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A Retake on Productivity Growth, Technical Progress and Efficiency Change using Malmquist Productivity Indexes

Replicating a Färe, Grosskopf, Norris and Zhang study from 1994

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Abstract

This thesis follows methods employed by Färe *et al*. (1994) in their influential article 'Productivity Growth, Technical Progress, and Efficiency Change in Industrialized Countries', published in the *American Economic Review*. The study is conducted using measures of output-oriented gross domestic product, the number of people working and the capital stock for 17 OECD countries from Penn World Tables (PWT), version 8.0, for 2002 to 2011. This retake use the same countries and the same data source as Färe *et al*. (1994) albeit their data was from the PWT, Mark 5 from 1991.

Productivity is defined as a ratio of outputs and inputs and this particular productivity analysis is performed using an output-oriented Malmquist productivity change index, an index that can be decomposed into technological change and efficiency change components. This is done using data envelopment analysis techniques meaning that a technological frontier is constructed using non-parametric linear programming given assumption of the returns to scale characteristics. The frontier is the efficient frontier that all data points are evaluated against using distance functions. In total, 612 linear programming problems need be computed per data set for which the mathematical programming software MATLAB was used. The methods were first tested on PWT data set that Färe *et al*. (1994) used. To yield the expected results, the returns to scale assumption had to be changed from constant returns to scale (CRS) to non-increasing returns to scale (NIRS). This is in contrast to the explicit description from Färe *et al*. (1994) which state CRS as the results clearly reveal that NIRS must have been used.

The same methods and assumptions were then used for the PWT version 8.0 data set. The results differed from those of Färe *et al*. (1994) with regards to which countries that established the frontier while the rate of productivity growth had slowed down. Depending on scale assumption, the determining countries were Ireland, Norway, Sweden and the United States under NIRS or Ireland and Sweden for CRS. Regardless of scale assumption, Sweden was the sole determinant of the frontier for the last year of 2011. Just as the 1994 results by Färe *et al*. (1994), productivity growth was driven by technological improvements rather than efficiency gains. Sweden was notably the worst performing country with respect to technology and the best performer regarding efficiency. Norway was the best performer with regards to overall productivity growth due to good results for both of the subcomponents.

Finally, the same techniques were applied to PWT 8.0 data for the same time period and countries as in the 1994 study and the results were significantly different. Canada, Ireland, Norway and the United States determined the frontier using NIRS meanwhile only Canada and Ireland were on the frontier given CRS. The overall productivity growth was slightly lower at 0.61 instead of 0.7 percent annually. That technological improvements were the main productivity driver, a conclusion by Färe *et al*. (1994), was reversed and Japan went from the best performing country to the fourth. Several countries shifted places and the discrepancies between the results for PWT Mark 5 and PWT 8.0 were wide-spread and vast.

Keywords: Productivity, Data Envelopment Analysis, Efficient Frontiers, Malmquist index, Technical Efficiency, Technological Change, Penn World Tables, OECD countries.

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1. Introduction

Färe *et al*. (1994) wrote an article on productivity published in *The American Economic Review* in March 1994. Productivity was measured as a geometric mean of Malmquist productivity indexes which enabled a decomposition of productivity growth into changes in technical efficiency and technological shifts over time. The empirical study by Färe *et al.* (1994) covered 17 OECD countries during 1979-1988 based on the Penn World Tables (PWT) Mark 5 (PWT5). Färe *et al.* (1985, p. 2) explained their outset in the following way:

> It is our view that the neglect of inefficiency in the modern mainstream literature, the rather disparate development of a heterogeneous fringe literature on efficiency measurement, and the role played by efficiency considerations in a wide range of applied fields, all point to the need for a development of a coherent theory of the producer in the presence of inefficiency. This is our goal.

Productivity is of central importance as Krugman (1997, p. 11) wrote that 'productivity isn't everything, but in the long run it is almost everything. A country's ability to improve its standard of living over time depends almost entirely on its ability to raise its output per worker.' According to a recent report from the Boston Consulting Group, Sweden is among the top ten countries in the world in terms of work-force productivity. Although the amount of working hours per Swede has gone down, the living standards have improved which can be attributed to productivity gains. However, as the present situation is comparatively well for Sweden from an international perspective, it is estimated that the Swedish people are at a risk of a slowing productivity growth by 0.4 percentage points. (Alsén *et al*., 2013)

As imperceptible as this decrease might seem, as noticeable could the long-term effects be on a national level. Unless the current situation is remedied, the Swedish population might have to either reduce the yearly vacation time to two weeks, increase the pensionable age by three years or raise taxes by three SEK, *ceteris paribus*, to finance the same welfare as the population currently enjoy. (Alsén *et al*., 2013) The issue of productivity is thus a highly contemporary concern. It is thus interesting to assess the most recent productivity development, from 2002 to 2011 by means of the methods used by Färe *et al*. (1994) to provide a further perspective Sweden's development compared to other OECD nations.

1.1 Purpose

As this thesis revolves around a replication and follow-up of a published article within economics and more specifically productivity analysis, the purpose could be described as two-fold. First, apply economic models on real-world data in a manner closely resembling that of economic researchers within the area of productivity analysis. Secondly, to contribute to the research area by conducting a similar study based on more recent data.

1.2 Research questions

The research questions assume that productivity measuring methods follow Färe *et al.* (1994).

R1. How can the productivity development for 2002 to 2011 be characterized?

R2. How does this compare with the findings from 1979 to 1988?

R3. Given an updated data set, are there any implications for the 1979 to 1988 findings?

2. Methodology

This paper revolves around a specific way of measuring productivity and further decomposing productivity changes into technical changes and efficiency improvements. As this is a unique feature for the models that will be applied, it can be useful to start broadly and narrow in on particularities and technicalities. First, productivity is briefly discussed as Färe *et al*. (1994) methods are placed in a broader context of productivity measurements. Second, the output-based Malmquist productivity change index is described by equations and figures. Third, the mathematical representations of the associated linear programming problems are explained. Fourth, the effects of scale assumptions are considered. Fifth, the index is rewritten for constant returns to scale. Sixth, the formulas are rewritten into a form that is congruent with the applied computing software. Seventh and finally, the data selection for the productivity measurements are described. As this chapter is rather technical and specific, hopefully it will be useful by providing the prerequisite understanding needed regarding the methods applied and remain on the specialized language side of Krugman's (1994, p. ix) notion that:

> Like any academic field, economics has its fair share of hacks and phonies, who use complicated language to hide the banality of their ideas; it also contains profound thinkers, who use the specialized language of the discipline as an efficiency way to express deep insights.

2.1 Productivity and how it can be measured

First off, productivity can be defined as the ratio of outputs to inputs (e. g. Coelli *et al*., 2005; Cooper *et al*., 2007). This means that an increased level of output for a given level of input or conversely a decreased level of input for some level of output or any combination yielding a higher ratio all imply improved productivity. It is a classic economic subject, recall for instance Adam Smith and the pin factory, and it is a contemporary subject of vast importance for our very wellbeing on a societal level as explained in the introduction. Within the specific economic area of productivity analysis, the measures and methods are more sophisticated than the ratio provided above although that is the very kernel of productivity. As given by the output to input ratio one can measure productivity with an output- or input-orientation and a further step would be to analyze the drivers behind productivity improvements.

There are four main means of economic analysis of productivity according to Coelli *et al*. (2005)[1]. Among these, a major sub-categorization can be made between parametric and non-parametric methods. Least-squares econometric production models and stochastic frontiers belong to the former while total factor productivity (TFP) indices, referring to Törnqvist and Fisher, and data envelopment analysis, often DEA, belong to the latter. The models in this report belong to data envelopment analysis which thus is a non-parametric method meaning that it does not rely on statistical methods. Compared with TFP, data envelopment analysis requires fewer inputs as it require input and output quantities where TFP also need input and output prices. Data envelopment analysis is suitable for panel data and does not deal with time series data as TFP does. Regarding the measures that can be produced, data envelopment analysis holds advantages as it can be used to measure for instance technical efficiency which is needed for the application in this report. (Coelli *et al*., 2005)

[1] See page 312 in Coelli *et al*. (2005) for a comprehensive overview and comparison

Data envelopment analysis involves the practice of taking a data set containing inputs and outputs and establishes a frontier that often is referred to as the efficient frontier. A unit of analysis is often denoted as a decision making unit, abbreviated DMU (e.g. Charnes *et al*., 1978).[2] The frontier touches at least one data point and envelops all points, creating a feasible output versus input ratio region. Cooper *et al*. (2007, p. 3) explains this by highlighting that 'the name Data Envelopment Analysis, as used in DEA, comes from the property because in mathematical parlance, such a frontier is said to "envelop" these points.' Instead of statistical habits such as describing data using mean values data points are evaluated against the frontier consisting of the best known possible combinations. Such frontiers are not static as technical change can alter the position of the frontier (Coelli *et al*., 2005)

The method of evaluation is typically through some distance measure. One example could be the distance from the origin of coordinates to the frontier divided by the distance along the same line to some data point. This could then be considered a ratio-based measure of productivity. (Cooper *et al.*, 2007) As for the techniques to actually perform these analyses, data envelopment analysis relies on linear programming techniques to construct non-parametric piecewise surfaces by which data points are evaluated. If a data point is on the frontier it is considered technically efficient whereas any distance to the frontier implies some degree of inefficiency. (Coelli *et al*., 2005) Such measures can be considered in an input-oriented model which either '…aims to minimize inputs while satisfying at least the given output levels' or an output-oriented model that '…attempts to maximize outputs without requiring more of any of the observed input values.' (Cooper *et al*., 2007, p. 41) This essentially means whether one takes distance measures for technical efficiency horizontally or vertically respectively for input- and output-oriented models.

Färe *et al*. (1985) set out to address what they perceived as a prevalent productivity and efficiency measurement neglect towards the possibility that there could be significant inefficiencies within production. Earlier, a notion that producers might conduct their operations inefficiently was traditionally dismissed within neoclassical production theory. Through various optimizations from the producers' point of view, different types of inefficiencies such as technical, behavioral, structural and allocative were dismissed. In 1985, soon to be 30 years ago, the literature regarding inefficiencies within production was described as thin and inhomogeneous. (Färe *et al*., 1985) Upon developing data envelopment analysis methods and applying them in various fields, Färe *et al*. (1994) applied these methods on macro level data to assess productivity growth for OECD countries by use of Malmquist indices of TFP growth. A paper described as 'very influential' by Coelli *et al*. (2005, p. 290). When calculating the Malmquist index, it is significantly easier if all decision making units, in this case nations, would be technically efficient. Being technically inefficient however, means that a productivity change could be either due to changed technical efficiency or an altered underlying technological base. (Coelli *et al*., 2005). This is just what this paper will do. It will assess productivity, thus the ratio of outputs to inputs, while estimating the subcomponents of productivity change namely technological and efficiency changes.

[2] This notation is not used throughout this report; the remark was rather made for general orientation within data envelopment analysis. In the case of this report, countries should be considered as decision making units.

2.2 The output-based Malmquist index of productivity change

The index used in this report, following Färe *et al*. (1994), is referred to as an output-based Malmquist index of productivity change. The Malmquist index of productivity change is in itself a geometric mean of two Malmquist indices which are denoted CCD indices, referring to Caves, Christensen and Diewert. Caves *et al*. (1982) had developed a method for productivity measurement using discrete index numbers rather than a measure based on continuous time for which they used Malmquist indices. For productivity indexes there are two main approaches. Either, the maximum output given a level of input or a minimum level of input given a level of output. These are denoted output-oriented and input-oriented measurements respectively. (Caves *et al*., 1982) As mentioned, this report follows Färe *et al*. (1994) in their output-orientation. This means that the benchmark of productivity for any data point will be its relative position to the maximum possible output given the level of input. To characterize the maximum, thus best practise, level of output a frontier is established, see figure 1 below for such frontiers denoted by S^t and S^{t+1}. These are to be interpreted as the maximum possible output level, y-values, given the input level, x-values, for time periods t and t+1 in that order.

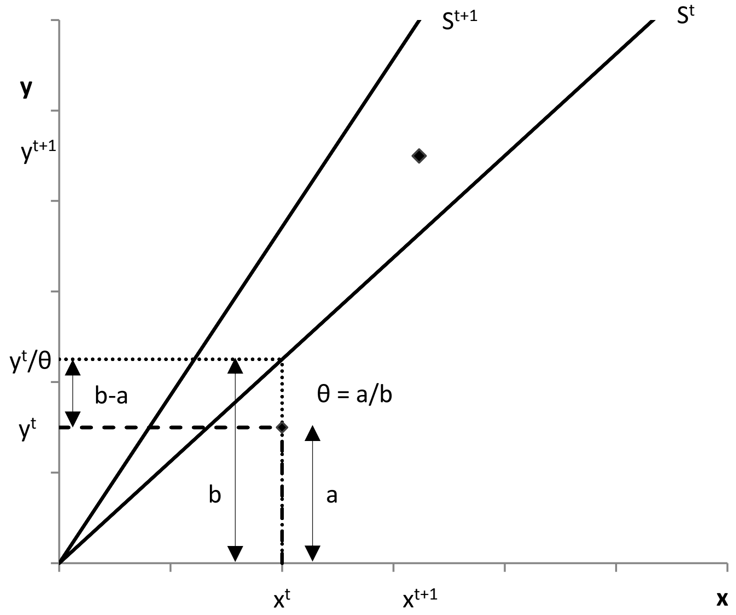

Figure 1: A graphical interpretation of technological frontiers and the calculation of theta

The frontier can be interpreted as the production technology for a given point in time, which can be written such as that $S^t = \{(x^t, y^t): x^t \text{ can produce } y^t\}$ when t = 1,…,T denote time period and x and y denote inputs and outputs respectively. To measure productivity, distance functions are utilized where theta (θ) is of integral importance. Theta is a measurement of technical efficiency as it measures the output at a given input level compared to what is technically possible given the underlying production technology described by the frontier. Figure 1 above visually describe how theta can be computed as the ratio of the distances through straight lines from the horizontal axis at x^t to the output value y^t, marked as a, and the horizontal axis at x^t to the output at the frontier marked b. Theta is thus a divided by b. (Färe *et al*., 1994)

This implies that theta assume values that are less or equal to one. If theta is equal to one, it infers that production is fully technically efficient whereas lower values imply inefficiencies. As could be seen in Figure 1 above, x^t is not bound by S^t for other time periods than at time t. The corresponding computation of theta at x^{t+1} and y^{t+1} for S^t would result in a theta value of exceeding one. This is allowed as it means that there has been technological progress which allow for higher levels of output at the same levels of input. Conversely, if the values for x^t and y^t were used to compute theta against S^{t+1}, the value of theta would be smaller than for S^t if there had been technological progress.

Mathematically, distance functions are characterized by Färe *et al.* (1994) as by equations 1 and 2 below respectively, calculating theta for x^t and y^t for S^t as well as x^{t+1} and y^{t+1} for S^t. Note that equation 2 is a mixed period distance function. Together, these two distance functions are the constituents of the CCD Malmquist productivity index M^t as expressed by equation 3.

$$(1) \qquad D_0^t(x^t, y^t) = \inf\left\{\theta : \left(x^t, \frac{y^t}{\theta}\right) \in S^t\right\}$$

$$(2) \qquad D_0^t(x^{t+1}, y^{t+1}) = \inf\left\{\theta : \left(x^{t+1}, \frac{y^{t+1}}{\theta}\right) \in S^t\right\}$$

$$(3) \qquad M_{CCD}^t = \frac{D_0^t(x^{t+1}, y^{t+1})}{D_0^t(x^t, y^t)}$$

Similar to equation 1 and 2 above, the distance functions needed to compute the CCD Malmquist productivity index at t+1, M^{t+1} describe the x^{t+1} and y^{t+1} distance to S^{t+1} as well the x^t and y^t compared to S^{t+1}. The ratio of these two distance functions, denoted by equation 4 and 5 respectively, constitute the CCD index described by equation 6.

$$(4) \qquad D_0^{t+1}(x^{t+1}, y^{t+1}) = \inf\left\{\theta : \left(x^{t+1}, \frac{y^{t+1}}{\theta}\right) \in S^{t+1}\right\}$$

$$(5) \qquad D_0^{t+1}(x^t, y^t) = \inf\left\{\theta : \left(x^t, \frac{y^t}{\theta}\right) \in S^{t+1}\right\}$$

$$(6) \qquad M_{CCD}^{t+1} = \frac{D_0^{t+1}(x^{t+1}, y^{t+1})}{D_0^{t+1}(x^t, y^t)}$$

The constituents of the Malmquist index of productivity change are now explained as it is the geometric mean of the product of equation 3 and 6 as presented by equation 7 below. This can then be rewritten as equation 8 before being decomposed into efficiency change and technical change as described by equations 9 and 10 below. For a further explanation of this decomposition see Coelli *et al.* (2005, p. 70-72). Note that this is a central property for the analysis put forth by Färe *et al.* (1994), this is what allows for the mutually exclusive and collectively exhaustive measures of changes in technical efficiency, catch-up, and technological shifts over time.

$$(7) \qquad M_0(x^{t+1}, y^{t+1}, x^t, y^t) = \left[\left(\frac{D_0^t(x^{t+1}, y^{t+1})}{D_0^t(x^t, y^t)}\right)\left(\frac{D_0^{t+1}(x^{t+1}, y^{t+1})}{D_0^{t+1}(x^t, y^t)}\right)\right]^{1/2}$$

$$(8) \quad M_0(x^{t+1}, y^{t+1}, x^t, y^t) = \frac{D_0^{t+1}(x^{t+1}, y^{t+1})}{D_0^t(x^t, y^t)}\left[\left(\frac{D_0^t(x^{t+1}, y^{t+1})}{D_0^{t+1}(x^{t+1}, y^{t+1})}\right)\left(\frac{D_0^t(x^t, y^t)}{D_0^{t+1}(x^t, y^t)}\right)\right]^{1/2}$$

$$(9) \qquad Efficiency\ change = \frac{D_0^{t+1}(x^{t+1}, y^{t+1})}{D_0^t(x^t, y^t)}$$

$$(10) \qquad Technical\ change = \left[\left(\frac{D_0^t(x^{t+1}, y^{t+1})}{D_0^{t+1}(x^{t+1}, y^{t+1})}\right)\left(\frac{D_0^t(x^t, y^t)}{D_0^{t+1}(x^t, y^t)}\right)\right]^{1/2}$$

2.3 Mathematical representation for linear optimization

As the previous section contained the models to be used, this section first describe the mathematical foundation for data envelopment analysis as presented by Färe *et al*. (1994), with slightly altered notations, before explaining how the mathematical expressions have been transformed into a linear programming problem. Data envelopment analysis is modelled through a frontier envelopment of data points. The data set is characterized by n = 1,…,N inputs producing m = 1,…,M outputs for each time period t = 1,…,T which will be used throughout this section. For this productivity purpose, the frontier is constructed as a technological frontier S^t, determined by three main restrictions where x and y denote input and output values respectively as stated by equation 10.

$$(11) \quad S^t = \left\{ \begin{array}{c} (x^t, y^t): \\ y_m^t \leq \sum_{k=1}^{K} \lambda^{k,t} y_m^{k,t} \quad m = 1, \ldots, M \\ \sum_{k=1}^{K} \lambda^{k,t} x_n^{k,t} \leq x_n^t \quad n = 1, \ldots, N \\ 0 \leq \lambda^{k,t} \qquad k = 1, \ldots, K \end{array} \right\}$$

Lambda (λ) is an intensity variable which reflects the returns to scale assumptions made. Equation 11 implies constant returns to scale (CRS). However, the presumed returns of scale can, quite easily, be altered to assume non-increasing returns to scale (NIRS) or variable returns to scale (VRS). This is accomplished by adding one of the following equations 12 or 13 as a fourth restriction to those presented by equation 11 above:

$$(12) \quad \sum_{k=1}^{K} \lambda^{k,t} \leq 1 \quad (NIRS)$$

$$(13) \quad \sum_{k=1}^{K} \lambda^{k,t} = 1 \quad (VRS)$$

Figure 2 below provides an illustration of how the technological frontier S^t varies with returns to scale assumptions. The CRS frontier has its origin at the point of the origin of coordinates and allows no data points to the left. An intuitive interpretation of this frontier is that it is determined by a point which allows for a straight line from the origin of coordinates to envelop all other data points. This is an equivalent to being determined by the data point with the largest tangential angle from the origin of coordinates. As can be seen, the CRS frontier coincides with the NIRS frontier until they reach data point A vertically. The NIRS is estimated differently as the sum of the intensity variables, lambdas, is not allowed to assume values greater than one. Visually, this means that the NIRS frontier will not exceed the maximum in-sample y-value. It does however, just as the CRS frontier, set out from the origin of coordinates. The VRS frontier is the frontier that most closely envelopes its data points. It is established by straight lines through the outermost data points within the sample. As can be seen, neither the CRS nor the NIRS use the value B to construct the frontier as the VRS do.

