu,time+1,'Dt-yt-xt')   * results(dmu,time,'Dt+1-yt-xt'))
   **(-1)
);




index(dmu,time,'PE')$(Ord(time) < Card(time)) =
sqrt(
```

```
    results(dmu,time,’wt−xt+1’) * results(dmu,time+1,’Ct−yt−wt’)   *
       results(dmu,time+1,’Dt−yt−xt’)
 *
  ( results(dmu,time+1,’wt−xt’) * results(dmu,time,’Ct−yt+1−wt’)   *
     results(dmu,time,’Dt−yt+1−xt+1’) )**(−1)
 *
   results(dmu,time,’wt−xt’)    * results(dmu,time,’Ct+1−yt−wt+1’) *
      results(dmu,time,’Dt+1−yt−xt’)
 *
  ( results(dmu,time,’wt+1−xt’) * results(dmu,time,’Ct−yt−wt’)     *
     results(dmu,time,’Dt−yt−xt’) )**(−1)
);

$libinclude XLdump index ’index.xls’
```

D Chi-Plots for Assessing Dependence

In probability theory two events are considered independent, if and only if

$$\Pr(A \cap B) = \Pr(A) \Pr(B).$$

Hence, one way to assess dependence of variates is to consider a measure of the degree to which an empirical distribution function fails to factorise into a product of marginal distribution functions. The chi-plots proposed by Fisher and Switzer (1985) use such a measure χ, and plot it against λ, a measure of a tuples' distance from the center of the data. The transformations used to construct χ and λ are

$$\begin{aligned}
F_i &= \sum_{j \neq i} I(d_j \leq d_i)/(n-1) \\
G_i &= \sum_{j \neq i} I(e_j \leq e_i)/(n-1) \\
H_i &= \sum_{j \neq i} I(d_j \leq d_i \wedge e_j \leq e_i)/(n-1)
\end{aligned}$$

where $I(\cdot)$ is the indicator function, such that $I(a) = 1$ if a is true, and $I(a) = 0$ otherwise.

$$\begin{aligned}
\chi_i &= (H_i - F_i\, G_i)/\left(F_i(1-F_i)\, G_i(1-G_i)\right)^{1/2} \\
\lambda_i &= 4 \operatorname{sgn}\left((F_i - \frac{1}{2})(G_i - \frac{1}{2})\right) \max\left\{\left(F_i - \frac{1}{2}\right)^2, \left(G_i - \frac{1}{2}\right)^2\right\}
\end{aligned}$$

Fisher and Switzer (1985) note that "the sampling behaviour of the χ transform of the data will be erratic for those sample points at the edges of the data distribution, and the asymptotic normal theory will be an inappropriate approximation. " They therefore suggest to truncate the data such that points for which

$$|\lambda_i| \geq 4 \left(\frac{1}{n-1} - \frac{1}{2}\right)^2$$

will not be plotted.

E Industry Sector Productivity Indices

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.979	1.004	0.975	0.992	1.012	0.986	0.988
1980	0.975	0.984	0.991	0.912	1.079	0.947	1.046
1981	0.982	0.918	1.070	1.036	0.885	0.933	1.147
1982	0.991	0.956	1.036	1.037	0.922	0.913	1.136
1983	0.974	0.985	0.988	1.082	0.910	0.914	1.082
1984	0.977	0.983	0.994	0.991	0.992	1.028	0.967
1985	0.957	0.962	0.995	1.031	0.933	0.975	1.021
1986	0.998	0.981	1.018	1.025	0.957	0.971	1.048
1987	0.972	0.991	0.981	0.992	0.999	0.971	1.011
1988	0.965	1.001	0.963	1.000	1.002	0.980	0.983
1989	0.967	1.009	0.958	0.988	1.022	0.962	0.996
1990	0.962	0.977	0.985	0.990	0.987	1.005	0.980
1991	0.973	0.997	0.976	0.938	1.063	1.047	0.932
1992	0.980	0.976	1.004	0.968	1.008	0.985	1.019
1993	1.012	1.022	0.990	1.037	0.985	1.006	0.984
1994	0.964	1.004	0.960	1.000	1.003	0.963	0.997
1995	0.960	0.982	0.977	1.006	0.977	0.992	0.985
1996	0.978	1.000	0.977	1.022	0.979	0.976	1.001
1997	0.973	0.981	0.992	1.032	0.951	0.982	1.009
1998	0.958	0.980	0.977	0.954	1.027	0.987	0.990
1999	0.940	0.965	0.974	0.961	1.004	0.980	0.993
2000	0.934	0.964	0.970	0.986	0.978	0.968	1.002
2001	0.972	0.973	0.999	0.985	0.988	0.993	1.006
2002	0.972	0.965	1.008	0.981	0.984	0.987	1.021
2003	0.962	0.965	0.997	0.998	0.967	0.984	1.013
2004	0.955	0.992	0.963	0.999	0.994	0.975	0.988
2005	0.973	0.995	0.978	1.024	0.972	0.977	1.002
2006	0.934	0.966	0.966	0.993	0.974	0.937	1.031
2007	0.961	0.976	0.985	0.937	1.041	1.029	0.957
Geo Mean	0.969	0.981	0.988	0.996	0.985	0.977	1.011
Median	0.972	0.981	0.985	0.993	0.987	0.980	1.002
Std Dev	0.017	0.020	0.024	0.036	0.042	0.030	0.046
Min	0.934	0.918	0.958	0.912	0.885	0.913	0.932
Max	1.012	1.022	1.070	1.082	1.079	1.047	1.147

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 6: Cost-Malmquist-Index – Industry Sector, Austria

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.958	1.011	0.947	0.980	1.032	0.991	0.955
1980	0.988	0.967	1.022	1.011	0.956	0.947	1.079
1981	0.986	0.928	1.063	0.989	0.938	0.977	1.088
1982	0.983	0.939	1.046	1.000	0.939	0.951	1.100
1983	0.973	0.981	0.992	1.000	0.981	0.949	1.045
1984	0.978	0.983	0.995	1.000	0.983	1.005	0.989
1985	0.968	0.973	0.995	1.000	0.973	0.978	1.017
1986	0.973	0.960	1.013	1.000	0.960	0.973	1.041
1987	0.987	1.010	0.977	1.000	1.010	0.991	0.986
1988	0.984	1.015	0.969	1.000	1.015	0.991	0.978
1989	0.981	1.018	0.964	1.000	1.018	0.978	0.986
1990	1.002	1.019	0.983	1.000	1.019	1.009	0.974
1991	0.993	1.014	0.978	1.000	1.014	1.034	0.946
1992	0.995	0.990	1.005	1.000	0.990	0.990	1.015
1993	0.988	0.997	0.992	1.000	0.997	0.999	0.993
1994	0.946	0.984	0.961	1.000	0.984	0.955	1.006
1995	0.994	1.019	0.976	1.000	1.019	0.994	0.982
1996	0.973	0.996	0.977	1.000	0.996	0.973	1.004
1997	0.997	1.004	0.993	1.000	1.004	0.985	1.007
1998	1.005	1.023	0.982	1.000	1.023	0.978	1.004
1999	0.989	1.011	0.978	1.000	1.011	0.988	0.990
2000	0.974	1.000	0.974	1.000	1.000	0.946	1.029
2001	0.993	0.993	1.000	1.000	0.993	1.007	0.993
2002	1.004	0.996	1.008	1.000	0.996	0.973	1.036
2003	0.984	0.984	1.000	1.000	0.984	0.995	1.005