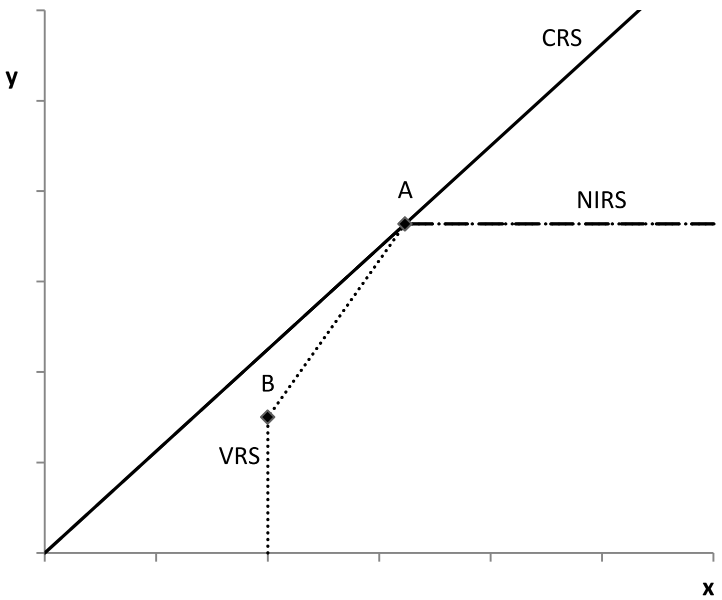

Figure 2: Frontier construction for different return to scale assumptions

To establish these frontiers and estimating distance functions, linear programming techniques are used. For the Malmquist index under CRS, four linear programming problems needs to be solved for each country and year in the sample. This require 612[3] linear programming problems to be solved as there are 17 countries and nine years for which mixed period distance functions can be computed. If the frontier instead would be constructed based on VRS, it require two additional linear programming problems which then results in the 918 linear programming problems that Färe *et al.* (1994) calculated. These linear programming problems will now be described after a brief discussion regarding the choice of scale returns for the linear programming.

[3] The number of linear programming problems that needs to be calculated is the product of the number of countries, the number of years minus one and the amount of linear programming problems that are needed. In the case of 612, it is the product of 17 countries, nine years and four linear programming problems. 918 are then computed using six linear programming problems instead of four.

Regarding returns to scale assumptions, Färe *et al*. (1994, p. 74) state that '…we choose to calculate the Malmquist productivity change index relative to the constant-returns-to-scale technology'. However, it is also mentioned while discussing CRS that 'in our empirical work, that maximum is the "best practice" or highest productivity observed in our sample of countries…' (Färe *et al*., 1994, p. 69). This is a relatively dubious description, but it is clear from the results put forth by Färe *et al*. (1994) that they used NIRS frontiers for their CRS estimations as will be explained later in section 3.1. The measure of technical efficiency used to compute CCD indexes are determined by theta, which is the ratio of the vertical distance from a data point from the horizontal axis and the corresponding vertical distance to the frontier. For the present time period t, this means that the maximum value is one which occurs when the frontier is established by that data point. However, during mixed period computation, theta can exhibit values exceeding one if there has been technological progress and the frontier has shifted.

It is time to review the linear programming problems that will be used to retrieve the values of theta that are used to compute CCD indexes and thus in turn the Malmquist index. All computations needs to be conducted for k'=1,…,K countries. Following Färe *et al*. (1994), the first and second linear problem are equations 14 and 15 respectively corresponding to equations 1 and 2 in that given order:

$$(14) \quad (D_0^t(x^{k',t}, y^{k',t}))^{-1} = max\theta^{k'} \; subject\ to$$

$$\begin{Bmatrix} \theta^{k'} y_m^{k',t} \leq \sum_{k=1}^{K} \lambda^{k,t} y_m^{k,t} & m = 1, \dots, M \\ \sum_{k=1}^{K} \lambda^{k,t} x_n^{k,t} \leq x_n^{k',t} & n = 1, \dots, N \\ 0 \leq \lambda^{k,t} & k = 1, \dots, K \\ \sum_{k=1}^{K} \lambda^{k,t} \leq 1 & (NIRS) \end{Bmatrix}$$

$$(15) \quad (D_0^{t+1}(x^{k',t+1}, y^{k',t+1}))^{-1} = max\theta^{k'} \; subject\ to$$

$$\begin{Bmatrix} \theta^{k'} y_m^{k',t+1} \leq \sum_{k=1}^{K} \lambda^{k,t+1} y_m^{k,t+1} & m = 1, \dots, M \\ \sum_{k=1}^{K} \lambda^{k,t+1} x_n^{k,t+1} \leq x_n^{k',t+1} & n = 1, \dots, N \\ 0 \leq \lambda^{k,t+1} & k = 1, \dots, K \\ \sum_{k=1}^{K} \lambda^{k,t+1} \leq 1 & (NIRS) \end{Bmatrix}$$

Then, to compute the distance function for mixed periods, the linear programming setup needs information from two time periods. Equations 16 and 17 below explain the computations that are conducted for the linear programming problems three and four, which correspond to equations 3 and 4 presented earlier in that order:

$$(16)\quad \left(D_0^t\left(x^{k',t+1}, y^{k',t+1}\right)\right)^{-1} = max\theta^{k'} \ subject\ to$$

$$\begin{cases} \theta^{k'} y_m^{k',t+1} \leq \sum_{k=1}^{K} \lambda^{k,t} y_m^{k,t} & m = 1, \dots, M \\ \sum_{k=1}^{K} \lambda^{k,t} x_n^{k,t} \leq x_n^{k',t+1} & n = 1, \dots, N \\ 0 \leq \lambda^{k,t} & k = 1, \dots, K \\ \sum_{k=1}^{K} \lambda^{k,t} \leq 1 & (NIRS) \end{cases}$$

$$(17)\quad \left(D_0^{t+1}\left(x^{k',t}, y^{k',t}\right)\right)^{-1} = max\theta^{k'} \ subject\ to$$

$$\begin{cases} \theta^{k'} y_m^{k',t} \leq \sum_{k=1}^{K} \lambda^{k,t+1} y_m^{k,t+1} & m = 1, \dots, M \\ \sum_{k=1}^{K} \lambda^{k,t+1} x_n^{k,t+1} \leq x_n^{k',t} & n = 1, \dots, N \\ 0 \leq \lambda^{k,t+1} & k = 1, \dots, K \\ \sum_{k=1}^{K} \lambda^{k,t+1} \leq 1 & (NIRS) \end{cases}$$

As can be seen, equations 16 and 17 above use t and t+1 opposite to each other. Equation 16, utilize the frontier established at t to evaluate the t+1 position whereas equation 17 use t positions which are evaluated against the t+1 frontier. Before equations 14 to 17 are used to line up linear programming problems used to reach the results in chapter 3, the effects of scale assumptions are discussed in section 2.4 before a rewriting of the indexes CRS are presented in section 2.5 to facilitate further understanding.

2.4 How scale assumption affects the productivity measure

At this point, it is important to understand how scale assumptions impact the results that the presented methodology yields. Figure 3 below visualize why CRS and NIRS yield different results. First off, the vertical distance between data points B and C is the same regardless if the CRS or NIRS assumption is used. This is true for all data points enveloped by the triangle from the origin of coordinates to the x and y-coordinated for the CRS frontier data point with the largest y-value. However, to the right of this 'CRS equals NIRS'-triangle, the distance functions will yield lower values for theta as specified by the equations above and figure 2.

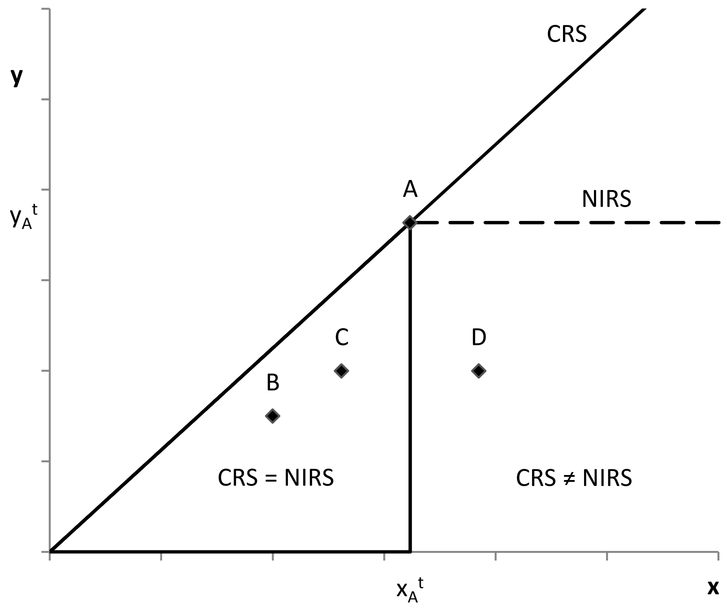

Figure 3: Difference between CRS and NIRS thetas depending on horizontal position

It should be mentioned that this is a characteristic that is specific for output-based measures and NIRS, as Coelli *et al*. (2005) emphasizes that input- and output-based measures are equivalent under a CRS assumption. In figure 3 above, this could be understood in terms of triangles using the CRS frontier as the hypotenuse whereas the input or output inefficiency distances to the frontier determine the catheti. As the catheti are at right angles with the frontier the catheti are of equal length. This is not the case for the NIRS part as for point D. The horizontal distance to the CRS frontier is longer than the vertical distance to the NIRS frontier. For an output-based approach this discussion can be readily summarized such as that a NIRS assumption essentially returns a higher rate of efficiency than a CRS assumption.

As CRS and NIRS differ for certain regions, it also affects the ability of a Malmquist productivity change index to yield results coherent with the fundamental output to input ratio measure of productivity[4]. The geometric mean the two Malmquist indexes presented by equation 7 have flaws for non-CRS frontiers. This have been shown before, notably by Grifell-Tatjé and Lovell (1995, p. 175) stating that '… the mere presence of increasing or decreasing returns can cause each of the three productivity indexes to mis-measure actual productivity change.'[5] In order to understand why, see figure 4 below on the following page.

According to the fundamental definition of productivity, productivity measures for the points marked for time t and t+1 would be 1.6 and 1.25 respectively. Clearly, the ratio at the time t is higher than that of t+1, almost 30 percent higher. Consider a case when the NIRS frontier remains for both time periods. The distance functions specified by 1, 2, 4 and 5 will thus all be equal to one as both t and t+1 are at the frontier during both periods. In turn, the Malmquist CCD indexes by equations 3 and 6 will be one and subsequently the geometric mean of these, the Malmquist productivity change index as specified by equation 7, will also be equal to one.

[4] Thanks to Hans Bjurek for suggesting this example

[5] The three productivity indexes refer to equations 3, 6 and 7 in this report respectively.

Thus, it is seen that the Malmquist productivity change index is unable to accurately reflect changes in productivity for non-CRS frontiers. It has thus become biased using a NIRS frontier. To see that this is not the case for CRS, it can be shown that equations 1, 2, 4 and 5 would yield theta values of 1, 0.7813, 0.7813 and 1 respectively.[6] These theta values lead to both Malmquist CCD indexes being 0.7813, as specified by equations 3 and 6, while the geometric mean of the product of these also becomes 0.7813 according to equation 7. The Malmquist productivity change index thus identifies decreased productivity using a CRS frontier as opposed to a non-CRS frontier as this example has shown. To address this bias, Grifell-Tatjé and Lovell (1995) suggests either the introduction of a new productivity index or scaling the index to account for non-CRS. For an example of an index that remedies the returns to scale bias, see the Malmquist total factor productivity index put forth by Bjurek (1996).

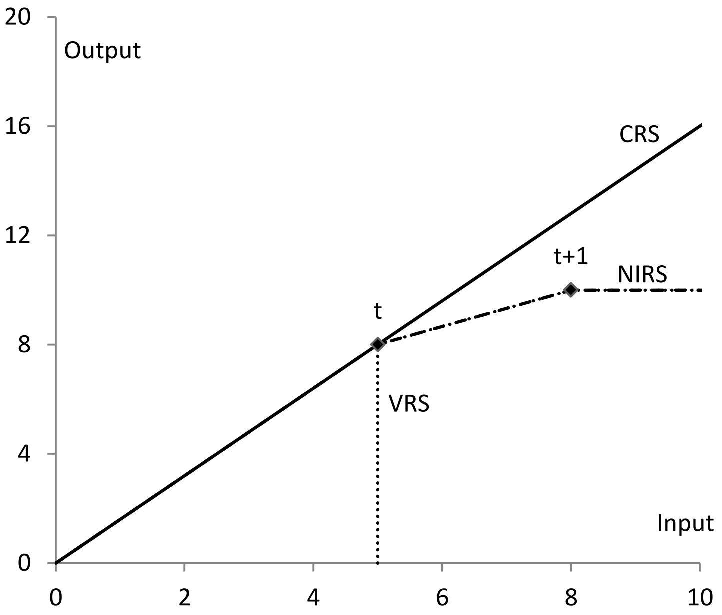

Figure 4: Non-CRS frontiers affect the used Malmquist productivity change index

Further, as the Malmquist productivity change index as specified by equation 7 result in biased productivity measures, choosing VRS instead result in ever greater issues[7]. Figure 5 below provide an illustration of how this can occur. Notice how a point can move outside the feasible region from a previous time period if the input value contracts enough, which imply a leftward horizontal movement. If this occurs, the mixed period distance functions specified by equation 2 cannot be computed. The reason for this is trivial as there simply is no frontier from time period t that is either below or above the data point at time t+1. Thus, as NIRS result in biased productivity measures, VRS can result in an absence of solutions to the distance functions. This problem holds for input-oriented indexes as well but in that case the issues would occur given a significant enough increase in output. That would lead to a situation where a frontier could not be reached by moving leftward nor rightward in the diagram from the point at time t+1.

[6] $D_0^t(x^t, y^t) = 1$ $D_0^t(x^{t+1}, y^{t+1}) = 0.78125$ $D_0^{t+1}(x^{t+1}, y^{t+1}) = 0.78125$ $D_0^{t+1}(x^t, y^t) = 1$

[7] Thanks to Hans Bjurek for suggesting this example

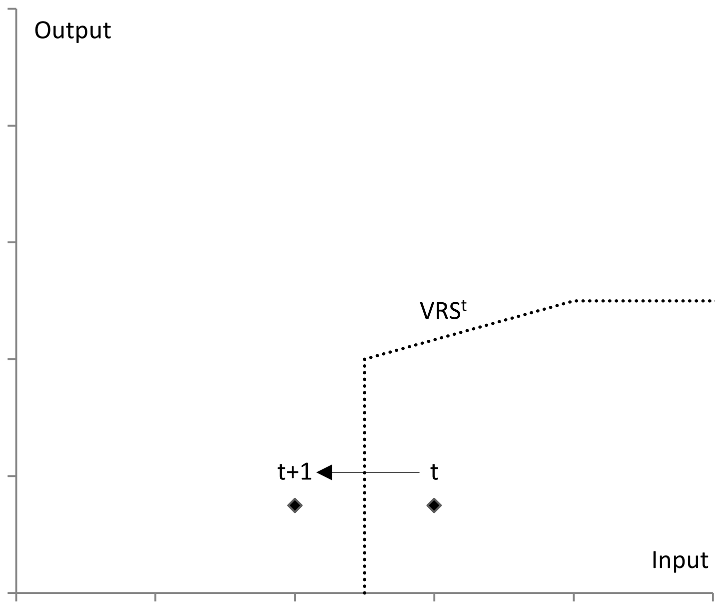

Figure 5: Why VRS frontiers could result in non-computable distance functions

2.5 Rewriting distance functions and indexes using slopes for CRS

A CRS frontier characterizes a constant ratio of outputs to inputs and all data points can be reviewed through a productivity measure of their ratio of output to input. See Appendix I for MATLAB code when using the method described in this section. The point marked DMU is used to illustrate this. First, consider the calculation of theta from the distance function specified by equation 1. In figure 6, the equation calculate the vertical distance from the horizontal axis of DMU, y^{DMU}, at x^{DMU} before dividing this distance with the corresponding distance for y^{CRS} at x^{DMU}. In this case theta would be 0.5 at x^{DMU} as y^{CRS} and y^{DMU} are 8 and 4 respectively. This ratio of 0.5 is equal to the ratio of the slope of the CRS-frontier divided by the slope of a line from the origin of coordinates through the point DMU.