2004	0.976	1.017	0.959	1.000	1.017	0.982	0.976
2005	0.961	0.979	0.982	1.000	0.979	0.952	1.031
2006	0.978	1.011	0.968	1.000	1.011	0.977	0.991
2007	1.030	1.042	0.989	1.000	1.042	0.991	0.998
Geo Mean	0.984	0.995	0.989	0.999	0.996	0.981	1.008
Median	0.984	0.997	0.983	1.000	0.997	0.982	1.004
Std Dev	0.016	0.025	0.025	0.005	0.026	0.021	0.036
Min	0.946	0.928	0.947	0.980	0.938	0.946	0.946
Max	1.030	1.042	1.063	1.011	1.042	1.034	1.100

[a] OEC = TEC × AEC
[b] CTC = TC × PE

Table 7: Cost-Malmquist-Index – Industry Sector, Denmark

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.966	1.021	0.947	1.000	1.021	0.998	0.948
1980	0.988	1.042	0.948	1.000	1.042	1.025	0.925
1981	0.997	0.958	1.040	1.000	0.958	1.049	0.991
1982	1.017	0.991	1.027	1.000	0.991	1.047	0.981
1983	0.989	0.991	0.998	1.000	0.991	1.026	0.973
1984	0.954	0.966	0.987	1.000	0.966	0.976	1.011
1985	0.987	0.979	1.008	1.000	0.979	1.009	0.999
1986	1.060	1.042	1.018	1.000	1.042	1.070	0.951
1987	1.001	1.041	0.962	1.057	0.985	0.960	1.002
1988	0.971	1.001	0.970	1.009	0.992	0.971	0.999
1989	0.942	0.979	0.962	0.967	1.013	0.989	0.973
1990	0.993	1.023	0.970	0.999	1.025	1.019	0.952
1991	1.002	1.052	0.952	1.050	1.002	1.022	0.932
1992	0.992	1.003	0.989	1.016	0.987	0.975	1.015
1993	1.000	1.030	0.970	1.020	1.009	0.989	0.981
1994	0.957	0.990	0.966	1.009	0.982	0.955	1.012
1995	0.963	0.993	0.970	0.985	1.008	0.987	0.983
1996	0.968	0.996	0.972	0.993	1.003	0.985	0.987
1997	0.965	0.969	0.996	0.985	0.984	0.984	1.012
1998	0.970	0.990	0.980	0.975	1.015	0.993	0.987
1999	0.964	0.989	0.975	0.981	1.008	0.988	0.987
2000	0.947	0.979	0.967	0.975	1.004	0.978	0.988
2001	0.977	0.979	0.997	0.984	0.995	1.003	0.995
2002	0.998	0.991	1.007	1.021	0.971	0.997	1.010
2003	0.972	0.976	0.995	1.033	0.945	1.002	0.994
2004	0.962	0.998	0.964	0.995	1.003	0.968	0.996
2005	0.968	0.988	0.980	0.987	1.001	0.992	0.989
2006	0.942	0.971	0.971	0.986	0.984	0.957	1.015
2007	0.957	0.970	0.987	0.979	0.991	0.967	1.020
Geo Mean	0.978	0.996	0.982	1.000	0.996	0.996	0.986
Median	0.971	0.991	0.975	1.000	0.995	0.989	0.989
Std Dev	0.025	0.025	0.023	0.021	0.022	0.028	0.025
Min	0.942	0.958	0.947	0.967	0.945	0.955	0.925
Max	1.060	1.052	1.040	1.057	1.042	1.070	1.020

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 8: Cost-Malmquist-Index – Industry Sector, Finland

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.974	0.972	1.003	0.998	0.974	0.986	1.016
1980	1.003	1.013	0.990	0.975	1.039	0.947	1.046
1981	0.989	0.926	1.068	0.999	0.927	0.933	1.145
1982	1.008	0.963	1.047	1.095	0.879	0.913	1.147
1983	0.997	1.019	0.978	1.064	0.957	0.920	1.063
1984	0.973	0.988	0.985	0.971	1.017	1.030	0.957
1985	0.976	0.978	0.997	0.972	1.006	0.982	1.015
1986	0.987	0.980	1.007	0.981	1.000	0.970	1.038
1987	0.975	0.984	0.990	1.000	0.984	0.976	1.014
1988	0.956	1.008	0.949	0.968	1.041	0.990	0.958
1989	0.970	1.012	0.959	1.011	1.001	0.964	0.994
1990	0.970	0.974	0.996	0.976	0.998	1.018	0.979
1991	1.001	1.034	0.968	0.906	1.141	1.059	0.914
1992	1.036	1.035	1.000	1.011	1.024	0.985	1.015
1993	1.019	1.034	0.986	0.996	1.037	1.006	0.980
1994	1.006	1.049	0.959	1.064	0.986	0.963	0.996
1995	0.980	1.003	0.977	1.008	0.995	0.992	0.984
1996	0.984	1.000	0.984	1.012	0.988	0.976	1.008
1997	0.991	0.999	0.993	1.009	0.990	0.979	1.014
1998	1.021	1.041	0.981	1.019	1.022	0.965	1.016
1999	1.010	1.035	0.976	1.059	0.977	0.987	0.989
2000	0.975	1.004	0.971	1.065	0.943	0.932	1.042
2001	1.006	1.002	1.005	0.965	1.038	1.020	0.985
2002	1.008	1.001	1.007	1.082	0.925	0.952	1.058
2003	0.985	0.991	0.994	0.962	1.030	1.012	0.982
2004	0.975	1.014	0.962	0.990	1.024	0.995	0.967
2005	0.985	0.999	0.986	1.050	0.951	0.945	1.043
2006	0.999	1.032	0.968	1.011	1.020	0.975	0.993
2007	0.981	0.981	1.000	1.001	0.980	0.974	1.027
Geo Mean	0.991	1.002	0.989	1.007	0.995	0.977	1.012
Median	0.987	1.002	0.986	1.001	0.998	0.976	1.014
Std Dev	0.018	0.027	0.025	0.042	0.048	0.033	0.049
Min	0.956	0.926	0.949	0.906	0.879	0.913	0.914
Max	1.036	1.049	1.068	1.095	1.141	1.059	1.147

[a] OEC = TEC × AEC
[b] CTC = TC × PE

Table 9: Cost-Malmquist-Index – Industry Sector, Germany

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.969	1.000	0.969	1.000	1.000	1.003	0.966
1980	0.996	1.000	0.996	1.000	1.000	0.942	1.057
1981	1.068	1.000	1.068	1.000	1.000	1.076	0.993
1982	1.044	1.000	1.044	1.000	1.000	1.043	1.000
1983	0.999	1.000	0.999	1.000	1.000	0.998	1.001
1984	0.996	1.000	0.996	1.000	1.000	0.995	1.001
1985	1.004	1.000	1.004	1.000	1.000	0.999	1.004
1986	1.029	1.000	1.029	1.000	1.000	1.015	1.014
1987	0.985	1.000	0.985	1.000	1.000	0.991	0.994
1988	0.970	1.000	0.970	1.000	1.000	0.951	1.021
1989	0.961	1.000	0.961	1.000	1.000	0.961	1.000
1990	0.985	1.000	0.985	1.000	1.000	0.984	1.002
1991	0.976	1.000	0.976	1.000	1.000	0.980	0.996
1992	1.005	1.000	1.005	1.000	1.000	1.001	1.004
1993	0.991	1.000	0.991	1.000	1.000	0.997	0.994
1994	0.965	1.000	0.965	1.000	1.000	0.959	1.006
1995	0.977	1.000	0.977	1.000	1.000	0.996	0.981
1996	0.977	1.000	0.977	1.000	1.000	0.980	0.998
1997	0.992	1.000	0.992	1.000	1.000	0.985	1.007
1998	0.980	1.000	0.980	1.000	1.000	0.980	1.000
1999	0.979	1.000	0.979	1.000	1.000	0.975	1.004
2000	0.970	1.000	0.970	1.000	1.000	0.981	0.989
2001	0.999	1.000	0.999	1.000	1.000	0.995	1.004
2002	1.009	1.000	1.009	1.000	1.000	1.010	0.999
2003	0.998	1.000	0.998	1.000	1.000	0.998	1.000
2004	0.962	1.000	0.962	1.000	1.000	0.964	0.998
2005	0.978	1.000	0.978	1.000	1.000	0.983	0.995
2006	0.968	1.000	0.968	1.000	1.000	0.946	1.022
2007	0.985	1.000	0.985	1.000	1.000	1.006	0.979
Geo Mean	0.990	1.000	0.990	1.000	1.000	0.989	1.001
Median	0.985	1.000	0.985	1.000	1.000	0.991	1.000
Std Dev	0.024	0.000	0.024	0.000	0.000	0.027	0.016
Min	0.961	1.000	0.961	1.000	1.000	0.942	0.966
Max	1.068	1.000	1.068	1.000	1.000	1.076	1.057

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 10: Cost-Malmquist-Index – Industry Sector, Italy

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	1.002	1.052	0.953	1.037	1.014	0.986	0.966
1980	1.030	1.031	0.999	1.092	0.944	0.947	1.054
1981	0.946	0.892	1.061	1.009	0.883	0.985	1.076
1982	0.973	0.932	1.043	0.975	0.956	0.977	1.068
1983	0.971	0.961	1.010	1.019	0.943	0.987	1.024
1984	0.926	0.931	0.995	0.985	0.945	0.982	1.014
1985	0.957	0.955	1.002	0.997	0.958	0.981	1.021
1986	1.054	1.010	1.043	1.049	0.962	0.985	1.059
1987	0.993	1.005	0.988	0.982	1.024	1.007	0.982
1988	0.967	1.001	0.966	0.979	1.022	0.995	0.971
1989	0.984	1.028	0.957	0.998	1.030	0.983	0.974
1990	0.998	1.024	0.975	0.990	1.034	1.010	0.965
1991	0.973	1.005	0.969	0.964	1.042	1.028	0.942
1992	0.997	1.002	0.995	1.020	0.983	0.977	1.018
1993	1.010	1.021	0.990	1.029	0.992	0.995	0.995
1994	0.935	0.965	0.969	1.013	0.953	0.957	1.012
1995	1.006	1.024	0.982	1.013	1.011	0.992	0.990
1996	1.019	1.042	0.977	0.994	1.049	0.986	0.991
1997	1.005	1.012	0.993	1.049	0.965	0.983	1.010
1998	0.999	1.019	0.980	1.000	1.020	0.993	0.987
1999	0.988	1.010	0.978	0.965	1.047	0.996	0.983
2000	0.986	1.009	0.978	1.048	0.962	0.980	0.998
2001	0.978	0.978	1.000	0.982	0.996	1.008	0.992
2002	0.975	0.963	1.013	0.984	0.978	0.990	1.023
2003	0.988	0.988	1.000	1.012	0.975	0.998	1.002
2004	0.993	1.028	0.966	1.039	0.990	0.958	1.008
2005	0.998	1.012	0.986	0.994	1.018	1.003	0.983
2006	0.972	1.007	0.965	0.871	1.157	0.987	0.978
2007	1.003	1.018	0.985	1.078	0.944	0.967	1.018
Geo Mean	0.987	0.997	0.990	1.005	0.992	0.987	1.003
Median	0.988	1.009	0.986	1.000	0.990	0.986	0.998
Std Dev	0.027	0.037	0.025	0.041	0.050	0.017	0.032
Min	0.926	0.892	0.953	0.871	0.883	0.947	0.942
Max	1.054	1.052	1.061	1.092	1.157	1.028	1.076

[a] OEC = TEC × AEC
[b] CTC = TC × PE

Table 11: Cost-Malmquist-Index – Industry Sector, Japan

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.948	0.936	1.013	1.000	0.936	1.018	0.995
1980	1.012	1.016	0.997	1.010	1.006	1.090	0.914
1981	1.021	1.001	1.021	1.052	0.951	1.053	0.969
1982	0.983	0.924	1.064	0.995	0.929	1.058	1.006
1983	0.963	0.943	1.021	1.009	0.935	1.011	1.011
1984	0.957	0.951	1.006	0.999	0.952	0.976	1.031
1985	0.994	1.005	0.989	1.017	0.989	1.003	0.985
1986	0.993	0.955	1.040	0.960	0.995	1.063	0.979
1987	0.994	1.015	0.979	1.050	0.967	0.970	1.009
1988	1.013	1.057	0.958	1.077	0.981	0.972	0.986
1989	1.004	1.059	0.948	1.077	0.983	0.978	0.970
1990	1.026	1.050	0.977	1.088	0.964	0.996	0.981
1991	1.018	1.053	0.967	1.112	0.946	0.991	0.975
1992	0.971	0.966	1.006	1.016	0.951	1.003	1.002
1993	0.968	0.980	0.989	0.992	0.988	0.990	0.999
1994	0.932	0.966	0.965	0.970	0.995	0.962	1.003
1995	0.966	0.987	0.979	0.988	0.999	0.973	1.006
1996	0.997	1.021	0.976	1.022	0.999	0.976	1.000
1997	0.955	0.962	0.993	0.947	1.015	0.992	1.001
1998	0.972	0.992	0.980	0.990	1.002	0.977	1.003
1999	0.964	0.986	0.977	0.983	1.004	0.977	1.000
2000	0.947	0.975	0.971	0.972	1.003	0.967	1.004
2001	1.007	1.008	0.999	1.011	0.998	1.000	0.999
2002	0.984	0.976	1.007	0.969	1.008	0.999	1.009
2003	0.979	0.984	0.995	0.982	1.002	0.982	1.013
2004	0.951	0.992	0.958	0.991	1.001	0.952	1.007
2005	0.974	0.997	0.977	0.995	1.002	0.972	1.005
2006	0.970	1.003	0.967	0.976	1.028	0.982	0.984
2007	1.003	1.016	0.986	1.026	0.991	0.975	1.012
Geo Mean	0.981	0.992	0.989	1.009	0.983	0.994	0.995
Median	0.979	0.992	0.986	0.999	0.995	0.982	1.001
Std Dev	0.025	0.035	0.026	0.040	0.027	0.033	0.021
Min	0.932	0.924	0.948	0.947	0.929	0.952	0.914
Max	1.026	1.059	1.064	1.112	1.028	1.090	1.031

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 12: Cost-Malmquist-Index – Industry Sector, Netherlands

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.952	0.973	0.978	0.955	1.019	0.992	0.986
1980	0.973	0.992	0.981	0.970	1.022	0.997	0.984
1981	0.989	0.941	1.051	0.949	0.991	1.061	0.990
1982	0.989	0.956	1.035	0.959	0.997	1.057	0.979
1983	0.959	0.956	1.003	0.966	0.990	1.013	0.991
1984	1.012	1.019	0.993	1.001	1.018	0.987	1.007
1985	0.954	0.965	0.989	0.969	0.996	1.010	0.979
1986	0.976	0.942	1.036	0.945	0.996	1.052	0.985
1987	0.966	0.977	0.989	0.998	0.978	0.977	1.012
1988	0.966	0.993	0.973	0.996	0.996	0.972	1.001
1989	0.972	1.014	0.959	1.003	1.010	0.976	0.983
1990	0.975	1.004	0.971	1.013	0.991	0.996	0.975
1991	1.010	1.052	0.960	1.101	0.956	0.992	0.968
1992	0.936	0.931	1.006	0.993	0.937	1.003	1.003
1993	0.935	0.948	0.987	0.947	1.001	0.992	0.995
1994	0.926	0.947	0.979	0.942	1.005	0.971	1.008
1995	0.975	0.993	0.982	1.003	0.991	0.973	1.009
1996	0.974	1.003	0.971	0.998	1.005	0.981	0.990
1997	0.964	0.970	0.993	0.953	1.019	0.996	0.997
1998	0.954	0.968	0.986	0.959	1.009	0.989	0.998
1999	0.959	0.979	0.980	0.971	1.008	0.985	0.995
2000	0.932	0.960	0.971	0.956	1.004	0.971	1.000