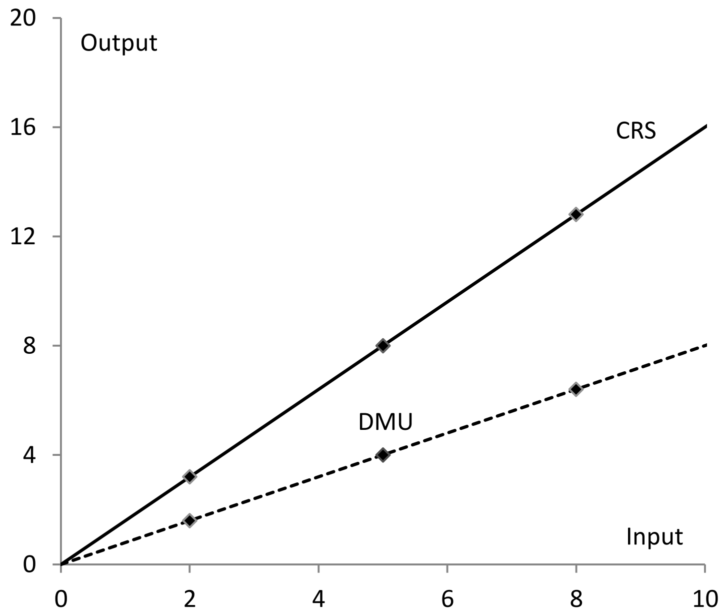

Figure 6: Using slopes to calculate theta under CRS

Every data point enveloped by a CRS frontier can be evaluated using a ratio of slopes. It then turns out that the Malmquist index of productivity change as specified in equation 7 can be calculated without estimating a frontier. In order to show this, the distance functions as well as the indexes used will be rewritten. For this purpose, figure 7 below provides notations that will be used subsequently throughout the rewriting process where slopes from the origin of coordinates for the data points are marked by the dotted lines.

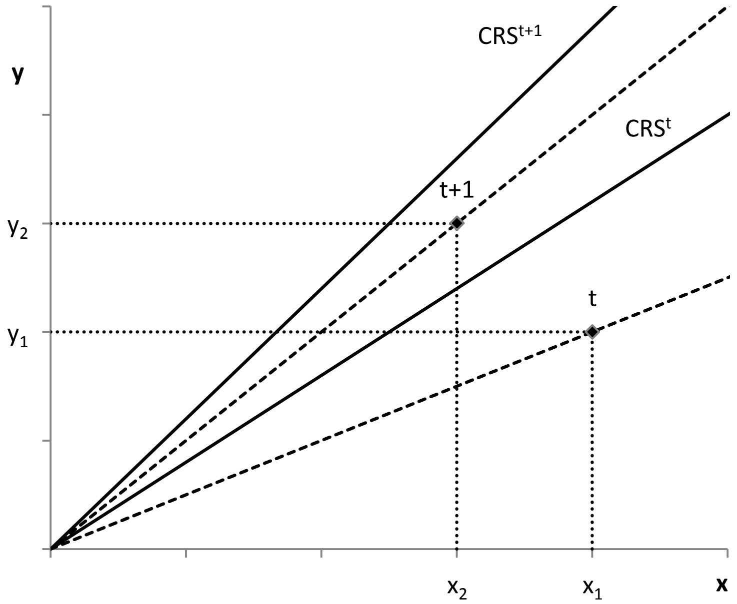

Figure 7: Notations used when rewriting indexes for CRS

Equations 18, 19, 21 and 22 show how the distance functions are rewritten while equations 20 and 23 display how the CRS frontier is eliminated as CCD indexes are formed. Then, the rewriting of the Malmquist productivity change index in equation 24 is computed without estimating a frontier. It is the productivity ratio for time period two multiplied with the inverse of the corresponding productivity ratio for the previous time period one.

(18) $$D_0^t(x^t, y^t) = \frac{\frac{y_1}{x_1}}{\frac{y_{CRS_1}}{x_{CRS_1}}} = \frac{y_1 x_{CRS_1}}{x_1 y_{CRS_1}}$$

(19) $$D_0^t(x^{t+1}, y^{t+1}) = \frac{\frac{y_2}{x_2}}{\frac{y_{CRS_1}}{x_{CRS_1}}} = \frac{y_2 x_{CRS_1}}{x_2 y_{CRS_1}}$$

(20) $$M_{CCD}^t = \frac{D_0^t(x^{t+1}, y^{t+1})}{D_0^t(x^t, y^t)} = \frac{\frac{y_2 x_{CRS_1}}{x_2 y_{CRS_1}}}{\frac{y_1 x_{CRS_1}}{x_1 y_{CRS_1}}} = \frac{\frac{y_2}{x_2}}{\frac{y_1}{x_1}} = \frac{y_2}{x_2}\left(\frac{y_1}{x_1}\right)^{-1}$$

(21) $$D_0^{t+1}(x^{t+1}, y^{t+1}) = \frac{\frac{y_2}{x_2}}{\frac{y_{CRS_2}}{x_{CRS_2}}} = \frac{y_2 x_{CRS_2}}{x_2 y_{CRS_2}}$$

$$(22) \qquad D_0^{t+1}(x^t, y^t) = \frac{\frac{y_1}{x_1}}{\frac{y_{CRS_2}}{x_{CRS_2}}} = \frac{y_1 x_{CRS_2}}{x_1 y_{CRS_2}}$$

$$(23) \qquad M_{CCD}^{t+1} = \frac{D_0^{t+1}(x^{t+1}, y^{t+1})}{D_0^{t+1}(x^t, y^t)} = \frac{\frac{y_2 x_{CRS_2}}{x_2 y_{CRS_2}}}{\frac{y_1 x_{CRS_2}}{x_1 y_{CRS_2}}} = \frac{\frac{y_2}{x_2}}{\frac{y_1}{x_1}} = \frac{y_2}{x_2}\left(\frac{y_1}{x_1}\right)^{-1}$$

$$(24) \qquad M_0(x^{t+1}, y^{t+1}, x^t, y^t) = \left(\left(\frac{y_2}{x_2}\left(\frac{y_1}{x_1}\right)^{-1}\right)\left(\frac{y_2}{x_2}\left(\frac{y_1}{x_1}\right)^{-1}\right)\right)^{1/2} = \frac{y_2}{x_2}\left(\frac{y_1}{x_1}\right)^{-1}$$

$$(25) \qquad Efficiency\ change = \frac{\frac{y_2 x_{CRS_2}}{x_2 y_{CRS_2}}}{\frac{y_1 x_{CRS_1}}{x_1 y_{CRS_1}}} = \left(\frac{y_2}{x_2}\left(\frac{y_1}{x_1}\right)^{-1}\right)\left(\frac{y_{CRS_1}}{x_{CRS_1}}\left(\frac{y_{CRS_2}}{x_{CRS_2}}\right)^{-1}\right)$$

$$(26) \quad Technical\ change = \left[\left(\frac{\frac{y_2 x_{CRS_1}}{x_2 y_{CRS_1}}}{\frac{y_2 x_{CRS_2}}{x_2 y_{CRS_2}}}\right)\left(\frac{\frac{y_1 x_{CRS_1}}{x_1 y_{CRS_1}}}{\frac{y_1 x_{CRS_2}}{x_1 y_{CRS_2}}}\right)\right]^{1/2} = \frac{\frac{x_{CRS_1}}{y_{CRS_1}}}{\frac{x_{CRS_2}}{y_{CRS_2}}} = \frac{y_{CRS_2}}{x_{CRS_2}}\left(\frac{y_{CRS_1}}{x_{CRS_1}}\right)^{-1}$$

Efficiency change and technical change are also rewritten in equations 25 and 26 below. The first component of efficiency change is the overall Malmquist productivity change index and the second is the inverse of the technical change component. Efficiency change depend on both frontiers as well as both data points from the time periods t and t+1. Technical change on the other hand is only concerned with the slope of the CRS frontier. Written in this form, it could readily be interpreted as the productivity at the CRS frontier according to the essential productivity definition for time t+1 multiplied with the inverse of the same measure at t. Now, the linear programming problems solved to yield the NIRS results in chapter 3 follow.

2.6 Formulating and computing the linear programming problems

To be able to compute the linear programming problems defined by equations 14 to 17 different techniques could be applied. For this report, MATLAB 7.12.0 (R2011a) have been used for programming and Microsoft Excel 2010 for iterative testing and visualization purposes. The MATLAB code used is available in Appendix II. MATLAB uses the function *linprog*[8] which is explained by equation 27 below.

$$(27) \qquad \min_{x} f_x^T \ such\ that \begin{cases} A \cdot x \leq b \\ Aeq \cdot x = beq \end{cases}$$

A is a matrix containing scalar weights for each row of a linear optimization problem. This matrix thus specifies the linear inequality constrains. The x denotes a vector with the unknowns to be determined by the linear optimization whereas b is a vector containing scalars denoting the right hand side of the equations characterizing the linear problem set. A and b are

[8] See http://www.mathworks.se/help/optim/ug/linprog.html for further information about *linprog*

used for inequality entries and Aeq and beq are used for equality constraints. This is not the form specified by Färe *et al*. (1994) whereby an explanation of how the linear programming problems have been rewritten to fit MATLAB notations follows. The rewriting is essentially the same for all distance functions whereby only the first linear programming problem is addressed here. Equation 14 is rewritten into equation 28 before the A matrix as well as the x and b vectors are specified by equation 29, 30 and 31 in that given order.

(28) $(D_0^t(x^{k',t}, y^{k',t}))^{-1} = max\theta^{k'}$ *is rewritten as*

$$\left\{\begin{array}{ll} \theta^{k'} y_m^{k',t} - \sum_{k=1}^{K} \lambda^{k,t} \mathrm{y}_m^{k,t} \leq 0 & m = 1, \dots, M \\ \sum_{k=1}^{K} \lambda^{k,t} \mathrm{x}_n^{k,t} \leq \mathrm{x}_n^{k',t} & n = 1, \dots, N \\ -\lambda^{k,t} \leq 0 & k = 1, \dots, K \\ \sum_{k=1}^{K} \lambda^{k,t} \leq 1 & (NIRS) \end{array}\right\}$$

(29)
$$A = \begin{pmatrix} a_{1,1} & \cdots & a_{1,K+1} \\ \vdots & \ddots & \vdots \\ a_{K+3,1} & \cdots & a_{K+3,K+1} \end{pmatrix}$$

$$a_1 = \begin{bmatrix} y_m^{k',t} & -\mathrm{y}_m^{1,t} & -\mathrm{y}_m^{2,t} & \cdots & \cdots & -\mathrm{y}_m^{K-1,t} & -\mathrm{y}_m^{K,t} \end{bmatrix}$$

$$a_2 = \begin{bmatrix} 0 & \mathrm{x}_n^{1,t} & \mathrm{x}_n^{2,t} & \cdots & \cdots & \mathrm{x}_n^{K-1,t} & \mathrm{x}_n^{K,t} \end{bmatrix}$$

$$a_3 = [0 \quad -1 \quad 0 \quad 0 \quad \cdots \quad 0 \quad 0]$$

$$a_4 = [0 \quad 0 \quad -1 \quad 0 \quad \cdots \quad 0 \quad 0]$$

$$a_5 = [0 \quad 0 \quad 0 \quad -1 \quad 0 \quad \cdots \quad 0]$$

$$a_K = [0 \quad 0 \quad \cdots \quad 0 \quad -1 \quad 0 \quad 0]$$

$$a_{K+1} = [0 \quad 0 \quad 0 \quad \cdots \quad 0 \quad -1 \quad 0]$$

$$a_{K+2} = [0 \quad 0 \quad 0 \quad \cdots \quad 0 \quad 0 \quad -1]$$

$$a_{K+3} = [0 \quad 1 \quad 1 \quad \cdots \quad \cdots \quad 1 \quad 1] \qquad (NIRS)$$

(30) $$x = [\theta^{k'} \quad \lambda^{1,t} \quad \lambda^{2,t} \quad \cdots \quad \cdots \quad \lambda^{K-1,t} \quad \lambda^{K,t}]$$

(31) $$b = \begin{bmatrix} 0 & \mathrm{x}_n^{k',t} & 0 & \cdots & \cdots & 0 & 1 \end{bmatrix}$$

There is one row in the A matrix per restriction which result in 20 rows given 17 countries, denoted by K. The number of columns is determined by the number of unknowns to be computed, which in this case are 18 as it is theta plus 17 lambdas. From this, the A matrix is multiplied from the left with the x vector consisting of one row and 18 row entries for the unknowns. This multiplication assigns the weighs for the unknowns that constitute the left side of the inequality equations that the linear programming needs to solve based on the vector b consisting of one row and 20 entries. The first row in A, a_1, correspond to the first constraint in equation 28 just as the second row, a_2, correspond to the second constraint in equation 28. This is displayed by equations 32 and 33 below which exemplifies the vector cross products that determine the left hand side conditions. Rows from a_3 to a_{K+1} correspond to the third restriction as the 17 rows state that each individual lambda needs to be greater or equal to zero, as the negative lambdas need to be less or equal to zero. This is exemplified by equation 34 below. The final row, equation 35 below, is determined by the returns of scale assumption which in this case is NIRS. Equation 28 has two non-zero right hand side entries which can be seen by the corresponding constituents of the right hand side vector b.

$$(32)\quad a_1 \times x = \begin{bmatrix} y_m^{k',t}\theta^{k'} & -y_m^{1,t}\lambda^{1,t} & -y_m^{2,t}\lambda^{2,t} & \cdots & \cdots & -y_m^{K-1,t}\lambda^{K-1,t} & -y_m^{K,t}\lambda^{K,t} \end{bmatrix}$$

$$(33)\quad a_2 \times x = \begin{bmatrix} 0 & x_n^{1,t}\lambda^{1,t} & x_n^{2,t}\lambda^{2,t} & \cdots & \cdots & x_n^{K-1,t}\lambda^{K-1,t} & x_n^{K,t}\lambda^{K,t} \end{bmatrix}$$

$$(34)\quad a_3 \times x = \begin{bmatrix} 0 & -\lambda^{1,t} & 0 & \cdots & 0 & 0 \end{bmatrix}$$

$$a_4 \times x = \begin{bmatrix} 0 & 0 & -\lambda^{2,t} & \cdots & 0 & 0 \end{bmatrix}$$

$$a_5 \times x = \begin{bmatrix} 0 & 0 & 0 & -\lambda^{3,t} & \cdots & 0 & 0 \end{bmatrix}$$

$$a_K \times x = \begin{bmatrix} 0 & 0 & 0 & 0 & \cdots & -\lambda^{K-2,t} & 0 & 0 \end{bmatrix}$$

$$a_{K+1} \times x = \begin{bmatrix} 0 & 0 & 0 & 0 & \cdots & 0 & -\lambda^{K-1,t} & 0 \end{bmatrix}$$

$$a_{K+2} \times x = \begin{bmatrix} 0 & 0 & 0 & \cdots & \cdots & 0 & 0 & -\lambda^{K,t} \end{bmatrix}$$

$$(35)\quad a_{K+3} \times x = \begin{bmatrix} 0 & -\lambda^{1,t} & -\lambda^{2,t} & -\lambda^{3,t} & \cdots & \cdots & -\lambda^{K-2,t} & -\lambda^{K-1,t} & -\lambda^{K,t} \end{bmatrix}$$

$$(36)\quad f = \begin{bmatrix} -1 & 0 & 0 & \cdots & 0 & 0 \end{bmatrix}$$

The equations 32 to 35 above exemplify and characterize the making of the linear optimizations left hand side. In order to solve the linear programming problems with respect to the right hand side characterized by the b-vector one further condition must be set. To change the returns on scale assumption to CRS the row a_{K+3} as well as the 20th entry in the b vector should be removed. If instead VRS is to be applied, the inequality sign between row a_{K+3} and the 20th entry in the b vector should be changed to an equality, as explained by equation 13. Equation 14 which portray the distance function as specified by Färe *et al.* (1994) state that theta is to be maximized. However, MATLAB's *linprog* syntax minimizes with respect to the function f. It is a vector of one row with 18 entries, K plus one, as it assigns scalar weights for the x vector. To produce the desired output from the linear programming, minus theta is minimized. This is achieved by the vector f as specified by equation 36 above. Theta, as illustrated in figure 1, is attained through taking the inverse of the theta that the MATLAB *linprog* computes. This concludes the description of mathematical representations and linear programming. Thus, it is time to review the data selection.

2.7 Data selection for inputs and outputs

PWT, version 5, is described as following by Summers and Heston (1991, p. 1): 'its unique feature is that its expenditure entries are denominated in a common set of prices in a common currency so that *real* international quantity comparisons can be made both between countries and over time.' This is a work in progress as the data set have been updated several times since. The most recent version of the PWT is 8.0 (PWT8) provided by Feenstra *et al*. (2013b), for which Feenstra *et al.* (2013a) has provided a user guide. Inklaar and Timmer (2013) elaborate further specifically regarding capital and labor for the interested reader.

As the model used for the linear programming is one input and one output there are two measures that needs be obtained namely output per worker and capital per worker. Unless directly provided, a measure of output needs to accompany capital and worker measures. Regarding data and measurement issues, Coelli *et al.* (2005) describe labor and capital as considerably important primary inputs before discussing how these can be treated. For labor, a few common alternative measures are number of employed persons, hours of labor input, full-time equivalent employees or total wages before stating that 'if we have to choose or recommend an appropriate measure of labour input, total numbers of hours worked is the best indicator of labour input.' (Coelli *et al*., 2005, p. 142)

As capital and labor inputs, Färe *et al*. (1994) used capital stock per worker[9] and real gross domestic product (GDP) per worker respectively. These were available as *KapW* and *RGDPW* in the PWT5 but are no longer directly provided. Therefore, they retrieved using intermediate variables. For real GDP per capita, *rgdpo*, measuring output-based real GDP at chained PPP's in million USD in 2005 prices is divided by *pop* which measured a country's population in millions. The measure thus represents USD per capita in 2005 prices. This output-based measure is a new feature in the PWT8. Overall, expenditure-based and output-based real GDP measures are comparable but some countries display significant differences; five percent of the PWT sample had expenditure contra output discrepancies exceeding 20 percent. (Feenstra *et al*., 2013) Feenstra *et al*. (2013, p. 29) state that '… for analyzing productivity differences across countries, real GDP^{o}[10] would be the appropriate measure'.

The needed input variable is not GDP per capita but rather output per worker for which *rgdpo* is divided by *emp*, a measure of the number of people in millions that are engaged in the workforce. Although, the total amount of labor hours are available through *avh* in PWT8, *emp* is chosen as it more closely resemble the measure used by Färe *et al*. (1994). For capital per worker, *rkna* which represents a country's capital stock in millions USD expressed in 2005 years prices is divided by *emp*. The variable *rkna* is a Törnqvist aggregate of individual asset growth rates (Inklaar & Timmer, 2013). So, the measure denotes capital stock in USD, again in 2005 years prices, per worker. Feenstra *et al*. (2005) label this measure tangible capital stock per worker in USD. These are the inputs and outputs used for the linear programming which results are presented in section 3.