2001	1.004	1.004	1.000	1.014	0.990	1.004	0.996
2002	0.990	0.982	1.008	0.976	1.006	1.019	0.989
2003	0.993	1.004	0.989	0.990	1.014	1.012	0.978
2004	0.957	0.995	0.962	0.990	1.005	0.969	0.992
2005	0.965	0.990	0.975	0.990	1.000	0.987	0.988
2006	0.949	0.977	0.971	0.959	1.018	0.974	0.997
2007	0.965	0.973	0.992	0.996	0.977	0.979	1.013
Geo Mean	0.968	0.979	0.988	0.981	0.998	0.996	0.993
Median	0.966	0.977	0.986	0.976	1.001	0.992	0.992
Std Dev	0.022	0.027	0.022	0.032	0.019	0.025	0.011
Min	0.926	0.931	0.959	0.942	0.937	0.969	0.968
Max	1.012	1.052	1.051	1.101	1.022	1.061	1.013

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 13: Cost-Malmquist-Index – Industry Sector, Spain

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	1.054	1.095	0.962	1.000	1.095	1.083	0.888
1980	1.035	1.083	0.956	1.000	1.083	0.990	0.966
1981	1.028	0.991	1.037	1.000	0.991	1.084	0.956
1982	0.972	0.919	1.058	1.000	0.919	1.005	1.053
1983	0.956	0.933	1.024	1.000	0.933	0.970	1.056
1984	0.992	1.001	0.991	1.000	1.001	0.990	1.001
1985	0.967	0.960	1.007	1.000	0.960	0.977	1.031
1986	0.972	0.940	1.034	1.000	0.940	0.982	1.053
1987	0.947	0.952	0.996	1.000	0.952	0.952	1.045
1988	0.975	1.013	0.963	1.000	1.013	0.963	1.000
1989	0.993	1.055	0.942	1.000	1.055	0.966	0.975
1990	1.017	1.030	0.987	1.000	1.030	1.034	0.954
1991	0.980	1.044	0.939	1.000	1.044	1.051	0.893
1992	0.941	0.938	1.003	1.000	0.938	0.989	1.014
1993	0.960	0.951	1.010	1.000	0.951	0.988	1.022
1994	0.950	0.968	0.981	1.000	0.968	0.955	1.028
1995	0.989	1.009	0.981	1.000	1.009	0.980	1.000
1996	0.979	0.985	0.994	1.000	0.985	0.993	1.001
1997	0.984	1.008	0.976	1.000	1.008	0.988	0.988
1998	1.009	1.044	0.967	1.000	1.044	1.002	0.965
1999	0.970	1.003	0.967	1.000	1.003	1.000	0.967
2000	0.982	1.031	0.952	1.000	1.031	0.994	0.958
2001	1.001	1.006	0.995	1.000	1.006	1.019	0.977
2002	0.984	0.985	0.998	1.000	0.985	1.000	0.998
2003	0.982	0.981	1.001	1.000	0.981	0.999	1.002
2004	0.963	1.004	0.959	1.000	1.004	0.957	1.001
2005	0.995	1.019	0.977	1.000	1.019	1.017	0.961
2006	1.002	1.034	0.969	1.000	1.034	0.999	0.970
2007	0.978	1.006	0.972	1.000	1.006	0.973	0.998
Geo Mean	0.984	0.999	0.986	1.000	0.999	0.996	0.990
Median	0.982	1.004	0.981	1.000	1.004	0.990	0.998
Std Dev	0.026	0.044	0.029	0.000	0.044	0.033	0.041
Min	0.941	0.919	0.939	1.000	0.919	0.952	0.888
Max	1.054	1.095	1.058	1.000	1.095	1.084	1.056

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 14: Cost-Malmquist-Index – Industry Sector, Sweden

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.959	0.997	0.963	0.998	0.999	0.986	0.976
1980	0.975	0.967	1.008	0.997	0.970	0.947	1.065
1981	0.986	0.929	1.062	1.003	0.926	0.933	1.138
1982	0.994	0.956	1.040	1.031	0.927	0.917	1.134
1983	0.971	0.977	0.993	1.044	0.936	0.922	1.077
1984	0.920	0.924	0.996	0.937	0.986	1.013	0.983
1985	0.976	0.978	0.998	0.983	0.994	0.981	1.017
1986	0.992	0.975	1.018	0.991	0.984	0.970	1.049
1987	0.970	0.984	0.986	1.036	0.950	0.976	1.010
1988	0.953	0.985	0.968	0.991	0.994	0.982	0.986
1989	0.960	1.002	0.958	0.991	1.011	0.983	0.975
1990	0.998	1.010	0.988	0.982	1.029	1.015	0.973
1991	1.008	1.033	0.976	0.943	1.095	1.053	0.927
1992	0.974	0.968	1.006	0.992	0.976	0.986	1.020
1993	1.010	1.013	0.997	1.002	1.011	1.006	0.991
1994	0.944	0.981	0.963	1.020	0.961	0.963	1.000
1995	0.937	0.952	0.985	0.970	0.981	0.992	0.992
1996	1.005	1.029	0.976	1.014	1.015	0.976	1.000
1997	0.975	0.985	0.990	1.017	0.969	0.979	1.011
1998	0.991	1.013	0.979	1.011	1.002	0.978	1.001
1999	0.988	1.010	0.978	1.016	0.994	0.989	0.990
2000	0.978	0.999	0.979	1.023	0.976	0.964	1.016
2001	1.006	1.005	1.001	0.998	1.008	0.996	1.005
2002	1.006	0.997	1.009	1.010	0.988	0.992	1.017
2003	1.014	1.011	1.003	1.027	0.985	1.004	0.999
2004	0.995	1.033	0.963	1.012	1.020	0.979	0.984
2005	1.002	1.013	0.989	1.031	0.983	0.969	1.021
2006	0.992	1.033	0.961	0.992	1.042	0.983	0.978
2007	0.992	0.997	0.995	0.991	1.006	0.986	1.009
Geo Mean	0.982	0.991	0.990	1.001	0.990	0.980	1.011
Median	0.988	0.997	0.989	1.002	0.988	0.982	1.001
Std Dev	0.023	0.029	0.023	0.025	0.035	0.027	0.045
Min	0.920	0.924	0.958	0.937	0.926	0.917	0.927
Max	1.014	1.033	1.062	1.044	1.095	1.053	1.138

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 15: Cost-Malmquist-Index – Industry Sector, United Kingdom

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	1.013	1.055	0.960	1.037	1.017	0.977	0.982
1980	1.038	1.050	0.989	1.060	0.991	1.014	0.975
1981	1.017	0.965	1.054	0.970	0.995	1.073	0.981
1982	0.998	0.967	1.031	0.998	0.970	1.062	0.971
1983	0.975	0.983	0.992	0.973	1.010	1.015	0.978
1984	0.973	0.979	0.993	0.955	1.026	0.996	0.997
1985	0.994	0.999	0.996	0.994	1.005	1.016	0.980
1986	0.991	0.954	1.039	0.960	0.993	1.043	0.996
1987	0.958	0.965	0.993	0.971	0.993	0.983	1.010
1988	0.980	1.006	0.974	1.002	1.004	0.972	1.002
1989	0.990	1.030	0.961	1.028	1.002	0.972	0.988
1990	0.995	1.004	0.991	1.019	0.985	0.991	1.000
1991	1.000	1.028	0.973	1.035	0.993	0.990	0.982
1992	0.957	0.951	1.006	0.967	0.983	1.003	1.004
1993	0.985	0.996	0.989	0.977	1.019	1.006	0.983
1994	0.968	0.999	0.969	0.999	1.000	0.965	1.004
1995	0.975	0.995	0.980	1.004	0.990	0.977	1.003
1996	0.976	0.999	0.977	1.000	1.000	0.982	0.995
1997	0.968	0.979	0.989	0.972	1.007	0.995	0.993
1998	0.987	1.009	0.978	0.996	1.013	0.994	0.984