[9] 'Capital stock does not include residential construction but does include gross domestic investment in producers' durables, as well as nonresidential construction. These are the cumulated and depreciated sums of past investments.' (Färe *et al*., 2004, p. 76)
[10] GDP^{o} denotes output-based real GDP

3. Results

This section contains the results of the methods applied to three sets of data which required 1836 linear programming problems to be solved as it is 612 per data set. First, the techniques are applied to the same data set as Färe *et al*. (1994) used. Secondly, the same techniques are applied to a more recent data set from the data base, albeit a much updated version. Finally, the techniques are applied to an updated data set from the same data base covering the same time period as Färe *et al*. (1994).

3.1 1979-1988 based on PWT5

To ensure that the interpretation of the models and the programming techniques applied are correctly applied, it was believed to be useful to perform the calculations on the same data which then should yield the same results. As this could be a sound approach, attaining the data set used 20 years earlier proved to be very difficult. The PWT version 5 (PWT5) was published as an appendix to the *Quarterly Journal of Economics* as a floppy disk (Summers & Heston, 1991). Swedish libraries as well as some international economics libraries were inquired but none of them had kept the floppy disk appendix. Neither could the publishing journal nor the digital publisher JSTOR assist. Not even the author, Alan Heston, knew how the data could be retrieved.

Upon extensive Googling, some economic researchers were found who had written about the PWT5. One of these researchers responded positively, namely Valerie Ramey, Professor of Economics at the University of California, San Diego, and the original data set was finally retrieved. This set containing the data used by Färe *et al*. (1994) from PWT5 is presented in Appendix III which is followed by Appendix IV which provides a selection of the results yielded by solving the linear programming problems in MATLAB[11]. These results are not copied from the article but rather reconstructed using the same linear programming techniques on the same data set.

Recall the discussion regarding the dubious description regarding which returns to scale constraints to apply. When applying linear programming techniques on the PWT5 data set, it is clear that Färe *et al*. (1994) established a NIRS frontier rather than a CRS frontier for the distance functions. Table 1 below presents results using the different returns to scale constraints regarding average annual index changes for the three most central indexes. The Malmquist productivity change index (MALM) is similar to the fourth decimal for all countries using NIRS as specified by equation 12 earlier. This holds true for technical change (TECHCH) as well. For efficiency change (EFFCH), Belgium and Finland differ with Färe *et al*. (1994) on the fourth decimal as they were 0.9932 and 1.0109 respectively while all other directly correspond. If CRS is used instead, thus not adding any constraints to those specified by equation 11, nine out of the 17 countries display deviating results. The explanations for eight of these are that they are situated to the right of the CRS frontier determining country as was the case for data point D in figure 3.

[11] This set include example graphs for three years with their NIRS and VRS frontiers, theta values for the same period NIRS frontier as well as Malmquist productivity, efficiency and technical change indexes along their geometric means and cumulated changes. Such result data is available for all three subsections in this chapter.

Table 1: Comparing CRS and NIRS results 1979-1988, PWT5

Average Annual Changes, 1979-1988, PWT5						
	Constant Returns to Scale (CRS)			Non-Increasing Returns to Scale (NIRS)		
	MALM	TECHCH	EFFCH	MALM	TECHCH	EFFCH
Australia	0,9973	1,0009	0,9964	0,9973	1,0009	0,9964
Austria	0,9981	1,0009	0,9972	0,9981	1,0009	0,9972
Belgium	1,0017	1,0009	1,0009	1,0092	1,0161	0,9931
Canada	0,9847	1,0009	0,9838	1,0151	1,0161	0,9990
Denmark	1,0026	1,0009	1,0017	1,0026	1,0009	1,0017
Finland	1,0030	1,0009	1,0021	1,0272	1,0161	1,0109
France	0,9915	1,0009	0,9907	1,0081	1,0161	0,9921
Germany	0,9946	1,0009	0,9937	1,0117	1,0161	0,9956
Greece	0,9962	1,0009	0,9953	0,9962	1,0009	0,9953
Ireland	0,9821	1,0009	0,9813	0,9821	1,0009	0,9813
Italy	1,0072	1,0009	1,0064	1,0195	1,0161	1,0033
Japan	0,9811	1,0009	0,9802	1,0287	1,0161	1,0124
Norway	0,9977	1,0009	0,9968	1,0236	1,0161	1,0073
Spain	0,9898	1,0009	0,9890	0,9898	1,0009	0,9890
Sweden	1,0019	1,0009	1,0010	1,0019	1,0009	1,0010
United Kingdom	1,0012	1,0009	1,0003	1,0012	1,0009	1,0003
United States	1,0009	1,0009	1,0000	1,0085	1,0085	1,0000
Mean:	0,9959	1,0009	0,9951	1,0070	1,0085	0,9986

The ninth was the United States which determined the frontier. As the input data summary found in Appendix III displays increased capital per worker each year and decreasing output per worker for two years. Figure 8 below illustrate how such development moves point A towards the fourth quadrant in a plane using A as the origin of coordinates from A^t to A^{t+1}, effectively moving the data point to the zone where CRS and NIRS are not equal.

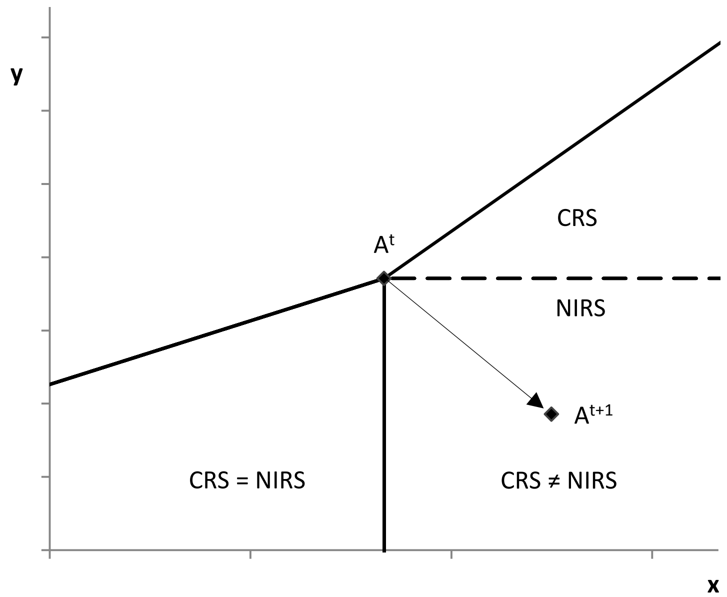

Figure 8: Why a frontier country can have different results using CRS and NIRS

3.2 2002-2011 based on PWT8

This section presents results using the same linear programming techniques used by Färe *et al*. (1994) on the most recent data available from the PWT data base, being version 8.0 (PWT8) as presented by Feenstra *et al*. (2013b). The sample consists of ten years, the same number of years as the 1994 study, and covers the time period between 2002 and 2011 for the same 17 countries. See Appendix V for the data set and for results see Appendix VI. The countries on the frontier were Ireland, Norway, Sweden and the United States. For NIRS frontier countries, see table 2 below. Although Ireland has a theta value of one for each year in the appendix table, these are rounded figures meanwhile the table below present years it was one.

Table 2: Frontier countries using NIRS 2002-2011, PWT8

Theta values equal to one at $D_0^t(x^t, y^t)$ for NIRS PWT8											
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Years
Ireland	1,0000	1,0000	1,0000		1,0000	1,0000	1,0000	1,0000	1,0000		8
Norway					1,0000	1,0000	1,0000				3
Sweden							1,0000	1,0000	1,0000	1,0000	4
United States	1,0000	1,0000	1,0000	1,0000				1,0000	1,0000		6

However, if one instead establishes a true CRS frontier, there is only one country at the frontier per year and neither Norway nor United States determined the frontier at any year. This is a quite remarkable difference. It is interesting to notice how Ireland determined the frontier between 2002 and 2007 only to pass the torch to Sweden in 2008 who remained the lone fully technically efficiency country for the remainder of the years in the sample. See table 3 below for a summary of the countries determining the frontier.

Table 3: Frontier countries using CRS 2002-2011, PWT8

Theta values equal to one at $D_0^t(x^t, y^t)$ for CRS PWT8											
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Years
Ireland	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000					6
Norway											0
Sweden							1,0000	1,0000	1,0000	1,0000	4
United States											0

The full summary of theta values along the most important indexes are put forth by table 4 below on the following page. On average[12], the annual Malmquist productivity index increased slightly less than 0.4 percentage points per year. Only three countries displayed deteriorating performance namely Greece, Ireland and the United Kingdom with decreasing average annual Malmquist productivity indexes. The best performing country was Norway with an increase of about 2.5 percent per year on average. It should be noted that this was the only result above two percentage points and there were only two countries with an average improvement about one percentage point.

[12] The geometric mean is used for average annual changes for individual countries as well as for the entire sample

Table 4: Main results using NIRS from 2002-2011, PWT8

Main results 2002-2011 PWT8							
	Mean	Average annual			Cumulated		
	$D_0^t(x^t,y^t)$	MALM	TECHCH	EFFCH	MALM	TECHCH	EFFCH
Australia	0,7978	1,0034	1,0115	0,9920	1,0306	1,1079	0,9302
Austria	0,8105	1,0039	1,0125	0,9915	1,0355	1,1187	0,9257
Belgium	0,8840	1,0000	1,0117	0,9885	1,0002	1,1099	0,9012
Canada	0,8035	0,9955	1,0121	0,9837	0,9606	1,1139	0,8624
Denmark	0,7428	1,0096	1,0131	0,9966	1,0898	1,1240	0,9696
Finland	0,7524	1,0078	1,0114	0,9965	1,0727	1,1075	0,9686
France	0,8075	1,0053	1,0115	0,9938	1,0488	1,1087	0,9460
Germany	0,7524	1,0089	1,0145	0,9945	1,0829	1,1382	0,9514
Greece	0,6788	0,9931	1,0039	0,9893	0,9394	1,0353	0,9073
Ireland	1,0000	0,9857	0,9857	1,0000	0,8784	0,8784	1,0000
Italy	0,7820	1,0011	1,0119	0,9893	1,0098	1,1127	0,9075
Japan	0,6794	1,0044	1,0115	0,9929	1,0401	1,1086	0,9382
Norway	0,9623	1,0248	1,0114	1,0132	1,2464	1,1076	1,1253
Spain	0,7486	1,0123	1,0103	1,0019	1,1159	1,0969	1,0173
Sweden	0,9091	1,0031	0,9816	1,0220	1,0284	0,8457	1,2160
United Kingdom	0,8527	0,9953	0,9934	1,0019	0,9582	0,9422	1,0170
United States	0,9921	1,0102	1,0109	0,9993	1,0960	1,1025	0,9941
Mean:	0,8209	1,0037	1,0069	0,9968	1,0342	1,0642	0,9718

Overall, changes were due to the technological improvement component rather than the efficiency increase component, similar to Färe *et al*. (1994). For technological improvement, 14 out of the 17 countries improved this aspect and Sweden was the worst performer and Germany the best. In terms of efficiency gains, five countries improved and Sweden was the best performer. Notably, the spread in annual performance seems larger with regards to efficiency than technology. Regarding the cumulative Malmquist productivity change index, Norway readily outperformed the other countries with their 24.6 percent, more than double that of the second country Spain. Figure 9 below illustrate differences between Sweden and Norway being the final frontier determinant and the best performing country respectively.

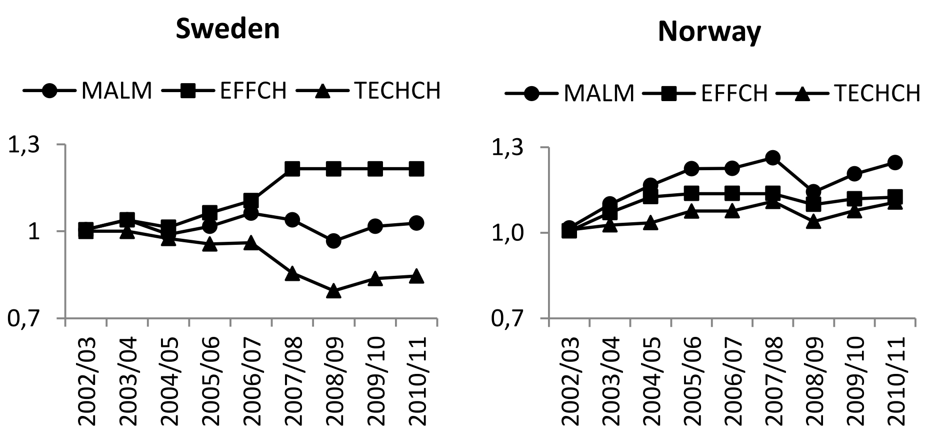

Figure 9: Swedish and Norwegian productivity development trajectories 2002-2011, PWT8

Sweden displayed the worst and best performances for technological change and efficiency change respectively. Norway, outperforming Sweden by far regarding the overall Malmquist index, did so by performing reasonably well in both of the productivity subcomponents. In the Färe *et al*. (1994) study, Norway was the third best performer and Sweden placed eleventh in the same sample of countries. Interestingly, Sweden maintained that eleventh place while Norway advanced. Japan who was the best performer back then placed only eight for the 2002 to 2011 sample. Finally, it can be noted that the entire sample on average was about 17.9 percentages short of the vertical frontier for the same time frontier as the data points.

3.3 1979-1988 based on PWT8

This section presents results when using the same methods, countries and time periods as Färe *et al*. (1994) on the PWT8 data set made available by Feenstra *et al*. (2013b). The data set is available in Appendix VII, for the full set of results see Appendix VIII. To evaluate if there are any implications of using an updated data set, it is useful to revisit the same pair of graphs used in figure 9 above for Japan and the United States. Figure 10 below presents the Malmquist productivity change index trajectories with its subcomponents below.

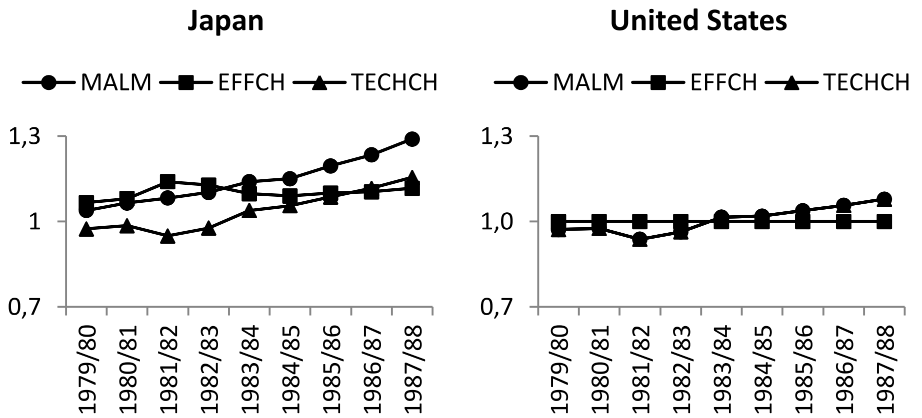

Figure 10: Japanese and American productivity development trajectories 1979-1988, PWT5

As PWT is updated several times since Färe *et al*. (1994) used its Mark 5, the PWT5, some differences could be expected but the extent of differences between figure 10 above and figure 11 below are substantial. Japan had a cumulated Malmquist productivity improvement of about 12.5 percent based on PWT8 compared with the 29.1 percent reported using PWT5. This difference can mainly be accredited to a significant difference regarding the technological component which was 15.5 compared with 2.4 for PWT5 and PWT8 respectively. On top of this drastic decrease, there was a slight decrease from 11.7 to 10 for the efficiency component as well. The United States on the other hand had a cumulated Malmquist productivity improvement of 9.4 percent using PWT8 compared to 7.9 percent using PWT5. However, it is noteworthy that the United States as the sole determinant of the NIRS frontier for Färe *et al*. (1994), no longer determined the frontier all years as the change in the efficiency curve reveal in figure 10 above. Determining the frontier implies full technical efficiency, thus equal to one, for all years which is seen in figure 11 below to the right.

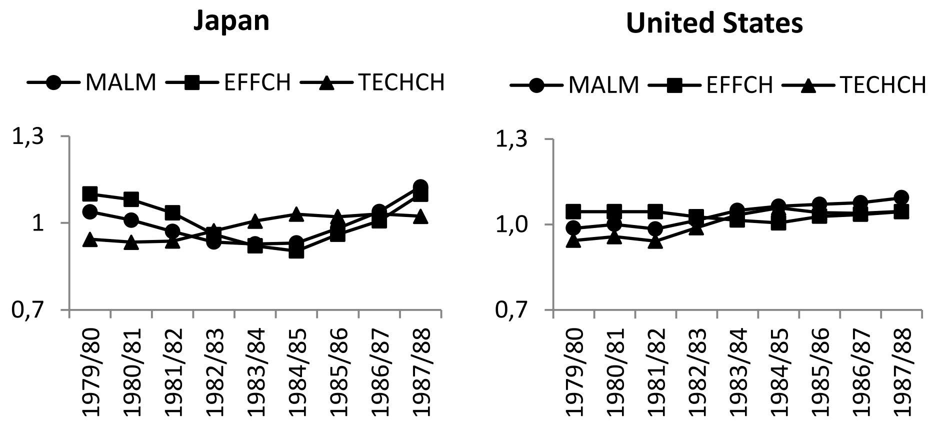

Figure 11: Japanese and American productivity development trajectories 1979-1988, PWT8

As it could be deduced that the United States was not fully technically efficient for all years, it is thus interesting to evaluate which countries that determined the boundaries for the technological frontier using PWT8 data. Table 5 presents the countries at the frontier for the time period. Canada is at the frontier for all ten years compared to three years for the United States. Norway, who was a strong performer for Färe *et al*. (1994) as well, notes nine years and Ireland five.

Table 5: Frontier countries using NIRS 1979-1988, PWT8

Theta values equal to one at $D_0^t(x^t, y^t)$ for NIRS PWT8											
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**Years**
Canada	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	10
Ireland		1,0000		1,0000				1,0000	1,0000	1,0000	5
Norway	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000		9
United States		1,0000	1,0000	1,0000							3

Table 5 above is on one hand based on the same linear programming problems that yielded the same results as Färe *et al*. (1994), however to determine the magnitude of change regarding country determining the frontier it seems interesting to review the CRS case as well. These are presented by table 6 below. The results are very different from those presented in the 1994 study as the United States are not on the technological frontier for a single year. Instead, Canada and Ireland took turns at determining the frontier. Given these quite remarkable findings the main results of the data envelopment analysis based on the PWT8 data will be briefly reviewed.