1999	0.975	0.998	0.977	0.997	1.001	0.986	0.991
2000	0.996	1.038	0.960	1.023	1.014	0.974	0.985
2001	1.005	1.009	0.996	1.044	0.967	1.005	0.990
2002	0.973	0.966	1.007	0.997	0.969	1.019	0.988
2003	0.978	0.981	0.997	0.988	0.993	1.012	0.985
2004	0.986	1.023	0.963	1.018	1.005	0.969	0.994
2005	0.968	0.988	0.980	0.968	1.021	0.990	0.990
2006	1.017	1.048	0.970	1.089	0.962	0.941	1.031
2007	1.023	1.040	0.983	1.016	1.025	1.014	0.970
Geo Mean	0.988	1.000	0.988	1.002	0.998	0.998	0.991
Median	0.986	0.999	0.989	0.998	1.000	0.994	0.990
Std Dev	0.020	0.029	0.023	0.032	0.017	0.028	0.013
Min	0.957	0.951	0.960	0.955	0.962	0.941	0.970
Max	1.038	1.055	1.054	1.089	1.026	1.073	1.031

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 16: Cost-Malmquist-Index – Industry Sector, USA

F Transport Sector Productivity Indices

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.974	1.064	0.916	1.038	1.024	0.945	0.969
1980	0.938	0.953	0.983	0.916	1.041	0.982	1.001
1981	0.986	0.997	0.988	1.032	0.966	0.932	1.060
1982	0.970	0.971	0.998	0.977	0.994	0.982	1.016
1983	0.975	0.937	1.040	0.958	0.978	1.034	1.006
1984	0.939	0.924	1.016	0.887	1.042	1.044	0.974
1985	0.972	0.932	1.044	0.863	1.080	1.129	0.925
1986	1.015	1.032	0.984	1.023	1.009	1.002	0.983
1987	0.976	1.049	0.931	1.075	0.976	0.927	1.004
1988	0.973	1.066	0.912	1.077	0.989	0.924	0.988
1989	0.981	1.024	0.958	1.016	1.008	0.967	0.991
1990	0.974	1.018	0.956	1.087	0.936	0.906	1.055
1991	1.018	1.006	1.012	1.025	0.981	1.040	0.973
1992	0.934	0.928	1.006	0.932	0.995	0.992	1.014
1993	0.991	0.990	1.001	0.974	1.016	1.015	0.986
1994	0.999	1.075	0.930	1.036	1.037	0.950	0.979
1995	1.039	1.066	0.975	1.086	0.982	0.961	1.014
1996	1.012	1.038	0.976	1.101	0.942	0.970	1.006
1997	0.927	0.949	0.976	0.929	1.022	0.968	1.008
1998	0.977	0.976	1.001	1.018	0.959	0.998	1.003
1999	0.964	1.003	0.961	0.998	1.005	0.972	0.989
2000	0.986	1.099	0.898	1.082	1.016	0.912	0.984
2001	1.031	1.035	0.996	1.003	1.032	1.012	0.985
2002	0.995	0.979	1.016	0.942	1.039	1.036	0.981
2003	1.009	1.029	0.980	1.013	1.016	0.985	0.995
2004	0.949	0.941	1.008	0.963	0.977	1.007	1.001
2005	0.959	1.042	0.920	1.028	1.014	0.939	0.980
2006	0.939	1.070	0.877	1.075	0.995	0.897	0.979
2007	0.990	0.987	1.003	0.994	0.993	0.994	1.009
Geo Mean	0.979	1.005	0.974	1.003	1.002	0.979	0.995
Median	0.976	1.006	0.983	1.016	1.005	0.982	0.991
Std Dev	0.029	0.051	0.042	0.063	0.032	0.050	0.025
Min	0.927	0.924	0.877	0.863	0.936	0.897	0.925
Max	1.039	1.099	1.044	1.101	1.080	1.129	1.060

[a] OEC = TEC × AEC
[b] CTC = TC × PE

Table 17: Cost-Malmquist-Index – Transport Sector, Austria

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.945	1.018	0.928	1.000	1.018	0.946	0.981
1980	1.006	1.006	1.000	1.000	1.006	0.985	1.015
1981	0.944	0.957	0.986	1.000	0.957	0.939	1.051
1982	0.983	0.981	1.001	1.000	0.981	0.984	1.018
1983	1.035	0.972	1.065	1.000	0.972	1.035	1.029
1984	1.007	1.000	1.007	1.000	1.000	1.023	0.985
1985	1.049	1.037	1.012	1.000	1.037	1.075	0.942
1986	0.985	0.979	1.005	1.000	0.979	1.002	1.004
1987	0.933	0.989	0.944	1.000	0.989	0.935	1.009
1988	0.920	0.996	0.924	1.000	0.996	0.926	0.997
1989	0.957	1.000	0.957	1.000	1.000	0.960	0.997
1990	0.973	1.000	0.973	1.000	1.000	0.952	1.022
1991	1.014	1.000	1.014	1.000	1.000	1.014	1.001
1992	1.012	1.000	1.012	1.000	1.000	1.003	1.009
1993	0.996	1.000	0.996	1.000	1.000	0.995	1.001
1994	0.927	1.000	0.927	1.000	1.000	0.930	0.997
1995	0.969	1.000	0.969	1.000	1.000	0.972	0.997
1996	0.981	1.000	0.981	1.000	1.000	0.984	0.997
1997	0.980	1.000	0.980	1.000	1.000	0.978	1.001
1998	1.005	1.000	1.005	1.000	1.000	1.000	1.005
1999	0.963	1.000	0.963	1.000	1.000	0.961	1.002
2000	0.899	1.000	0.899	1.000	1.000	0.892	1.008
2001	0.998	1.000	0.998	1.000	1.000	0.998	1.000
2002	1.017	1.000	1.017	1.000	1.000	1.017	1.000
2003	0.980	1.000	0.980	1.000	1.000	0.978	1.002
2004	1.012	1.000	1.012	1.000	1.000	1.010	1.003
2005	0.929	1.000	0.929	1.000	1.000	0.927	1.003
2006	0.882	1.000	0.882	1.000	1.000	0.880	1.003
2007	0.998	1.000	0.998	1.000	1.000	0.998	1.000
Geo Mean	0.975	0.998	0.977	1.000	0.998	0.975	1.002
Median	0.981	1.000	0.986	1.000	1.000	0.984	1.002
Std Dev	0.040	0.014	0.041	0.000	0.014	0.043	0.017
Min	0.882	0.957	0.882	1.000	0.957	0.880	0.942
Max	1.049	1.037	1.065	1.000	1.037	1.075	1.051

[a] OEC = TEC × AEC
[b] CTC = TC × PE

Table 18: Cost-Malmquist-Index – Transport Sector, Denmark

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.939	1.019	0.921	1.009	1.010	0.936	0.985
1980	0.926	0.949	0.975	0.923	1.029	1.020	0.956
1981	0.959	0.978	0.980	0.994	0.984	1.005	0.976
1982	1.006	1.012	0.995	1.020	0.992	1.008	0.987
1983	0.991	0.950	1.043	0.917	1.036	1.097	0.951
1984	0.973	0.952	1.022	0.960	0.992	1.016	1.006
1985	0.957	0.920	1.040	0.987	0.933	0.982	1.059
1986	1.051	1.047	1.004	1.060	0.988	0.978	1.026
1987	0.996	1.065	0.935	1.053	1.011	0.939	0.996
1988	0.967	1.047	0.924	1.009	1.038	0.952	0.970
1989	0.962	0.998	0.964	0.954	1.046	1.013	0.952
1990	0.941	0.980	0.960	0.980	1.001	0.952	1.009
1991	0.974	0.973	1.002	1.000	0.973	1.040	0.963
1992	0.979	0.991	0.987	1.011	0.980	1.012	0.976
1993	0.986	0.995	0.992	0.976	1.019	1.037	0.956
1994	0.934	1.001	0.933	1.009	0.992	0.962	0.970
1995	0.952	0.973	0.978	0.998	0.975	0.971	1.007
1996	0.978	1.006	0.972	1.004	1.003	0.985	0.987