Table 6: Frontier countries using CRS 1979-1988, PWT8

Theta values equal to one at $D_0^t(x^t, y^t)$ for CRS PWT8											
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**Years**
Canada	1,0000				1,0000	1,0000	1,0000				4
Ireland		1,0000	1,0000	1,0000				1,0000	1,0000	1,0000	6
Norway											0
United States											0

Table 7 below presents a summary of the main results for 1979 to 1988 based on PWT8 and a NIRS frontier. First, it is noteworthy that the United States which did not determine the frontier one single year displays a mean theta value around 98.5 meaning that although they did not determine the frontier they were just beneath it. The mean Malmquist productivity improvement index was slightly lower than the 0.7 percent reported by Färe *et al*. (1994) at 0.61 percent. For technological improvements and efficiency, these results are to the contrary of Färe *et al*. (1994, p. 78) who stated that 'on average, that growth was due to innovation (TECHCH) rather than improvements in efficiency (EFFCH).' They reported a sample mean annual efficiency change below zero whereas the PWT8 data set yields a positive efficiency development around 0.5 percent. It seems as the conclusions from the PWT5 data set overestimated technological improvements as it yielded 0.9 compared to the 0.1 percentages based on PWT8 data.

Table 7: Main results using NIRS from 1979-1988, PWT8

Main results 1979-1988 PWT8							
	Mean	Average annual			Cumulated		
	$D_0^t(x^t,y^t)$	MALM	TECHCH	EFFCH	MALM	TECHCH	EFFCH
Australia	0,8493	1,0162	1,0032	1,0130	1,1561	1,0294	1,1231
Austria	0,6714	1,0062	0,9990	1,0072	1,0570	0,9906	1,0670
Belgium	0,8306	1,0070	0,9985	1,0086	1,0652	0,9866	1,0797
Canada	1,0000	1,0030	1,0030	1,0000	1,0274	1,0274	1,0000
Denmark	0,7014	1,0049	0,9990	1,0060	1,0452	0,9909	1,0549
Finland	0,6469	1,0160	0,9974	1,0186	1,1535	0,9770	1,1806
France	0,8009	1,0059	1,0031	1,0028	1,0544	1,0282	1,0254
Germany	0,6518	1,0043	1,0018	1,0024	1,0390	1,0166	1,0220
Greece	0,5752	0,9985	1,0058	0,9927	0,9866	1,0534	0,9365
Ireland	0,9883	0,9987	0,9983	1,0003	0,9880	0,9850	1,0030
Italy	0,7614	1,0151	1,0044	1,0107	1,1444	1,0400	1,1004
Japan	0,5960	1,0132	1,0026	1,0106	1,1252	1,0236	1,0993
Norway	0,9993	0,9987	0,9995	0,9992	0,9883	0,9952	0,9930
Spain	0,6652	1,0011	1,0010	1,0001	1,0102	1,0089	1,0012
Sweden	0,8865	1,0042	0,9974	1,0069	1,0387	0,9765	1,0636
United Kingdom	0,8028	1,0013	0,9975	1,0038	1,0118	0,9780	1,0346
United States	0,9847	1,0100	1,0051	1,0049	1,0941	1,0468	1,0452
Mean:	0,7889	1,0061	1,0010	1,0051	1,0565	1,0088	1,0473

Based on the new data, Japan was no longer the best performer with respect to Malmquist productivity improvement as Australia and Finland received higher cumulated values. Notably, Australia displayed the fourth worst cumulated productivity development for Färe *et al*. (1994) meanwhile Finland was the second best based on PWT5 as well. For the technological development component, the results are vastly different. Although Greece had a modest annual improvement about 0.6 percent it was enough to have the best cumulated value of 5.3 percent. As for efficiency development, Finland, Australia, Italy and Japan placed the highest in that given order. Besides Australia, they all displayed high values using PWT5 as well. However, Norway who had 15.5 percent and a shared first place was now second worst.

4. Conclusions

This section addresses the research questions stated in section 1.2 which are addressed in their stated order.

R1.How can the productivity development for 2002 to 2011 be characterized?

There was an average productivity improvement, based on the output-oriented Malmquist productivity change index, just short of 0.4 percent annually. Out of the 17 countries, only four saw deteriorating productivity. The main productivity driver was technological improvements, only five countries had an annual growth in efficiency. Depending on choice of scale, four or two countries determined the frontier for NIRS and CRS respectively. These were Ireland, Norway, Sweden and the United States with Sweden being the sole determinant of the frontier regardless of NIRS or CRS for the final year of 2011. Sweden was an interesting country in the sample as the country was the worst performer with regards to technological improvements meanwhile the best with regards to efficiency development. Norway was the best performing country with a 24.6 percent productivity improvement with solid performances regarding both technological improvement and efficiency.

R2. How does this compare with the findings from 1979 to 1988?

Compared with the 1979 to 1988 results from Färe *et al*. (1994) based on the PWT5 data set the productivity growth was about half, 0.4 compared with 0.7 percent, due to slightly lower results for the subcomponents. These resulted in 0.7 and 0.9 percent for technological improvements and minus 0.3 and minus 0.1 percent for efficiency for the 1979 to 1988 PWT5 and 2002 to 2011 PWT8 respectively. Although productivity growth was slower, the growth was due to technological improvements rather than efficiency gains just as for Färe *et al*. (1994).

R3. Given an updated data set, what are the implications for 1979 to 1988 findings?

There are significant differences. If assuming that the revisions of the PWT data have improved its reliance the new results could possibly be considered more accurate. However, it should be emphasized that the exact same categories of inputs and outputs no longer exist which likely impacted the results to some extent. Besides individual countries results, one major conclusion in Färe *et al.* (1994) was that growth from 1979 to 1988 was mostly due to technological improvements for OECD countries is not supported by the updated data set. This data set showed that it rather was efficiency gains that were the driver behind productivity improvements during this period. Also, it highlights the important of estimating the reliability of a data set that is used for analysis. The capital per worker measure is much higher for PWT8 compared with PWT5, as the estimations seemingly have changed quite a lot in retrospect during the almost 25 years since PWT5. And the differences are of significant importance, as Japan for instance went from being the furthest to the right to being mid-sample as time passed and the PWT was updated from PWT5 to PWT8.

5. Discussion

Data envelopment analysis provides interesting techniques to determine positions relative to some best practice benchmark. Compared to statistical methods, it seems useful to compare something to the best known possible performance rather than the average performance. After all, in terms of GDP, the goal of a society is likely not to ensure that the GDP per capita is average or above average. Instead it seem more likely that a decision making unit such as a country would want to evaluate itself compared to countries with similar preconditions and strive to improve according to the findings. Although the data envelopment analysis use highly aggregated data in this report, it seems interesting to benchmark a country with similar countries in terms of capital per worker or industry structure. The sample was chosen based on the choices made by Färe *et al*. (1994). However their choices were not based on industry structure but rather because of the fact that the data sought for was available for just these particular countries.

In addition, the data envelopment analysis provided plenty of learning opportunities both regarding mathematical understanding but also more operational aspects of conducting the linear programming to reach the results that the methods can yield. Regardless of how solid the results presented based on such a seemingly rigorous mathematical foundation appears, the data set still determines the reliability of the results. In this case, the choice of data set and the version thereof proved to be of the utmost importance. Some changes were to be expected but the finding that the productivity growth for the best performing country of Japan would drop so significantly during the same time period was unexpected. Although it casts a shadow of doubt regarding the overall results derived based on the old data set, it simultaneously reduces the perceived reliability of the new analysis based on updated figures as well. Perhaps the main conclusion and learning from this example was the importance of a carefully chosen data set.

Turning to the methods, it was difficult to follow the methods described by Färe *et al*. (1994). To some extent, Krugman's notion of how highly specialized language can be used to hide the banality of an idea was one source for the threshold to follow the footsteps of the economists publishing in *The American Economic Review*. Another was that the information provided was inaccurate or at least dubious. When the results of an inexperienced economic student do not match those expected, it is easy to doubt the methodological understanding or the application. Which one to blame feels impossible to determine during the struggle. In this case, some results were right and others wrong. Upon greater understanding of the methods, the explanation was that the data points to the left of the frontier determining nation was correct as these yield identical results under CRS and NIRS assumptions.

Deviating from the CRS assumption was necessary to provide the results needed, however the implications for the productivity measure of such sidestep were not immediately obvious. Given scale changes, the Malmquist productivity change index had been criticized for its ability to satisfy the most fundamental productivity measure being the ratio of output to input. This measure is just as sophisticated in its simplicity as it is intuitive for the single input, single output case. However, the methods that were to be applied did no longer adhere to this definition. It is noteworthy that this was not mentioned by Färe *et al*. (1994).

Regarding the results, industrial nations such as Japan and Germany being widely known for their high level of productivity could be expected to place higher. The Färe *et al*. (1994) study was interesting in the aspect as it was able to pinpoint the sharp rise in productivity that Japan displayed during the 1980's. Although their position in terms of the cumulative Malmquist productivity change index results worsened, Japan still placed fourth. On the other hand, Norway who is not really known for their productive capabilities were the best performer with regards to cumulative Malmquist productivity change index results for the most recent sample from 2002 to 2011. As this might be accurate for living standards through an intermediary measure of GDP per worker, it does not necessarily have to do with neither technological improvement nor efficiency gains as it could be due to for instance oil findings. Another concern is how the model premiers less capital intense countries. A capital intense industry structure would mean that the country would be place far to the right in the input- and output-diagram. This would, given a comparable GDP per worker level to a country with a less capital intensive industry structure, mean that the angle from the origin of coordinates would be lesser and the technical efficiency under CRS could be relatively low. Such characteristic could be interpreted as that the model favors less capital industries. An example would be that a country of Spotify-like companies would be considered more productive than a country of Volvo's and ABB's.

Although it should be considered bad that a method is presented in a manner by which it is very difficult to follow, back and forth struggles do lead to learning opportunities as many areas of the methods needs to be explored in order to yield the expected outputs. Through this understanding and upon guidance from a highly initiated and experienced supervisor, new heights of understanding could be reached. This enabled the slope CRS rewriting which is useful to understand some of the discrepancies regarding the results between PWT5 and PWT8 and some of the unexpected characteristics of the results in general.

As it was shown that technical efficiency under CRS only depend on the frontier which explains the clustering of technical change results for 1979-1988 under NIRS. For a CRS frontier, the technical change component does not vary. This alone could have revealed that Färe *et al*. (1994) did not use CRS. However it is not easily spotted without the rewriting in equation 26, showing that the frontier alone determines the component. The reason that a lot of countries had identical results for PWT5 was that many of these were positioned to the left of the frontier-determining country thus adhering to a CRS frontier. Although it is not shown in this report, the reason for all the other countries sharing the technical change component is most likely similar but for NIRS. If countries had moved back and forth between CRS and NIRS, different values would have been expected which was not the case.

To conclude, there were two main factors which altered the Malmquist index's ability to actually measure what it was supposed to measure. First, the choice of frontier of NIRS rather than CRS and second the inconsistencies over time for the data set when moving from PWT5 to PWT8. These kinds of issues do reduce the credibility of the findings. To remedy the first, the CRS frontier can be used which accurately reflect the ratio of output to input or some version of Malmquist productivity indexes put forth by the research communities. For the second, the findings during this thesis work point towards careful input data scrutinizing.

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Appendix I: MATLAB code for CRS slope method

This appendix contains the MATLAB code used to compute the Malmquist index and its subcomponents efficiency change and technical change under CRS without linear programming techniques. To identify the CRS frontier for each year, the output vector is divided term by term with the input vector and the highest value was chosen for each year. If this code is to be used, use the following steps to choose the desired data set:

1. Change `'MATLABinput.xlsx'` to an MS Excel file placed in the same folder as the MATLAB m-file
2. Choose the desired sheet, default is 1
3. Select the area for the input and output
   a. Input default is `'B3:K19'`
   b. Output default is `'M3:V19'`

```
clear
clc

Xinput = xlsread('MATLABinput.xlsx',1,'B3:K19').';
Yinput = xlsread('MATLABinput.xlsx',1,'M3:V19').';

[T,K] = size(Yinput); % Set T as time periods and K as DMUs in sample

for t = 1:T-1,
   for k = 1:K,

       MALMcrs(t,k) =
inv(Yinput(t,k)/Xinput(t,k))*(Yinput(t+1,k)/Xinput(t+1,k));

        TECHCHcrs(t,k) =
inv(max(Yinput(t,1:K)./Xinput(t,1:K)))*max(Yinput(t+1,1:K)./Xinput(t+1,1:K)
);

       EFFCHcrs(t,k) =
(inv((Yinput(t,k)/Xinput(t,k))*inv(Yinput(t+1,k)/Xinput(t+1,k))))*((max(Yin
put(t,1:K)./Xinput(t,1:K))*inv(max(Yinput(t+1,1:K)./Xinput(t+1,1:K))));

   end
end

clearvars k t
```

Appendix II: MATLAB code for linear programming

This appendix contains the MATLAB code used to compute the 918 linear programming problems computed by Färe *et al*. (1994), denoted FGNZ in the code. If this code is to be used, the following steps explain how a data set can be entered:

1. Change 'MATLABinput.xlsx' to an MS Excel file placed in the same folder as the MATLAB m-file
2. Choose the desired sheet, default is 1
3. Select the area for the input and output
    a. Input default is 'B3:K19'
    b. Output default is 'M3:V19'

```
% FGNZ: Färe, R., Grosskopf, S., Norris, M., & Zhang, Z. (1994).
Productivity Growth, Technical Progress, and Efficiency Change in
Industrialized Countries. The American Economic Review, 84(1), 66-83.
% Stable URL: http://www.jstor.org/stable/2117971

%%% Code %%%
clear
clc

X1994PWT5 = xlsread('MATLABinputPWT.xlsx',1,'B3:K19'); % K/L data, 1979-
1988 from PWT5
Y1994PWT5 = xlsread('MATLABinputPWT.xlsx',1,'M3:V19'); % Y/L data, 1979-
1988 from PWT5
X1994PWT8 = xlsread('MATLABinputPWT.xlsx',2,'B3:K19'); % K/L data, 1979-
1988 from PWT8
Y1994PWT8 = xlsread('MATLABinputPWT.xlsx',2,'M3:V19'); % Y/L data, 1979-
1988 from PWT8
X2014PWT8 = xlsread('MATLABinputPWT.xlsx',3,'B3:K19'); % K/L data, 2002-
2011 from PWT8
Y2014PWT8 = xlsread('MATLABinputPWT.xlsx',3,'M3:V19'); % Y/L data, 2002-
2011 from PWT8

% Default input matrices: FGNZ PWT5 1979-1988 data
Xinput = X2014PWT8.'; % Choose and transpose input data source
Yinput = Y2014PWT8.'; % Choose and transpose output data source
Years = xlsread('MATLABinputPWT.xlsx',1,'B2:K2').'; % Gathering year list

% Default label vectors: FGNZ PWT5 1979-1988 data
[~, Countries] = xlsread('MATLABinputPWT.xlsx',1,'A3:A19'); % Gathering
country list, ~ skips numeric output
Countries = Countries.'; % Transpose country list
[T,K] = size(Yinput); % Set T as years in sample and K as countries in
sample
clearvars X1994PWT5 Y1994PWT5 X1994PWT8 Y1994PWT8 X2014PWT8 Y2014PWT8; %
Clear from Workspace

A = zeros(K+3, K+1); % Constraint matrix A
[Arow, Acol] = size(A); % Assess row and colum numbers for A
f = zeros(1,K+1); % Establish minimizing function vector
f(1) = -1; % Minimizing "theta" (first variable) function for linear
optimization

for k = 1:K,
    A(2+k,k+1) = -1;
    A(K+3,k+1) = 1;
```

```
end

Aeq = A(K+3,1:K+1); % VRS condition row for matrix A
beq = 1; % VRS condition for vector b

for t = 1:T, % Choosing year
    for k = 1:K, % Choosing country

        %%% t %%%
        A(1,1) = Yinput(t,k); % Setting ymkt as theta-weight at t
        A(1,2:Acol) = -Yinput(t,1:K); % Assigning negative Y-weights for
lambda at t
        A(2,2:Acol) = Xinput(t,1:K); % Assigning positive X-weights for
lambda at t

        b = zeros(1,K+3); % Clearing and establishing output restriction
vector at t
        b(1,2) = Xinput(t,k); % Setting nkt as right hand side for
restriction (2) at t
        b(1,K+3) = 1; % NIRS
%       A(Arow,1:Acol) = zeros(1,1:Acol); % CRS

        linprog(f, A, b); % Solves min f'*x such that A*x ? b. See
http://www.mathworks.se/help/optim/ug/linprog.html
        D1(t,k) = 1/ans(1); % CRS Dt at time t, FGNZ equation 16

        linprog(f, A, b, Aeq, beq);
        D5(t,k) = 1/ans(1); % VRS Dt at time t, FGNZ footnote 17

        %%% t+1 %%%
        if t<T

            t=t+1; % Setting t to t+1 for mixed-period comparison

            At = A;
            bt = b;

            At(1,1) = Yinput(t,k); % Setting ymkt as theta-weight at t+1
            bt(1,2) = Xinput(t,k); % Setting nkt as right hand side for
restriction (2) at t+1

            linprog(f, At, bt);
            D2(t-1,k) = 1/ans(1); % CRS Dt at t+1, FGNZ equation 17

            CCD1(t-1,k) = D2(t-1,k)./D1(t-1,k); % CCD Malmquist index at t,
FGNZ equation 4

            At(1,2:Acol) = -Yinput(t,1:K); % Assigning negative Y-weights
for lambda at t
            At(2,2:Acol) = Xinput(t,1:K); % Assigning positive X-weights
for lambda at t

            linprog(f, At, bt);
            D4(t-1,k) = 1/ans(1); % CRS Dt+1 at t+1, FGNZ equation 16 at
t+1

            linprog(f, At, bt, Aeq, beq);
            D6(t-1,k) = 1/ans(1); % VRS Dt+1 at t+1, FGNZ equation 16 at
t+1

            At(1,1) = Yinput(t-1,k); % Setting ymkt as theta-weight at t
```

```
            bt(1,2) = Xinput(t-1,k); % Setting nkt as right hand side for
restriction (2) at t

            linprog(f, At, bt);
            D3(t-1,k) = 1/ans(1); % CRS Dt+1 at t, FGNZ equation 17 with
transposed t and t+1

            CCD2(t-1,k) = D4(t-1,k)./ D3(t-1,k); % CCD Malmquist index at
t+1, equation 5
            MALM(t-1,k) = sqrt(CCD1(t-1,k).* CCD2(t-1,k)); % Malmquist
index, FGNZ equation 6
            EFFCH(t-1,k) = D4(t-1,k)./ D1(t-1,k); % Efficiency change, FGNZ
equation 7
            TECHCH(t-1,k) =  MALM(t-1,k) ./ EFFCH(t-1,k); % Technical
change, FGNZ equation 7
            t=t-1; % Restore time count to period t
        end
    end
end

clearvars Acol ans Arow At bt

for k = 1:K,
    OutputGeomean(k,1) = geomean(MALM(1:T-1,k)); % Annual change
geometrical means for MALM
    OutputGeomean(k,2) = geomean(TECHCH(1:T-1,k)); % Annual change
geometrical means for TECHCH
    OutputGeomean(k,3) = geomean(EFFCH(1:T-1,k)); % Annual change
geometrical means for EFFCH

    ans1 = cumprod(MALM(1:T-1,k));
    ans2 = cumprod(TECHCH(1:T-1,k));
    ans3 = cumprod(EFFCH(1:T-1,k));

    OutputCumsum(k,1) = ans1(T-1,1); % Cumulative sums for MALM
    OutputCumsum(k,2) = ans2(T-1,1); % Cumulative sums for TECHCH
    OutputCumsum(k,3) = ans3(T-1,1); % Cumulative sums for EFFCH
end

[row, col] = size(OutputGeomean);

for k = 1:col,
    OutputGeomean(K+1,k) = geomean(OutputGeomean(1:K,k)); % Geometrical
sample means
    OutputCumsum(K+1,k) = geomean(OutputCumsum(1:K,k)); % Cumulative sample
sums
end

clearvars ans1 ans2 ans3 col k row t; % Clear from Workspace
clc
```