1997	0.971	0.976	0.995	1.030	0.948	0.954	1.044
1998	0.990	0.982	1.009	1.004	0.978	0.991	1.018
1999	0.949	0.988	0.961	0.945	1.045	1.007	0.954
2000	0.951	1.066	0.892	1.028	1.038	0.949	0.940
2001	0.997	0.995	1.002	1.001	0.994	1.017	0.985
2002	1.003	0.986	1.017	0.982	1.005	1.040	0.977
2003	0.990	1.018	0.972	1.024	0.994	0.998	0.974
2004	0.971	0.951	1.021	0.994	0.957	0.984	1.038
2005	0.938	1.007	0.931	0.989	1.019	0.977	0.953
2006	0.947	1.071	0.884	1.033	1.037	0.938	0.942
2007	0.924	0.920	1.004	0.968	0.951	0.997	1.007
Geo Mean	0.969	0.993	0.976	0.995	0.998	0.991	0.984
Median	0.971	0.991	0.980	1.000	0.994	0.991	0.977
Std Dev	0.028	0.040	0.041	0.034	0.030	0.037	0.031
Min	0.924	0.920	0.884	0.917	0.933	0.936	0.940
Max	1.051	1.071	1.043	1.060	1.046	1.097	1.059

[a] OEC = TEC × AEC
[b] CTC = TC × PE

Table 19: Cost-Malmquist-Index – Transport Sector, Finland

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	1.016	1.081	0.940	1.086	0.995	0.945	0.995
1980	0.974	0.982	0.992	0.995	0.987	0.982	1.010
1981	0.980	1.021	0.959	1.042	0.980	0.932	1.029
1982	1.004	1.011	0.992	0.993	1.018	0.982	1.010
1983	0.988	0.967	1.022	0.957	1.011	1.034	0.988
1984	0.958	0.951	1.008	0.929	1.024	1.044	0.966
1985	0.981	0.931	1.053	0.865	1.076	1.129	0.933
1986	1.032	1.119	0.922	1.032	1.084	1.002	0.921
1987	0.989	1.080	0.917	1.082	0.997	0.927	0.989
1988	0.962	1.083	0.889	1.063	1.019	0.924	0.962
1989	0.972	1.002	0.970	1.029	0.974	0.967	1.003
1990	1.010	1.052	0.960	1.161	0.906	0.906	1.059
1991	0.979	0.965	1.014	0.972	0.993	1.040	0.975
1992	1.011	1.008	1.003	1.022	0.987	0.992	1.010
1993	1.003	1.003	1.001	0.994	1.009	1.015	0.986
1994	0.988	1.062	0.930	1.073	0.990	0.950	0.979
1995	0.998	1.053	0.948	1.044	1.009	0.961	0.986
1996	1.072	1.099	0.975	1.102	0.998	0.970	1.005
1997	0.986	1.012	0.974	1.036	0.977	0.968	1.006
1998	1.009	1.015	0.994	1.038	0.978	0.984	1.011
1999	1.018	1.059	0.962	1.082	0.978	0.948	1.014
2000	1.007	1.121	0.898	1.152	0.973	0.868	1.035
2001	1.000	1.009	0.992	1.036	0.973	0.986	1.006
2002	0.982	0.975	1.006	0.965	1.011	1.017	0.990
2003	0.996	1.018	0.979	0.977	1.042	0.998	0.980
2004	0.981	0.970	1.012	0.954	1.017	1.031	0.981
2005	0.975	1.046	0.932	1.043	1.003	0.937	0.994
2006	0.987	1.114	0.886	1.078	1.034	0.888	0.997
2007	0.972	0.996	0.977	0.957	1.041	0.997	0.980
Geo Mean	0.994	1.026	0.968	1.024	1.002	0.975	0.993
Median	0.988	1.015	0.975	1.036	0.998	0.982	0.994
Std Dev	0.023	0.052	0.042	0.065	0.034	0.053	0.028
Min	0.958	0.931	0.886	0.865	0.906	0.868	0.921
Max	1.072	1.121	1.053	1.161	1.084	1.129	1.059

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 20: Cost-Malmquist-Index – Transport Sector, Germany

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.957	1.035	0.925	1.025	1.009	0.924	1.001
1980	0.977	0.988	0.989	1.008	0.980	0.973	1.016
1981	0.988	1.004	0.984	0.995	1.009	0.987	0.997
1982	1.036	1.037	0.999	1.046	0.991	0.999	1.000
1983	1.043	0.976	1.069	0.944	1.034	1.076	0.993
1984	0.986	0.979	1.007	0.972	1.008	1.007	1.000
1985	1.004	0.983	1.022	1.000	0.983	1.002	1.020
1986	1.027	1.024	1.002	1.032	0.992	1.001	1.001
1987	0.978	1.034	0.945	1.046	0.989	0.933	1.013
1988	0.965	1.038	0.930	1.029	1.008	0.947	0.981
1989	0.984	1.025	0.960	0.984	1.041	1.005	0.956
1990	0.983	1.013	0.970	1.049	0.966	0.941	1.031
1991	0.989	0.973	1.016	0.989	0.984	1.016	1.000
1992	0.993	0.981	1.012	0.965	1.017	1.029	0.984
1993	0.987	0.990	0.996	0.932	1.062	1.057	0.942
1994	0.969	1.040	0.932	1.003	1.037	0.980	0.950
1995	0.988	1.026	0.963	0.997	1.029	0.994	0.968
1996	0.971	0.996	0.975	0.973	1.024	1.004	0.971
1997	0.952	0.957	0.995	0.995	0.962	0.958	1.038
1998	0.959	0.944	1.016	0.969	0.974	0.997	1.019
1999	0.996	1.046	0.952	0.998	1.048	0.995	0.957
2000	0.977	1.093	0.893	1.052	1.039	0.935	0.955
2001	1.005	1.004	1.001	0.995	1.009	1.017	0.984
2002	1.015	1.002	1.013	0.977	1.025	1.041	0.973
2003	1.019	1.050	0.971	1.030	1.019	0.999	0.972
2004	0.977	0.969	1.009	0.999	0.970	0.982	1.027
2005	0.965	1.036	0.931	0.989	1.047	0.982	0.948
2006	0.998	1.130	0.883	1.052	1.074	0.947	0.933
2007	0.961	0.960	1.001	0.966	0.993	0.997	1.004
Geo Mean	0.988	1.011	0.977	1.000	1.011	0.990	0.987
Median	0.986	1.004	0.989	0.997	1.009	0.997	0.993
Std Dev	0.023	0.041	0.042	0.032	0.030	0.036	0.029
Min	0.952	0.944	0.883	0.932	0.962	0.924	0.933
Max	1.043	1.130	1.069	1.052	1.074	1.076	1.038

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 21: Cost-Malmquist-Index – Transport Sector, Italy

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	1.020	1.100	0.927	1.088	1.012	0.936	0.991
1980	0.973	0.975	0.998	0.989	0.986	1.020	0.978
1981	0.925	0.933	0.990	0.957	0.975	1.005	0.986
1982	0.961	0.958	1.003	0.989	0.968	1.008	0.995
1983	1.000	0.916	1.091	0.927	0.988	1.097	0.994
1984	0.935	0.928	1.007	0.941	0.987	1.016	0.992
1985	0.972	0.961	1.011	1.012	0.950	0.982	1.030
1986	1.023	1.014	1.010	1.040	0.975	0.988	1.022
1987	1.014	1.071	0.947	1.061	1.010	0.950	0.996
1988	1.013	1.071	0.946	1.038	1.031	0.955	0.991
1989	0.995	1.041	0.956	0.993	1.048	1.021	0.937
1990	0.969	1.004	0.965	1.064	0.943	0.925	1.044
1991	1.004	0.995	1.009	0.953	1.044	1.063	0.949
1992	0.974	0.964	1.011	0.974	0.990	1.010	1.000
1993	0.981	0.972	1.009	0.940	1.035	1.063	0.949
1994	0.997	1.054	0.945	1.018	1.036	0.971	0.973
1995	0.963	0.982	0.980	0.989	0.994	0.982	0.998
1996	1.002	1.030	0.973	0.996	1.035	0.994	0.979
1997	0.980	0.994	0.985	1.043	0.953	0.954	1.033
1998	1.004	0.976	1.028	0.995	0.981	0.991	1.037
1999	0.975	1.007	0.968	0.968	1.040	1.007	0.961
2000	1.016	1.161	0.875	1.100	1.055	0.948	0.923
2001	1.016	1.015	1.001	1.017	0.998	1.016	0.985
2002	1.011	0.985	1.027	0.997	0.987	1.040	0.988
2003	1.030	1.055	0.977	1.047	1.007	0.995	0.982
2004	1.018	1.028	0.990	1.036	0.992	0.991	0.999
2005	1.010	1.100	0.918	1.060	1.038	0.965	0.952
2006	1.007	1.148	0.877	1.107	1.036	0.925	0.949
2007	0.978	0.979	0.998	1.008	0.971	0.996	1.003
Geo Mean	0.992	1.013	0.979	1.011	1.002	0.993	0.986
Median	1.000	1.004	0.990	1.008	0.994	0.994	0.991
Std Dev	0.026	0.061	0.045	0.048	0.032	0.041	0.030
Min	0.925	0.916	0.875	0.927	0.943	0.925	0.923
Max	1.030	1.161	1.091	1.107	1.055	1.097	1.044

[a] OEC = TEC × AEC
[b] CTC = TC × PE

Table 22: Cost-Malmquist-Index – Transport Sector, Japan

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.936	1.000	0.936	1.000	1.000	0.935	1.001
1980	0.997	1.000	0.997	1.000	1.000	0.995	1.002
1981	0.989	1.000	0.989	1.000	1.000	0.988	1.001
1982	0.999	1.000	0.999	1.000	1.000	1.002	0.997
1983	1.086	1.000	1.086	1.000	1.000	1.085	1.001
1984	1.021	1.016	1.005	1.000	1.016	1.013	0.992
1985	0.985	0.984	1.001	1.000	0.984	0.986	1.016
1986	1.006	1.000	1.006	1.000	1.000	1.001	1.005
1987	0.945	1.000	0.945	1.000	1.000	0.948	0.998
1988	0.960	1.024	0.937	1.000	1.024	0.957	0.979
1989	1.017	1.066	0.954	1.000	1.066	1.020	0.936
1990	0.892	0.920	0.970	1.000	0.920	0.912	1.064
1991	1.028	1.011	1.017	1.000	1.011	1.042	0.976
1992	1.003	0.988	1.015	1.000	0.988	1.003	1.012
1993	1.036	1.040	0.996	1.000	1.040	1.052	0.946
1994	0.981	1.052	0.932	1.000	1.052	0.978	0.953
1995	0.979	0.999	0.981	1.000	0.999	0.990	0.990
1996	0.995	1.025	0.971	1.000	1.025	1.007	0.964
1997	0.940	0.960	0.980	1.000	0.960	0.957	1.024
1998	0.986	0.977	1.009	1.000	0.977	1.000	1.009
1999	0.997	1.036	0.962	1.000	1.036	1.005	0.957
2000	1.011	1.141	0.886	1.104	1.033	0.932	0.951
2001	0.978	0.976	1.002	0.983	0.993	1.013	0.990
2002	1.023	1.005	1.018	1.000	1.005	1.036	0.982
2003	1.011	1.032	0.980	1.038	0.994	0.985	0.995
2004	1.000	0.988	1.012	1.000	0.987	1.007	1.005
2005	0.967	1.041	0.928	1.038	1.004	0.940	0.987
2006	0.980	1.112	0.882	1.112	1.000	0.897	0.983
2007	1.010	1.013	0.998	1.016	0.997	0.994	1.003
Geo Mean	0.991	1.013	0.978	1.010	1.003	0.988	0.990
Median	0.997	1.000	0.989	1.000	1.000	0.995	0.995
Std Dev	0.036	0.043	0.042	0.029	0.028	0.042	0.026
Min	0.892	0.920	0.882	0.983	0.920	0.897	0.936
Max	1.086	1.141	1.086	1.112	1.066	1.085	1.064

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 23: Cost-Malmquist-Index – Transport Sector, Netherlands

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.937	1.036	0.905	1.030	1.006	0.945	0.957
1980	0.964	0.950	1.014	0.966	0.984	0.982	1.033
1981	1.009	1.011	0.998	1.069	0.946	0.932	1.070
1982	1.019	1.015	1.004	1.050	0.967	0.982	1.022
1983	0.989	0.943	1.049	0.976	0.966	1.034	1.015
1984	0.996	0.987	1.009	0.965	1.023	1.044	0.967
1985	0.995	0.966	1.029	0.901	1.072	1.129	0.912
1986	1.020	1.045	0.977	1.051	0.994	1.002	0.975
1987	0.980	1.036	0.946	1.085	0.954	0.927	1.021
1988	0.962	1.045	0.921	1.040	1.005	0.924	0.997
1989	0.970	1.012	0.958	1.023	0.989	0.967	0.991
1990	0.949	0.992	0.957	1.053	0.942	0.906	1.056
1991	1.023	1.002	1.021	0.998	1.004	1.023	0.998
1992	1.014	1.015	0.999	0.995	1.020	1.001	0.997
1993	0.949	0.960	0.989	0.958	1.002	0.975	1.014
1994	0.974	1.053	0.925	1.053	1.000	0.931	0.994
1995	0.962	0.990	0.972	0.978	1.013	0.961	1.011
1996	0.964	0.981	0.983	0.973	1.008	0.970	1.013
1997	0.976	1.001	0.975	1.024	0.978	0.968	1.007
1998	0.976	0.974	1.002	0.981	0.993	0.984	1.018
1999	1.000	1.038	0.963	1.067	0.973	0.948	1.016
2000	0.972	1.081	0.899	1.088	0.994	0.890	1.011
2001	0.989	0.993	0.996	0.984	1.009	0.993	1.003
2002	1.008	0.989	1.020	1.023	0.966	0.991	1.029
2003	0.993	1.010	0.983	1.020	0.991	0.971	1.012
2004	0.996	0.981	1.015	0.966	1.016	1.031	0.984
2005	0.972	1.045	0.930	1.039	1.006	0.937	0.993
2006	0.987	1.117	0.884	1.106	1.010	0.888	0.994
2007	0.989	0.992	0.996	0.993	0.999	0.997	1.000
Geo Mean	0.984	1.008	0.976	1.015	0.994	0.972	1.003
Median	0.987	1.002	0.983	1.023	0.999	0.971	1.007
Std Dev	0.022	0.039	0.042	0.047	0.026	0.051	0.029
Min	0.937	0.943	0.884	0.901	0.942	0.888	0.912
Max	1.023	1.117	1.049	1.106	1.072	1.129	1.070

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 24: Cost-Malmquist-Index – Transport Sector, Spain

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.993	1.080	0.920	1.084	0.997	0.936	0.983
1980	1.056	1.078	0.979	1.038	1.039	1.020	0.960
1981	0.967	1.006	0.961	0.998	1.008	1.005	0.957
1982	1.032	1.062	0.971	1.008	1.053	1.008	0.963
1983	1.000	0.941	1.062	0.900	1.046	1.097	0.968
1984	0.992	0.981	1.011	0.956	1.027	1.016	0.995
1985	0.959	0.944	1.017	0.995	0.949	0.982	1.035
1986	0.937	0.915	1.024	0.980	0.933	0.966	1.061
1987	0.955	0.987	0.968	1.000	0.987	0.923	1.049
1988	0.982	1.058	0.929	1.000	1.058	0.941	0.987
1989	0.997	1.041	0.958	1.000	1.041	0.988	0.970
1990	0.976	1.016	0.961	1.000	1.016	1.005	0.955
1991	0.984	0.972	1.013	1.000	0.972	1.009	1.004
1992	1.009	1.014	0.996	1.000	1.014	1.011	0.985
1993	0.959	0.977	0.982	1.000	0.977	0.982	1.000