Appendix III: The PWT5 data used by Färe *et al.* (1994)

This table contains the input data set denoted X1994PWT5 in the MATLAB code:

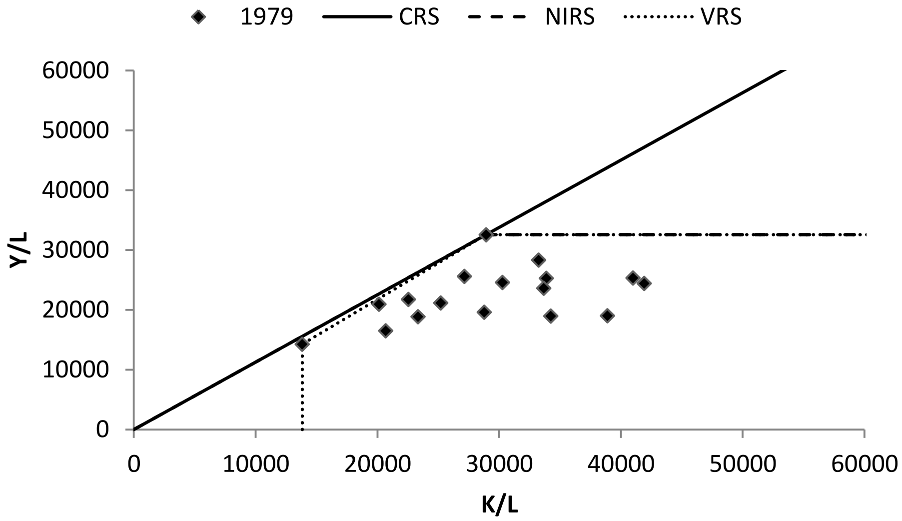
x: K/L (KapW)	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Australia	27154	27494	28164	28404	28606	28985	29436	29843	30299	31028
Austria	25192	25972	26524	26706	26802	26973	27320	27843	28351	28964
Belgium	41003	41909	42063	42120	42009	41972	41964	42254	42792	43832
Canada	33242	34286	36194	37268	37918	38598	39491	40550	41829	43724
Denmark	28769	28811	28539	28522	28460	28668	29309	30342	31028	31516
Finland	38884	39719	40555	41459	42578	43431	44367	45453	46688	48195
France	33877	34796	35503	36109	36461	36679	37040	37623	38327	39331
Germany	33658	34662	35270	35586	35923	36208	36600	37401	38237	39245
Greece	13834	14226	14572	14801	14971	15113	15305	15378	15368	15454
Ireland	20693	21589	22588	23313	23547	23643	23484	23286	23109	22949
Italy	30280	31114	31592	31793	31856	32036	32260	32593	33133	33769
Japan	34242	36249	38198	39988	41626	43420	45354	47388	49650	52470
Norway	41925	42283	44019	44836	45886	47500	48175	49922	51369	52818
Spain	23334	23951	24283	24607	24857	24923	25114	25617	26494	27711
Sweden	22554	22874	23176	23424	23695	24031	24498	24899	25353	25872
United Kingdom	20137	20401	20438	20561	20744	21134	21633	22094	22655	23570
United States	28923	29072	29501	29633	29738	30293	31041	31667	32326	33147

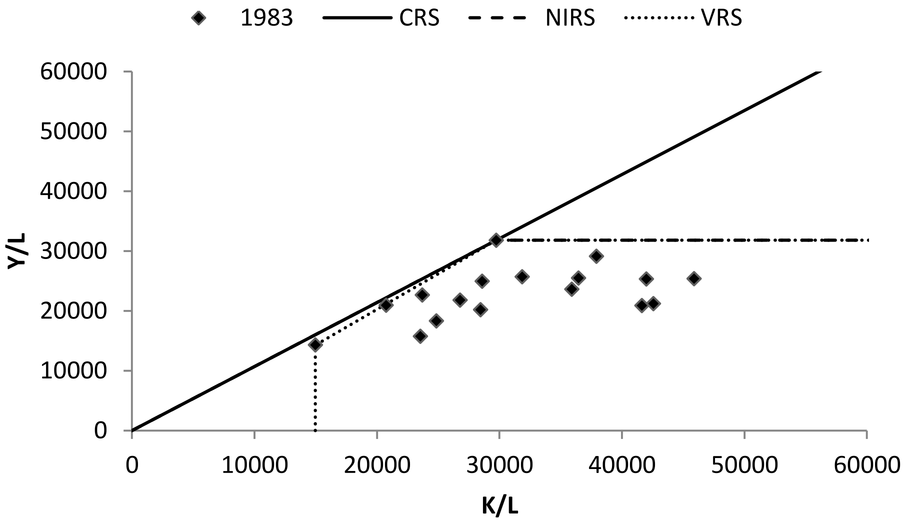
This table contains the output data set denoted Y1994PWT5 in the MATLAB code:

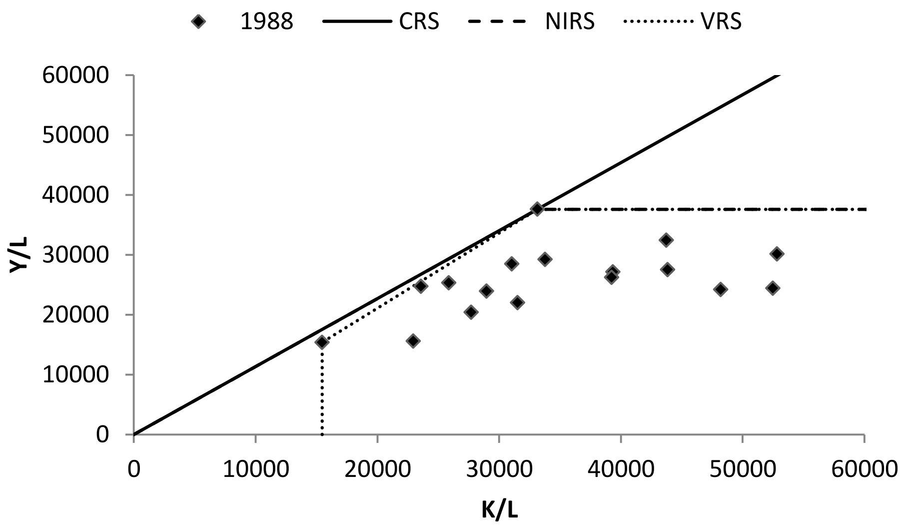
y: Y/L (RGDPW)	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Australia	25553	25521	25860	25339	24910	26295	26855	27258	27879	28490
Austria	21154	21593	21487	21557	21787	22027	22189	22621	22990	23907
Belgium	25310	26186	25636	25682	25313	25574	25194	25810	26324	27481
Canada	28329	27937	28710	27327	29090	29653	29947	31628	32280	32421
Denmark	19587	19556	19418	19859	20185	20939	22006	22258	22047	21969
Finland	19004	20015	20349	20823	21201	21654	22143	22587	23163	24190
France	25234	25417	25427	25693	25473	25427	25472	26058	26388	27140
Germany	23617	23885	23842	23369	23596	24109	24175	24866	25255	26219
Greece	14240	14401	14269	14296	14267	14475	14989	15184	14886	15366
Ireland	16486	16702	16845	16459	15758	15754	15475	15076	15597	15546
Italy	24537	25682	25724	25619	25670	26329	26569	27410	28214	29201
Japan	18927	19666	20158	20487	20860	21579	21780	22625	23360	24417
Norway	24405	24930	24789	24424	25389	26667	27486	28647	29497	30103
Spain	18830	18886	18491	18355	18276	18152	18056	18712	19609	20398
Sweden	21711	21778	21977	22190	22621	23466	24402	24346	24856	25330
United Kingdom	20900	20384	20042	20296	20946	21333	22041	22706	23724	24725
United States	32559	31729	32092	30911	31809	33821	34374	35373	36375	37608

Appendix IV: 1979-1988 PWT5 figures and tables

This appendix provides figures and tables with results from 1979 to 1988 and PWT5.







Theta values at $D_0^t(x^t, y^t)$ for NIRS (CRS) PWT5										
	1979	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**
Australia	0,8360	0,8505	0,8441	0,8552	0,8141	0,8126	0,8239	0,8177	0,8177	0,8093
Austria	0,7459	0,7618	0,7447	0,7738	0,7600	0,7314	0,7334	0,7273	0,7206	0,7275
Belgium	0,7774	0,8253	0,7988	0,8308	0,7958	0,7562	0,7329	0,7297	0,7237	0,7307
Canada	0,8701	0,8805	0,8946	0,8841	0,9145	0,8768	0,8712	0,8941	0,8874	0,8621
Denmark	0,6048	0,6219	0,6255	0,6675	0,6631	0,6542	0,6780	0,6567	0,6315	0,6144
Finland	0,5837	0,6308	0,6341	0,6736	0,6665	0,6403	0,6442	0,6385	0,6368	0,6432
France	0,7750	0,8011	0,7923	0,8312	0,8008	0,7518	0,7410	0,7367	0,7254	0,7217
Germany	0,7254	0,7528	0,7429	0,7560	0,7418	0,7128	0,7033	0,7030	0,6943	0,6972
Greece	0,9144	0,9275	0,9001	0,9259	0,8909	0,8579	0,8844	0,8839	0,8608	0,8764
Ireland	0,7077	0,7089	0,6855	0,6768	0,6256	0,5968	0,5951	0,5796	0,5998	0,5971
Italy	0,7536	0,8094	0,8016	0,8288	0,8070	0,7785	0,7729	0,7749	0,7756	0,7765
Japan	0,5813	0,6198	0,6281	0,6628	0,6558	0,6380	0,6336	0,6396	0,6422	0,6493
Norway	0,7496	0,7857	0,7724	0,7901	0,7982	0,7885	0,7996	0,8099	0,8109	0,8004
Spain	0,7169	0,7225	0,7000	0,7151	0,6874	0,6523	0,6492	0,6539	0,6577	0,6488
Sweden	0,8551	0,8724	0,8717	0,9082	0,8925	0,8746	0,8995	0,8753	0,8713	0,8629
United Kingdom	0,9220	0,9155	0,9015	0,9463	0,9440	0,9041	0,9201	0,9200	0,9306	0,9246
United States	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000

Malmquist Productivity Change Index PWT5									
	1979/80	**1980/81**	**1981/82**	**1982/83**	**1983/84**	**1984/85**	**1985/86**	**1986/87**	**1987/88**
Australia	0,9864	0,9892	0,9716	0,9761	1,0418	1,0056	1,0012	1,0074	0,9979
Austria	0,9901	0,9744	0,9964	1,0070	1,0046	0,9946	1,0003	0,9981	1,0179
Belgium	1,0346	0,9790	1,0018	0,9856	1,0103	0,9851	1,0245	1,0199	1,0440
Canada	0,9862	1,0277	0,9518	1,0645	1,0194	1,0099	1,0561	1,0206	1,0044
Denmark	0,9970	1,0024	1,0233	1,0186	1,0298	1,0280	0,9770	0,9686	0,9810
Finland	1,0532	1,0167	1,0233	1,0182	1,0214	1,0226	1,0201	1,0255	1,0443
France	1,0073	1,0004	1,0105	0,9914	0,9982	1,0018	1,0230	1,0127	1,0285
Germany	1,0113	0,9982	0,9802	1,0097	1,0217	1,0027	1,0286	1,0156	1,0382
Greece	0,9834	0,9673	0,9864	0,9866	1,0050	1,0225	1,0082	0,9810	1,0265
Ireland	0,9711	0,9640	0,9467	0,9479	0,9957	0,9889	0,9825	1,0425	1,0037
Italy	1,0467	1,0016	0,9959	1,0020	1,0257	1,0091	1,0317	1,0293	1,0348
Japan	1,0390	1,0250	1,0163	1,0182	1,0345	1,0093	1,0388	1,0325	1,0452
Norway	1,0215	0,9943	0,9853	1,0395	1,0503	1,0307	1,0422	1,0297	1,0205
Spain	0,9771	0,9657	0,9796	0,9857	0,9906	0,9871	1,0160	1,0132	0,9946
Sweden	0,9891	0,9960	0,9990	1,0078	1,0229	1,0201	0,9816	1,0027	0,9986
United Kingdom	0,9627	0,9814	1,0066	1,0229	0,9997	1,0094	1,0087	1,0190	1,0017
United States	0,9720	1,0041	0,9611	1,0272	1,0535	1,0040	1,0188	1,0178	1,0210

Efficiency Change Index PWT5									
	1979/80	**1980/81**	**1981/82**	**1982/83**	**1983/84**	**1984/85**	**1985/86**	**1986/87**	**1987/88**
Australia	1,0174	0,9924	1,0132	0,9519	0,9981	1,0139	0,9925	1,0000	0,9897
Austria	1,0212	0,9776	1,0391	0,9821	0,9625	1,0027	0,9917	0,9908	1,0095
Belgium	1,0617	0,9679	1,0401	0,9578	0,9502	0,9693	0,9955	0,9918	1,0097
Canada	1,0120	1,0160	0,9882	1,0345	0,9587	0,9937	1,0263	0,9925	0,9714
Denmark	1,0283	1,0057	1,0672	0,9934	0,9866	1,0364	0,9686	0,9615	0,9730
Finland	1,0808	1,0052	1,0624	0,9894	0,9606	1,0061	0,9912	0,9973	1,0101
France	1,0336	0,9891	1,0491	0,9634	0,9388	0,9857	0,9941	0,9848	0,9948
Germany	1,0378	0,9869	1,0176	0,9812	0,9610	0,9866	0,9995	0,9877	1,0041
Greece	1,0144	0,9705	1,0287	0,9622	0,9629	1,0309	0,9995	0,9738	1,0181
Ireland	1,0016	0,9671	0,9873	0,9244	0,9539	0,9971	0,9740	1,0349	0,9954
Italy	1,0740	0,9903	1,0340	0,9737	0,9647	0,9929	1,0025	1,0010	1,0011
Japan	1,0662	1,0134	1,0552	0,9895	0,9729	0,9931	1,0095	1,0040	1,0110
Norway	1,0482	0,9831	1,0229	1,0102	0,9879	1,0141	1,0128	1,0013	0,9871
Spain	1,0079	0,9689	1,0216	0,9612	0,9490	0,9952	1,0072	1,0058	0,9864
Sweden	1,0202	0,9993	1,0418	0,9828	0,9800	1,0284	0,9732	0,9953	0,9904
United Kingdom	0,9930	0,9847	1,0498	0,9976	0,9578	1,0176	1,0000	1,0115	0,9935
United States	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000

Technical Change Index PWT5									
	1979/80	**1980/81**	**1981/82**	**1982/83**	**1983/84**	**1984/85**	**1985/86**	**1986/87**	**1987/88**
Australia	0,9695	0,9967	0,9589	1,0254	1,0438	0,9919	1,0087	1,0074	1,0083
Austria	0,9695	0,9967	0,9589	1,0254	1,0438	0,9919	1,0087	1,0074	1,0083
Belgium	0,9745	1,0114	0,9632	1,0291	1,0633	1,0164	1,0291	1,0283	1,0339
Canada	0,9745	1,0114	0,9632	1,0291	1,0633	1,0164	1,0291	1,0283	1,0339
Denmark	0,9695	0,9967	0,9589	1,0254	1,0438	0,9919	1,0087	1,0074	1,0083
Finland	0,9745	1,0114	0,9632	1,0291	1,0633	1,0164	1,0291	1,0283	1,0339
France	0,9745	1,0114	0,9632	1,0291	1,0633	1,0164	1,0291	1,0283	1,0339
Germany	0,9745	1,0114	0,9632	1,0291	1,0633	1,0164	1,0291	1,0283	1,0339
Greece	0,9695	0,9967	0,9589	1,0254	1,0438	0,9919	1,0087	1,0074	1,0083
Ireland	0,9695	0,9967	0,9589	1,0254	1,0438	0,9919	1,0087	1,0074	1,0083
Italy	0,9745	1,0114	0,9632	1,0291	1,0633	1,0164	1,0291	1,0283	1,0337
Japan	0,9745	1,0114	0,9632	1,0291	1,0633	1,0164	1,0291	1,0283	1,0339
Norway	0,9745	1,0114	0,9632	1,0291	1,0633	1,0164	1,0291	1,0283	1,0339
Spain	0,9695	0,9967	0,9589	1,0254	1,0438	0,9919	1,0087	1,0074	1,0083
Sweden	0,9695	0,9967	0,9589	1,0254	1,0438	0,9919	1,0087	1,0074	1,0083
United Kingdom	0,9695	0,9967	0,9589	1,0254	1,0438	0,9919	1,0087	1,0074	1,0083
United States	0,9720	1,0041	0,9611	1,0272	1,0535	1,0040	1,0188	1,0178	1,0210

Average Annual Changes, 1979-1988, PWT5			
	Malmquist index (MALM)	**Technical change (TECHCH)**	**Efficiency change (EFFCH)**
Australia	0,9973	1,0009	0,9964
Austria	0,9981	1,0009	0,9972
Belgium	1,0092	1,0161	0,9931
Canada	1,0151	1,0161	0,9990
Denmark	1,0026	1,0009	1,0017
Finland	1,0272	1,0161	1,0109
France	1,0081	1,0161	0,9921
Germany	1,0117	1,0161	0,9956
Greece	0,9962	1,0009	0,9953
Ireland	0,9821	1,0009	0,9813
Italy	1,0195	1,0161	1,0033
Japan	1,0287	1,0161	1,0124
Norway	1,0236	1,0161	1,0073
Spain	0,9898	1,0009	0,9890
Sweden	1,0019	1,0009	1,0010
United Kingdom	1,0012	1,0009	1,0003
United States	1,0085	1,0085	1,0000
Mean:	1,0071	1,0085	0,9986