1994	0.905	0.948	0.954	1.000	0.948	0.944	1.010
1995	0.912	0.923	0.988	1.000	0.923	0.926	1.066
1996	0.936	0.936	1.000	1.000	0.936	0.937	1.066
1997	0.940	1.006	0.935	1.000	1.006	0.960	0.973
1998	0.947	0.930	1.019	1.000	0.930	0.971	1.050
1999	0.993	1.039	0.957	1.000	1.039	1.000	0.957
2000	0.959	1.092	0.878	1.000	1.092	0.997	0.880
2001	0.995	1.012	0.984	1.000	1.012	1.030	0.955
2002	1.013	1.011	1.002	1.000	1.011	1.070	0.936
2003	0.985	1.003	0.982	1.000	1.003	1.036	0.948
2004	0.938	0.934	1.004	1.000	0.934	0.959	1.048
2005	1.023	1.106	0.924	1.000	1.106	1.034	0.894
2006	0.996	1.127	0.883	1.000	1.127	1.016	0.869
2007	0.969	0.967	1.002	1.000	0.967	1.005	0.997
Geo Mean	0.976	1.002	0.974	0.998	1.004	0.991	0.982
Median	0.982	1.006	0.982	1.000	1.008	1.000	0.983
Std Dev	0.035	0.059	0.042	0.027	0.054	0.042	0.052
Min	0.905	0.915	0.878	0.900	0.923	0.923	0.869
Max	1.056	1.127	1.062	1.084	1.127	1.097	1.066

[a] OEC = TEC × AEC
[b] CTC = TC × PE

Table 25: Cost-Malmquist-Index – Transport Sector, Sweden

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.936	0.999	0.937	1.010	0.989	0.936	1.001
1980	1.010	1.005	1.005	1.006	0.999	1.020	0.985
1981	1.008	1.016	0.992	1.025	0.992	1.005	0.988
1982	1.020	1.021	0.999	1.013	1.008	1.008	0.991
1983	1.032	0.952	1.084	0.953	0.998	1.097	0.988
1984	0.983	0.970	1.013	0.995	0.976	1.016	0.997
1985	0.972	0.964	1.009	1.012	0.952	0.982	1.027
1986	0.986	0.973	1.013	1.013	0.960	0.984	1.030
1987	0.992	1.055	0.940	1.071	0.984	0.948	0.992
1988	0.975	1.057	0.923	1.050	1.006	0.956	0.965
1989	0.969	1.025	0.946	0.975	1.051	1.025	0.923
1990	0.982	1.023	0.959	1.142	0.896	0.917	1.047
1991	0.983	0.969	1.014	0.970	0.999	1.064	0.953
1992	1.003	1.003	1.000	1.000	1.003	1.016	0.985
1993	0.970	0.963	1.007	0.940	1.025	1.062	0.949
1994	0.951	1.002	0.950	0.993	1.009	0.977	0.972
1995	0.956	0.983	0.972	0.983	1.000	0.988	0.984
1996	1.007	1.034	0.974	1.000	1.034	0.999	0.974
1997	0.962	0.988	0.974	1.024	0.965	0.958	1.016
1998	0.981	0.964	1.018	0.986	0.977	0.994	1.024
1999	1.003	1.057	0.949	1.016	1.040	0.995	0.954
2000	0.930	1.025	0.906	1.002	1.024	0.936	0.968
2001	0.990	0.987	1.003	0.987	0.999	1.013	0.991
2002	1.019	0.993	1.026	0.976	1.018	1.047	0.980
2003	1.016	1.038	0.979	1.009	1.028	1.007	0.972
2004	1.026	1.007	1.019	1.058	0.952	0.985	1.034
2005	0.967	1.057	0.915	0.999	1.059	0.982	0.932
2006	1.012	1.160	0.872	1.092	1.062	0.943	0.925
2007	0.990	0.987	1.003	1.010	0.977	0.997	1.006
Geo Mean	0.987	1.009	0.978	1.010	0.999	0.994	0.984
Median	0.986	1.003	0.992	1.006	0.999	0.995	0.985
Std Dev	0.026	0.043	0.044	0.041	0.036	0.041	0.032
Min	0.930	0.952	0.872	0.940	0.896	0.917	0.923
Max	1.032	1.160	1.084	1.142	1.062	1.097	1.047

[a] OEC = TEC × AEC
[b] CTC = TC × PE

Table 26: Cost-Malmquist-Index – Transport Sector, United Kingdom

	CM	**OEC**[a]	**CTC**[b]	**TEC**	**AEC**	**TC**	**PE**
1979	0.955	1.083	0.882	1.066	1.016	0.936	0.942
1980	1.013	1.095	0.925	1.051	1.042	1.020	0.907
1981	1.025	1.071	0.957	1.029	1.041	1.005	0.953
1982	1.030	1.021	1.010	1.035	0.986	1.008	1.002
1983	0.950	0.863	1.101	0.861	1.001	1.097	1.004
1984	0.973	0.941	1.034	0.930	1.012	1.016	1.018
1985	0.997	0.992	1.006	1.012	0.980	0.982	1.024
1986	0.979	0.864	1.133	0.994	0.869	0.974	1.163
1987	0.974	1.008	0.967	1.013	0.995	0.936	1.033
1988	0.960	0.991	0.968	0.987	1.004	0.948	1.022
1989	0.975	1.052	0.927	0.966	1.090	1.002	0.925
1990	0.958	0.981	0.977	0.992	0.988	0.968	1.009
1991	0.992	0.941	1.054	0.973	0.967	1.029	1.024
1992	0.957	0.934	1.024	0.934	1.000	1.012	1.012
1993	1.003	0.957	1.048	0.989	0.968	1.002	1.046
1994	0.977	1.018	0.960	1.031	0.987	0.940	1.022
1995	0.979	0.976	1.003	1.060	0.920	0.928	1.081
1996	0.974	1.003	0.971	1.053	0.953	0.929	1.045
1997	0.985	1.012	0.974	1.048	0.966	0.954	1.021
1998	0.982	0.934	1.051	1.028	0.909	0.972	1.082
1999	0.995	1.072	0.928	0.999	1.073	0.999	0.929
2000	1.007	1.264	0.797	1.030	1.227	0.995	0.800
2001	1.032	1.057	0.976	1.019	1.037	1.037	0.942
2002	0.986	0.901	1.094	0.920	0.980	1.077	1.016
2003	1.000	0.991	1.009	0.951	1.042	1.055	0.957
2004	0.955	0.962	0.993	0.981	0.981	0.965	1.029
2005	0.980	1.104	0.887	0.946	1.167	1.040	0.853
2006	0.991	1.147	0.864	0.988	1.161	1.021	0.846
2007	1.007	1.001	1.006	1.014	0.988	1.009	0.997
Geo Mean	0.986	1.005	0.981	0.995	1.009	0.994	0.987
Median	0.982	1.001	0.977	0.999	0.995	1.002	1.012
Std Dev	0.023	0.085	0.073	0.048	0.076	0.044	0.076
Min	0.950	0.863	0.797	0.861	0.869	0.928	0.800
Max	1.032	1.264	1.133	1.066	1.227	1.097	1.163

[a] OEC = TEC × AEC

[b] CTC = TC × PE

Table 27: Cost-Malmquist-Index – Transport Sector, USA

G Curriculum Vitæ

Sebastian Wehrle

Experience

JBC Energy	**Vienna**
Analyst	*since 2008*
PVM Oil Associates	**Vienna**
Energy Market Analyst	*2007 – 2008*
Technical University of Vienna	**Vienna**
Teaching Assistant, Institute for Mathematical Methods in Economics	*2006 – 2007*
Technical University of Vienna	**Vienna**
Teaching Assistant, Institute for Mathematical Methods in Economics	*2005 – 2006*
Psychiatrische Universitätsklinik an der Nußbaumstraße	**Munich**
Civil Service	*1998 – 1999*

Education

University of Vienna	**Vienna**
Economics	*since 2001*
Ludwig Maximilian University	**Munich**
European Anthropology	*1999 – 2001*
Willi-Graf-Gymnasium	**Munich**
Abitur	*1997*