Cumulated Productivity, 1979-1988, PWT5			
	Malmquist index (MALM)	**Technical change (TECHCH)**	**Efficiency change (EFFCH)**
Australia	0,9757	1,0079	0,9681
Austria	0,9830	1,0079	0,9753
Belgium	1,0858	1,1551	0,9400
Canada	1,1444	1,1551	0,9908
Denmark	1,0238	1,0079	1,0158
Finland	1,2729	1,1551	1,1020
France	1,0755	1,1551	0,9311
Germany	1,1102	1,1551	0,9611
Greece	0,9660	1,0079	0,9584
Ireland	0,8503	1,0079	0,8436
Italy	1,1898	1,1548	1,0303
Japan	1,2901	1,1551	1,1169
Norway	1,2335	1,1551	1,0679
Spain	0,9122	1,0079	0,9050
Sweden	1,0171	1,0079	1,0091
United Kingdom	1,0107	1,0079	1,0028
United States	1,0790	1,0790	1,0000
Mean:	1,0718	1,0813	0,9893

Appendix V: The PWT8 data for 2002-2011

This table contains the input data set denoted X2014PWT8 in the MATLAB code:

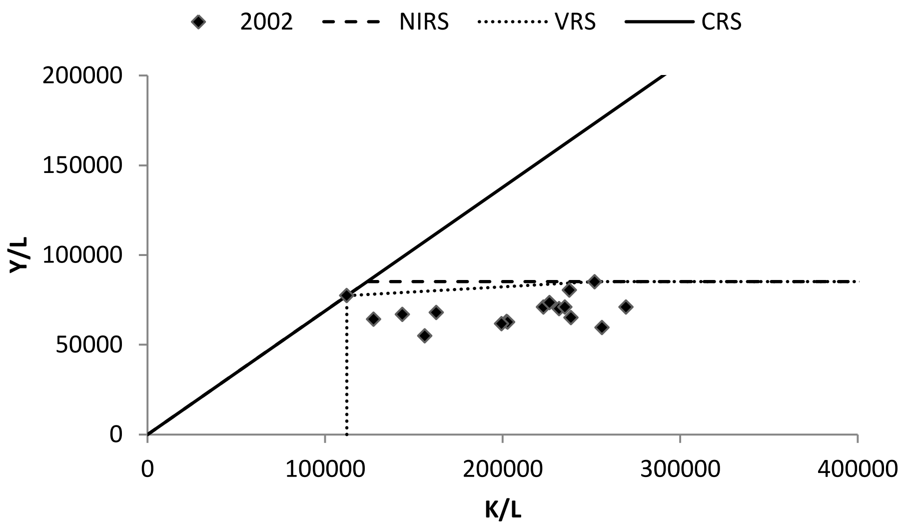
x: K/L (rkna/emp)	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Australia	231828	235987	241057	242687	245998	248513	250765	258304	262659	269896
Austria	235074	237058	238771	239076	238200	237583	236593	240723	241132	240338
Belgium	237691	242065	244346	246352	249284	251802	253466	259455	261858	263126
Canada	162648	165057	169283	175079	180652	185068	190543	199907	204790	209983
Denmark	202375	208377	213646	215193	215934	214600	214831	222001	228832	231637
Finland	238521	243093	247282	248707	248773	248989	247700	257279	260613	261718
France	223117	226754	230558	233577	235981	238218	242452	249409	253346	256341
Germany	202929	207330	209038	211611	213288	212714	212813	213915	214657	214448
Greece	156265	161373	164086	164506	168669	173803	177836	182699	189490	200658
Ireland	112308	121204	130413	140282	150395	159464	172958	193921	203905	208483
Italy	269601	270930	275543	279362	279206	281409	285923	293623	298703	300627
Japan	256052	260162	262706	264576	266248	268122	271212	276057	279203	280390
Norway	226540	234480	239804	244481	244637	243798	244549	251934	258267	260940
Spain	199382	202089	203976	205424	207844	212445	222217	243210	253152	260620
Sweden	127383	130422	134001	136607	137671	138187	140331	145154	145434	144866
United Kingdom	143651	146087	148766	151465	154588	158708	161913	166840	168944	170367
United States	251929	255514	259205	261588	263409	266488	272388	284950	288349	288607

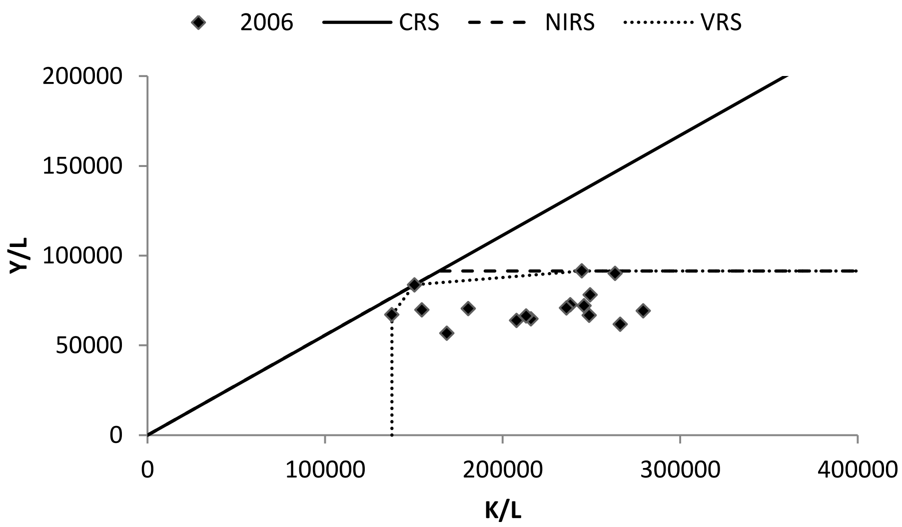
This table contains the output data set denoted Y2014PWT8 in the MATLAB code:

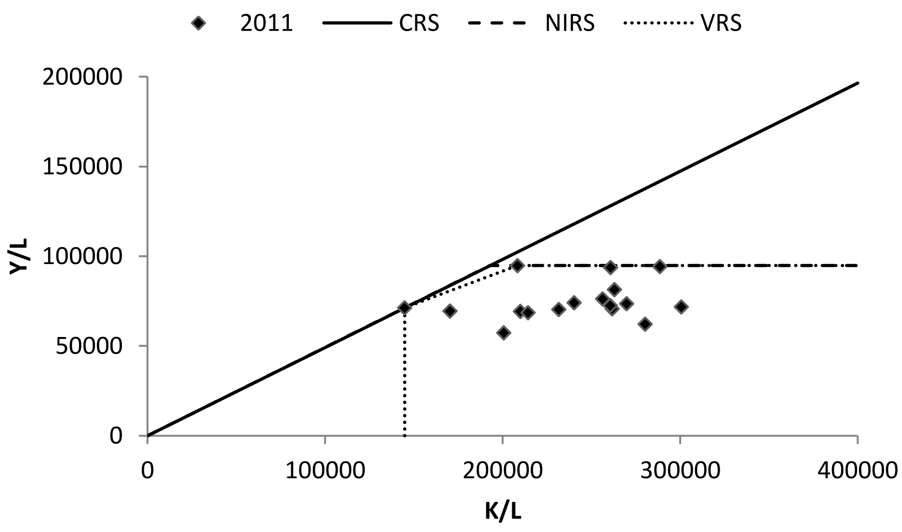
y: Y/L (rgdpo/emp)	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Australia	70150	71447	72236	71849	72049	71658	69939	70040	72270	73577
Austria	71074	70408	71650	70621	72587	73687	73483	72067	73957	74020
Belgium	80379	78265	78188	77001	78128	79814	79988	78750	81883	81355
Canada	67936	68185	69476	70850	70486	69723	68898	65509	67874	69238
Denmark	62993	61032	63732	62604	64762	65811	66604	64710	70106	70239
Finland	65021	63378	66230	65426	66637	70643	70928	67671	69609	70697
France	71048	67567	68770	69396	70777	73699	73959	73398	75670	76222
Germany	62666	63247	64009	64453	66401	68222	68288	65170	68085	68541
Greece	54920	55389	56821	54287	56684	57975	59262	58848	58540	57345
Ireland	77334	77796	78348	79614	83705	89160	84408	84817	90141	94717
Italy	71078	68943	68792	68149	69297	72023	73222	71862	72420	71772
Japan	59521	60503	61462	61357	61773	62828	61602	60018	62760	62137
Norway	73578	75229	81787	87064	91424	91455	94310	85571	90599	93684
Spain	61746	60468	61120	60929	63815	67106	68411	70892	71953	72388
Sweden	64290	64824	67226	64647	67033	70263	69812	67019	70677	71177
United Kingdom	66882	66859	68803	68330	69829	70900	68742	66653	69622	69332
United States	85126	86382	88430	89308	90027	90749	89669	90676	93183	94155

Appendix VI: 2002-2011 PWT8 figures and tables

This appendix provides figures and tables with results from 2002 to 2011 and PWT8.







Theta values at $D_0^t(x^t, y^t)$ for NIRS (CRS) PWT8										
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Australia	0,8351	0,8392	0,8302	0,8183	0,7881	0,7835	0,7416	0,7873	0,7833	0,7768
Austria	0,8443	0,8264	0,8252	0,8070	0,7986	0,8072	0,7884	0,8205	0,8084	0,7815
Belgium	0,9531	0,9151	0,8960	0,8741	0,8546	0,8727	0,8481	0,8845	0,8878	0,8589
Canada	0,8477	0,8460	0,8536	0,8599	0,8179	0,7759	0,7934	0,7689	0,7527	0,7310
Denmark	0,7649	0,7321	0,7510	0,7313	0,7271	0,7259	0,7384	0,7470	0,7701	0,7416
Finland	0,7706	0,7405	0,7570	0,7411	0,7289	0,7724	0,7521	0,7612	0,7551	0,7464
France	0,8507	0,7992	0,7979	0,7970	0,7802	0,8072	0,7866	0,8304	0,8232	0,8047
Germany	0,7606	0,7593	0,7575	0,7555	0,7473	0,7529	0,7594	0,7569	0,7521	0,7236
Greece	0,6883	0,6892	0,7016	0,6657	0,6653	0,6474	0,6965	0,7290	0,6859	0,6245
Ireland	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Italy	0,8350	0,7981	0,7779	0,7631	0,7580	0,7875	0,7764	0,7925	0,7772	0,7578
Japan	0,6992	0,7004	0,6950	0,6870	0,6757	0,6870	0,6532	0,6661	0,6759	0,6560
Norway	0,8790	0,8847	0,9410	0,9900	1,0000	1,0000	1,0000	0,9663	0,9837	0,9891
Spain	0,7512	0,7288	0,7267	0,7183	0,7218	0,7407	0,7500	0,8057	0,7828	0,7643
Sweden	0,8224	0,8270	0,8550	0,8339	0,8748	0,9094	1,0000	1,0000	1,0000	1,0000
United Kingdom	0,8457	0,8422	0,8624	0,8487	0,8308	0,7990	0,8650	0,8895	0,8869	0,8601
United States	1,0000	1,0000	1,0000	1,0000	0,9847	0,9923	0,9508	1,0000	1,0000	0,9941

Malmquist Productivity Change Index PWT8									
	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11
Australia	1,0155	1,0068	0,9932	1,0004	0,9946	0,9760	0,9987	1,0293	1,0167
Austria	0,9893	1,0162	0,9854	1,0287	1,0155	0,9981	0,9763	1,0260	1,0010
Belgium	0,9707	0,9971	0,9830	1,0133	1,0216	1,0022	0,9824	1,0384	0,9933
Canada	1,0019	1,0152	1,0141	0,9896	0,9864	0,9830	0,9348	1,0263	1,0117
Denmark	0,9647	1,0396	0,9809	1,0338	1,0170	1,0118	0,9637	1,0792	1,0013
Finland	0,9716	1,0414	0,9866	1,0185	1,0601	1,0040	0,9508	1,0267	1,0154
France	0,9486	1,0146	1,0063	1,0177	1,0399	0,9998	0,9884	1,0287	1,0067
Germany	1,0061	1,0106	1,0045	1,0286	1,0278	1,0009	0,9531	1,0443	1,0067
Greece	1,0047	1,0234	0,9550	1,0399	1,0195	1,0182	0,9782	0,9668	0,9371
Ireland	0,9653	0,9672	0,9750	1,0103	1,0299	0,9103	0,9424	1,0391	1,0404
Italy	0,9700	0,9978	0,9906	1,0168	1,0393	1,0166	0,9814	1,0078	0,9911
Japan	1,0165	1,0159	0,9983	1,0068	1,0171	0,9805	0,9726	1,0439	0,9898
Norway	1,0167	1,0824	1,0600	1,0499	1,0007	1,0306	0,9049	1,0550	1,0335
Spain	0,9774	1,0092	0,9955	1,0450	1,0486	1,0104	1,0123	1,0093	1,0046
Sweden	1,0060	1,0337	0,9512	1,0289	1,0443	0,9784	0,9297	1,0528	1,0105
United Kingdom	0,9978	1,0266	0,9905	1,0188	1,0001	0,9582	0,9449	1,0346	0,9896
United States	1,0134	1,0220	1,0089	1,0081	1,0080	0,9881	1,0067	1,0270	1,0104

Efficiency Change Index PWT8									
	2002/03	**2003/04**	**2004/05**	**2005/06**	**2006/07**	**2007/08**	**2008/09**	**2009/10**	**2010/11**
Australia	1,0050	0,9892	0,9857	0,9630	0,9942	0,9465	1,0617	0,9950	0,9917
Austria	0,9788	0,9986	0,9780	0,9895	1,0108	0,9766	1,0408	0,9853	0,9667
Belgium	0,9601	0,9790	0,9756	0,9776	1,0212	0,9719	1,0428	1,0038	0,9675
Canada	0,9980	1,0090	1,0074	0,9511	0,9487	1,0225	0,9691	0,9790	0,9712
Denmark	0,9572	1,0258	0,9738	0,9941	0,9984	1,0172	1,0117	1,0308	0,9630
Finland	0,9609	1,0222	0,9791	0,9835	1,0598	0,9736	1,0122	0,9919	0,9885
France	0,9395	0,9984	0,9989	0,9789	1,0346	0,9745	1,0556	0,9913	0,9776
Germany	0,9982	0,9977	0,9974	0,9891	1,0075	1,0086	0,9966	0,9937	0,9622
Greece	1,0013	1,0180	0,9488	0,9994	0,9731	1,0759	1,0467	0,9409	0,9105
Ireland	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Italy	0,9559	0,9747	0,9809	0,9933	1,0390	0,9859	1,0208	0,9807	0,9750
Japan	1,0017	0,9923	0,9885	0,9835	1,0167	0,9508	1,0198	1,0147	0,9706
Norway	1,0065	1,0637	1,0521	1,0101	1,0000	1,0000	0,9663	1,0180	1,0055
Spain	0,9702	0,9971	0,9885	1,0048	1,0261	1,0125	1,0743	0,9716	0,9763
Sweden	1,0056	1,0338	0,9753	1,0491	1,0395	1,0996	1,0000	1,0000	1,0000
United Kingdom	0,9958	1,0239	0,9842	0,9789	0,9617	1,0827	1,0283	0,9970	0,9698
United States	1,0000	1,0000	1,0000	0,9847	1,0077	0,9582	1,0518	1,0000	0,9941

Technical Change Index PWT8									
	2002/03	**2003/04**	**2004/05**	**2005/06**	**2006/07**	**2007/08**	**2008/09**	**2009/10**	**2010/11**
Australia	1,0105	1,0178	1,0076	1,0388	1,0003	1,0312	0,9407	1,0345	1,0252
Austria	1,0107	1,0177	1,0075	1,0395	1,0047	1,0220	0,9380	1,0414	1,0355
Belgium	1,0110	1,0185	1,0076	1,0365	1,0003	1,0312	0,9420	1,0345	1,0267
Canada	1,0039	1,0061	1,0067	1,0404	1,0397	0,9614	0,9646	1,0484	1,0417
Denmark	1,0079	1,0134	1,0072	1,0399	1,0187	0,9947	0,9526	1,0469	1,0398
Finland	1,0111	1,0188	1,0076	1,0356	1,0003	1,0312	0,9393	1,0351	1,0273
France	1,0097	1,0162	1,0075	1,0396	1,0051	1,0259	0,9363	1,0377	1,0298
Germany	1,0078	1,0130	1,0072	1,0399	1,0201	0,9923	0,9563	1,0509	1,0463
Greece	1,0034	1,0053	1,0066	1,0406	1,0476	0,9464	0,9346	1,0275	1,0292
Ireland	0,9653	0,9672	0,9750	1,0103	1,0299	0,9103	0,9424	1,0391	1,0404
Italy	1,0148	1,0237	1,0099	1,0237	1,0003	1,0312	0,9615	1,0277	1,0165
Japan	1,0148	1,0237	1,0099	1,0237	1,0003	1,0312	0,9537	1,0287	1,0198
Norway	1,0102	1,0175	1,0076	1,0395	1,0007	1,0306	0,9364	1,0364	1,0279
Spain	1,0074	1,0121	1,0071	1,0400	1,0219	0,9979	0,9423	1,0388	1,0290
Sweden	1,0004	0,9999	0,9753	0,9807	1,0046	0,8898	0,9297	1,0528	1,0105
United Kingdom	1,0020	1,0026	1,0064	1,0408	1,0399	0,8850	0,9189	1,0376	1,0204
United States	1,0134	1,0220	1,0089	1,0237	1,0003	1,0312	0,9572	1,0270	1,0165

Average Annual Changes, 2002-2011, PWT8			
	Malmquist index (MALM)	**Technical change (TECHCH)**	**Efficiency change (EFFCH)**
Australia	1,0034	1,0115	0,9920
Austria	1,0039	1,0125	0,9915
Belgium	1,0000	1,0117	0,9885
Canada	0,9955	1,0121	0,9837
Denmark	1,0096	1,0131	0,9966
Finland	1,0078	1,0114	0,9965
France	1,0053	1,0115	0,9938
Germany	1,0089	1,0145	0,9945
Greece	0,9931	1,0039	0,9893
Ireland	0,9857	0,9857	1,0000
Italy	1,0011	1,0119	0,9893
Japan	1,0044	1,0115	0,9929
Norway	1,0248	1,0114	1,0132
Spain	1,0123	1,0103	1,0019
Sweden	1,0031	0,9816	1,0220
United Kingdom	0,9953	0,9934	1,0019
United States	1,0102	1,0109	0,9993
Mean:	1,0038	1,0070	0,9969

Cumulated Productivity, 2002-2011, PWT8			
	Malmquist index (MALM)	**Technical change (TECHCH)**	**Efficiency change (EFFCH)**
Australia	1,0306	1,1079	0,9302
Austria	1,0355	1,1187	0,9257
Belgium	1,0002	1,1099	0,9012
Canada	0,9606	1,1139	0,8624
Denmark	1,0898	1,1240	0,9696
Finland	1,0727	1,1075	0,9686
France	1,0488	1,1087	0,9460
Germany	1,0829	1,1382	0,9514
Greece	0,9394	1,0353	0,9073
Ireland	0,8784	0,8784	1,0000
Italy	1,0098	1,1127	0,9075
Japan	1,0401	1,1086	0,9382
Norway	1,2464	1,1076	1,1253
Spain	1,1159	1,0969	1,0173
Sweden	1,0284	0,8457	1,2160
United Kingdom	0,9582	0,9422	1,0170
United States	1,0960	1,1025	0,9941
Mean:	1,0373	1,0682	0,9752

Appendix VII: The PWT8 data for 1979-1988

This table contains the input data set denoted X1994PWT8 in the MATLAB code:

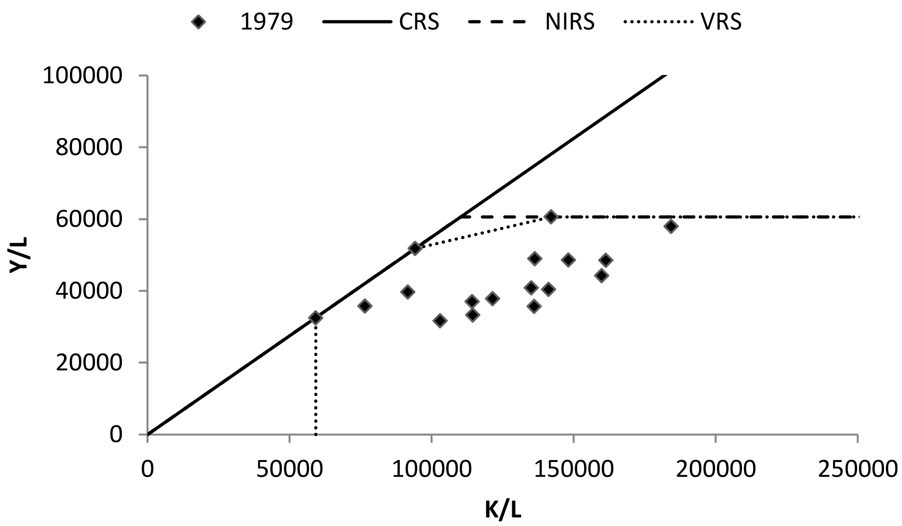
x: K/L (rkna/emp)	1979	1980	1981	1982	1983	1984	1985	1986	1987
Australia	161335	163886	169291	175174	184014	184480	185104	183555	186074
Austria	141204	146812	152218	152378	157517	157741	162193	164143	167792
Belgium	136409	142604	149286	154340	158868	161681	163835	166120	168540
Canada	94195	96415	98762	106078	109049	110042	110907	111592	113353
Denmark	135139	139664	143612	145354	147723	148775	149538	151385	155713
Finland	136171	137310	140579	144306	149238	153335	158129	163532	167872
France	148235	153016	158222	162472	166386	171050	175016	177826	180379
Germany	121512	123586	126929	131439	136711	139717	142526	144189	146739
Greece	114483	117564	115290	119280	121532	123174	124534	126548	128625
Ireland	59234	63110	67281	71030	74337	78351	80586	82819	83996
Italy	159943	164799	171321	176443	181163	186766	190416	194563	199974
Japan	103003	109012	115242	121023	125340	131191	137445	144092	151361
Norway	142148	144436	148502	154202	160704	165443	166120	166612	169036
Spain	114327	121731	128874	134185	138625	145263	150843	152335	151263
Sweden	76528	77846	79483	81321	82849	84352	85811	87572	89504
United Kingdom	91614	93644	98617	101647	104462	104861	105561	107214	108149
United States	184305	189174	192137	197557	199286	197088	199079	200249	200477

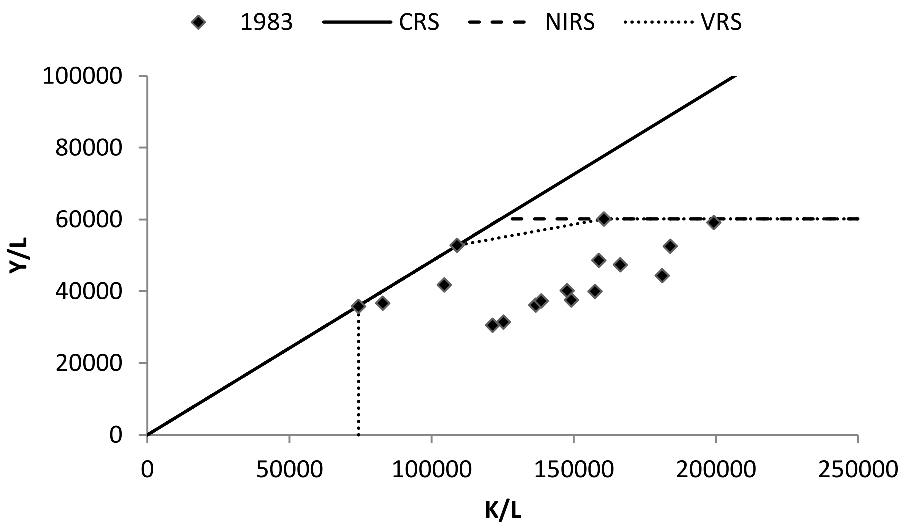
This table contains the output data set denoted Y1994PWT8 in the MATLAB code:

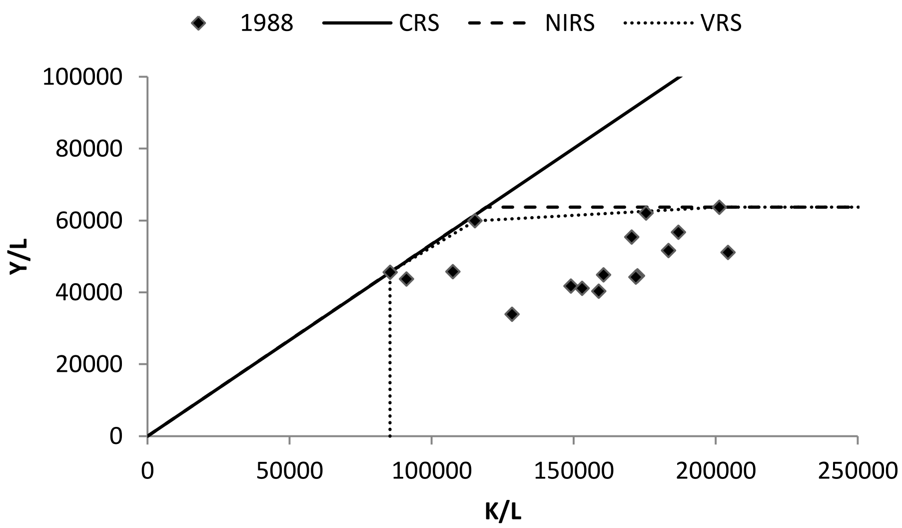
y: Y/L (rgdpo/emp)	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Australia	48545	47644	49124	48572	52568	52764	52692	52614	55413	56709
Austria	40439	40085	39698	38813	39934	38647	39482	40666	42157	44557
Belgium	48978	50795	49305	49067	48591	48173	47338	50336	52573	55340
Canada	51812	49533	49713	50928	52760	54757	56267	56448	58897	59915
Denmark	40803	40156	39110	39984	40178	40276	40840	43712	45066	44903
Finland	35710	36429	36729	36944	37506	38052	38218	40388	41630	44200
France	48571	49131	48164	48069	47345	47056	46806	48886	49810	51680
Germany	37771	37179	36149	35614	36120	36369	36329	38647	40208	41706
Greece	33252	33273	31588	31168	30460	31200	32153	32793	32333	33917
Ireland	32483	34821	35417	36078	35777	36975	38646	42194	45025	45604
Italy	44203	46564	45818	44963	44290	44917	45058	47166	49428	51101
Japan	31693	33553	33152	32272	31378	31618	32233	34508	36965	40311
Norway	60615	56640	55603	56167	60130	62863	64363	63338	63221	62115
Spain	37050	39695	38796	37933	37244	37452	37505	38654	39803	41146
Sweden	35761	35197	35263	35704	36696	38032	38495	40996	42577	43734
United Kingdom	39679	39082	39294	40211	41752	41531	42027	43370	45219	45788
United States	57994	57289	58157	57272	59086	61068	61931	62326	62643	63682

Appendix VIII: 1979-1988 PWT8 figures and tables

This appendix provides figures and tables with results from 1979 to 1988 and PWT8.







Theta values at $D_0^t(x^t, y^t)$ for NIRS (CRS) PWT8										
	1979	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**
Australia	0,8009	0,8370	0,8646	0,8566	0,8742	0,8393	0,8187	0,8307	0,8765	0,8995
Austria	0,6691	0,7073	0,7112	0,6935	0,6692	0,6260	0,6190	0,6452	0,6678	0,7139
Belgium	0,8223	0,9011	0,8860	0,8735	0,8116	0,7731	0,7393	0,7955	0,8321	0,8878
Canada	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Denmark	0,6878	0,7179	0,7108	0,7243	0,6894	0,6665	0,6594	0,7116	0,7247	0,7255
Finland	0,6000	0,6554	0,6719	0,6706	0,6412	0,6229	0,6048	0,6416	0,6594	0,7084
France	0,8013	0,8655	0,8574	0,8526	0,7874	0,7485	0,7272	0,7718	0,7879	0,8217
Germany	0,6647	0,6942	0,6814	0,6633	0,6370	0,6154	0,5965	0,6385	0,6539	0,6793
Greece	0,5987	0,6318	0,6113	0,5952	0,5585	0,5505	0,5518	0,5623	0,5381	0,5607
Ireland	0,9970	1,0000	1,0000	1,0000	0,9948	0,9484	0,9452	1,0000	1,0000	1,0000
Italy	0,7292	0,8178	0,8047	0,7925	0,7366	0,7145	0,7001	0,7447	0,7818	0,8024
Japan	0,5932	0,6528	0,6417	0,6141	0,5696	0,5465	0,5358	0,5702	0,5977	0,6521
Norway	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	0,9930
Spain	0,6675	0,7450	0,7282	0,7026	0,6536	0,6251	0,6037	0,6280	0,6436	0,6683
Sweden	0,8495	0,8516	0,8609	0,8829	0,9155	0,9061	0,8842	0,9203	0,8940	0,9036
United Kingdom	0,7874	0,8090	0,7915	0,8198	0,8261	0,7959	0,7847	0,7990	0,8012	0,8146
United States	0,9568	1,0000	1,0000	1,0000	0,9826	0,9714	0,9622	0,9840	0,9909	1,0000

Malmquist Productivity Change Index PWT8									
	1979/80	**1980/81**	**1981/82**	**1982/83**	**1983/84**	**1984/85**	**1985/86**	**1986/87**	**1987/88**
Australia	0,9811	1,0275	0,9845	1,0801	1,0037	0,9986	0,9985	1,0532	1,0231
Austria	0,9854	0,9859	0,9775	1,0200	0,9673	1,0110	1,0257	1,0318	1,0544
Belgium	1,0197	0,9612	0,9878	0,9839	0,9860	0,9778	1,0582	1,0424	1,0516
Canada	0,9428	0,9893	0,9842	1,0185	1,0318	1,0224	0,9993	1,0340	1,0080
Denmark	0,9715	0,9648	1,0187	0,9996	0,9999	1,0122	1,0660	1,0237	0,9917
Finland	1,0168	1,0003	0,9981	1,0042	1,0046	0,9931	1,0446	1,0249	1,0594
France	1,0109	0,9770	0,9949	0,9841	0,9939	0,9947	1,0444	1,0189	1,0364
Germany	0,9782	0,9642	0,9758	1,0021	0,9994	0,9921	1,0599	1,0360	1,0348
Greece	0,9913	0,9549	0,9781	0,9721	1,0199	1,0270	1,0151	0,9825	1,0493
Ireland	1,0062	0,9600	0,9684	0,9511	0,9805	1,0162	1,0624	1,0523	0,9970
Italy	1,0528	0,9799	0,9776	0,9840	1,0142	1,0031	1,0468	1,0480	1,0333
Japan	1,0388	0,9723	0,9612	0,9626	0,9927	1,0038	1,0547	1,0584	1,0825
Norway	0,9316	0,9769	1,0015	1,0607	1,0397	1,0231	0,9836	0,9967	0,9802
Spain	1,0475	0,9601	0,9668	0,9720	0,9892	0,9881	1,0273	1,0316	1,0319
Sweden	0,9690	0,9841	0,9926	1,0102	1,0179	0,9950	1,0438	1,0177	1,0095
United Kingdom	0,9651	0,9669	1,0057	1,0120	0,9909	1,0052	1,0162	1,0341	1,0176
United States	0,9872	1,0136	0,9836	1,0317	1,0335	1,0141	1,0064	1,0051	1,0163

Efficiency Change Index PWT8									
	1979/80	**1980/81**	**1981/82**	**1982/83**	**1983/84**	**1984/85**	**1985/86**	**1986/87**	**1987/88**
Australia	1,0451	1,0329	0,9908	1,0206	0,9601	0,9754	1,0146	1,0552	1,0262
Austria	1,0571	1,0055	0,9751	0,9650	0,9355	0,9888	1,0424	1,0351	1,0689
Belgium	1,0958	0,9832	0,9859	0,9291	0,9525	0,9563	1,0760	1,0460	1,0670
Canada	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Denmark	1,0439	0,9900	1,0190	0,9519	0,9668	0,9893	1,0790	1,0185	1,0011
Finland	1,0923	1,0252	0,9981	0,9561	0,9714	0,9710	1,0608	1,0278	1,0742
France	1,0801	0,9907	0,9944	0,9235	0,9507	0,9715	1,0613	1,0208	1,0429
Germany	1,0444	0,9816	0,9735	0,9602	0,9661	0,9693	1,0704	1,0241	1,0389
Greece	1,0552	0,9676	0,9736	0,9383	0,9857	1,0025	1,0189	0,9571	1,0420
Ireland	1,0030	1,0000	1,0000	0,9948	0,9534	0,9967	1,0579	1,0000	1,0000
Italy	1,1215	0,9839	0,9849	0,9294	0,9701	0,9798	1,0637	1,0499	1,0264
Japan	1,1005	0,9829	0,9569	0,9277	0,9594	0,9804	1,0642	1,0482	1,0910
Norway	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	0,9930
Spain	1,1162	0,9774	0,9649	0,9303	0,9564	0,9657	1,0402	1,0249	1,0384
Sweden	1,0024	1,0110	1,0255	1,0369	0,9897	0,9759	1,0407	0,9714	1,0108
United Kingdom	1,0274	0,9783	1,0358	1,0077	0,9635	0,9859	1,0182	1,0027	1,0167
United States	1,0452	1,0000	1,0000	0,9826	0,9886	0,9905	1,0227	1,0069	1,0092

Technical Change Index PWT8									
	1979/80	**1980/81**	**1981/82**	**1982/83**	**1983/84**	**1984/85**	**1985/86**	**1986/87**	**1987/88**
Australia	0,9388	0,9947	0,9936	1,0584	1,0455	1,0239	0,9841	0,9982	0,9970
Austria	0,9321	0,9806	1,0024	1,0570	1,0340	1,0225	0,9840	0,9968	0,9864
Belgium	0,9305	0,9776	1,0019	1,0590	1,0351	1,0224	0,9835	0,9965	0,9855
Canada	0,9428	0,9893	0,9842	1,0185	1,0318	1,0224	0,9993	1,0340	1,0080
Denmark	0,9306	0,9745	0,9997	1,0502	1,0342	1,0231	0,9879	1,0051	0,9906
Finland	0,9309	0,9757	1,0000	1,0503	1,0341	1,0227	0,9847	0,9971	0,9862
France	0,9359	0,9862	1,0005	1,0656	1,0455	1,0239	0,9841	0,9982	0,9938
Germany	0,9366	0,9823	1,0024	1,0436	1,0344	1,0235	0,9902	1,0116	0,9961
Greece	0,9394	0,9869	1,0047	1,0361	1,0348	1,0244	0,9963	1,0265	1,0070
Ireland	1,0031	0,9600	0,9684	0,9561	1,0285	1,0196	1,0042	1,0523	0,9970
Italy	0,9387	0,9959	0,9927	1,0587	1,0455	1,0239	0,9841	0,9982	1,0068
Japan	0,9439	0,9892	1,0045	1,0376	1,0346	1,0239	0,9910	1,0097	0,9922
Norway	0,9316	0,9769	1,0015	1,0607	1,0397	1,0231	0,9836	0,9967	0,9872
Spain	0,9385	0,9823	1,0020	1,0449	1,0343	1,0231	0,9875	1,0065	0,9938
Sweden	0,9666	0,9735	0,9679	0,9743	1,0285	1,0196	1,0030	1,0476	0,9987
United Kingdom	0,9394	0,9883	0,9710	1,0043	1,0285	1,0196	0,9981	1,0313	1,0009
United States	0,9446	1,0136	0,9836	1,0499	1,0455	1,0239	0,9841	0,9982	1,0070

Average Annual Changes, 1979-1988, PWT8			
	Malmquist index (MALM)	**Technical change (TECHCH)**	**Efficiency change (EFFCH)**
Australia	1,0162	1,0032	1,0130
Austria	1,0062	0,9990	1,0072
Belgium	1,0070	0,9985	1,0086
Canada	1,0030	1,0030	1,0000
Denmark	1,0049	0,9990	1,0060
Finland	1,0160	0,9974	1,0186
France	1,0059	1,0031	1,0028
Germany	1,0043	1,0018	1,0024
Greece	0,9985	1,0058	0,9927
Ireland	0,9987	0,9983	1,0003
Italy	1,0151	1,0044	1,0107
Japan	1,0132	1,0026	1,0106
Norway	0,9987	0,9995	0,9992
Spain	1,0011	1,0010	1,0001
Sweden	1,0042	0,9974	1,0069
United Kingdom	1,0013	0,9975	1,0038
United States	1,0100	1,0051	1,0049
Mean:	1,0061	1,0010	1,0052

Cumulated Productivity, 1979-1988, PWT8			
	Malmquist index (MALM)	**Technical change (TECHCH)**	**Efficiency change (EFFCH)**
Australia	1,1561	1,0294	1,1231
Austria	1,0570	0,9906	1,0670
Belgium	1,0652	0,9866	1,0797
Canada	1,0274	1,0274	1,0000
Denmark	1,0452	0,9909	1,0549
Finland	1,1535	0,9770	1,1806
France	1,0544	1,0282	1,0254
Germany	1,0390	1,0166	1,0220
Greece	0,9866	1,0534	0,9365
Ireland	0,9880	0,9850	1,0030
Italy	1,1444	1,0400	1,1004
Japan	1,1252	1,0236	1,0993
Norway	0,9883	0,9952	0,9930
Spain	1,0102	1,0089	1,0012
Sweden	1,0387	0,9765	1,0636
United Kingdom	1,0118	0,9780	1,0346
United States	1,0941	1,0468	1,0452
Mean:	1,0579	1,0091	1,0488