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Capacity utilization in a generalized Malmquist index including environmental factors
A decomposition analysis

Abstract:
Productivity measures ignoring environmental effects may give misleading information on total productivity growth. Further, business cycles in the form of capacity utilization may also significantly influence productivity measures. In this paper, we develop an overall Malmquist productivity index and decompose changing efficiency rates into a contribution from environmental factors, capacity utilization and other traditional factors. The capacity utilization element is a contribution to the literature in that it takes into account the capacity for producing negative externalities. We decompose the frontier movements into a contribution from traditional factors and environmental factors and apply the model to a micro data set for two Norwegian industries: the pulp and paper industry and the inorganic chemistry industry. We find frontier improvements over the period included in the analysis, while the distance to the frontier has increased. Capacity utilization increased over the period and contributed to an average approach to the frontier, while environmental indicators contributed negatively. Analysis of the two industries indicates that differences between the traditional and revised efficiency measures changes are ambiguous, except from the capacity utilization element. This indicates that the environment loses when business cycles improve.

Keywords: Emissions; Productivity change; Pulp and paper; Inorganic chemistry; Malmquist index; Frontier technology; Capacity utilization

JEL classification: L73; O12; O14; O33; O41; Q48; R38

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1. Introduction

In this article, we elaborate on earlier productivity analyses in the literature decomposing productivity changes in technical change and efficiency change with respect to the contribution from traditional input factors, environmental factors and capacity utilization. We develop a new Malmquist index approach that includes elements from this earlier work, and elaborate on a *combination* of elements that is not reported in the earlier literature.

Caves et al. introduced the Malmquist productivity index approach in their "Economic theory of index numbers"—a framework for input, output and productivity measurement [1]. This approach is based on discrete data points, i.e., a discrete approximation to the time derivative (see also Diewert [2]). The approach is used in numerous articles to measure efficiency and productivity change in traditional input factors in several industries (see for instance Berg et al. [3] for a short survey).

Färe et al. [4] calculated productivity change using a non-parametric linear programming method. They also relaxed the implicit hypothesis of technical efficiency introduced in Caves et al. [1] and showed that the Malmquist productivity index can be decomposed into technical efficiency change (movement towards the frontier) and technology shifts (shifts in the frontier). Since then, productivity analysis based on Malmquist indexes has taken two directions: i) introduction of negative externalities (environmental factors) as either an input or a separate output [5], [6], and ii) allowing for variation in capacity utilization, when the time span of available data renders this approach necessary [7].

Many industries are characterized by the production of several outputs, some of which may be considered as negative externalities (pollution for instance). An improvement or worsening of "bads" could be credited or debited in productivity analysis. Pittman [8] and Färe et al. [6] provide alternative approaches to account for such improvements (see also [9]). Useful applications of how environmental regulation may affect productivity in an industry include Yaisawarng and Klein [10] and Reinhard et al. [11].

Johansen [12] introduced a measure of plant capacity utilization in productivity analysis, and De Borger and Kerstens [13] integrated the Johansen approach into the Malmquist index (see also [7] and [14]). This allowed for a decomposition of the productivity changes into frontier shifts, variation in technical efficiency and capacity utilization.

In our approach, we combine the negative externality and the capacity utilization approaches in a Malmquist index that allows us to decompose productivity changes into traditional technical efficiency and technology shifts, and further decompose the efficiency change into both an environmental and capital effect and the effect of capital utilization. Our approach also involves capacity utilization in terms of traditional input factors *restricted to the detrimental input*. We also provide an empirical application to the Norwegian inorganic chemistry and pulp and paper industries.

2. The Malmquist index and decomposing components

We define an *input* distance function $D_i^t\left(x^t, y^t\right)$ in year *t* as:

(1) $$D_i^t\left(x^t, y^t\right) = \max\left\{\theta \middle| \left(y, x^t/\theta\right) \in P^t\left(x^t\right)\right\}$$

with an input vector x^t and output y^t in the technology set $P^t(x^t)$. We include detrimental environmental factors as undesirable inputs, see Tyteca [15]. In line with Färe et al. [16] we define an input-oriented Malmquist productivity index $M_i(\bullet)$:

(2) $$M_i\left(x^t, y^t, x^{t+1}, y^{t+1}\right) = \sqrt{\frac{D_i^t\left(x^{t+1}, y^{t+1}\right)}{D_i^t\left(x^t, y^t\right)} \frac{D_i^{t+1}\left(x^{t+1}, y^{t+1}\right)}{D_i^{t+1}\left(x^t, y^t\right)}} = 1/M_o\left(x^t, y^t, x^{t+1}, y^{t+1}\right),$$

which equals the inverse of the output-oriented index, $M_o(\bullet)$, under the assumption of constant returns-to-scale. We first split the Malmquist index into two components, *technical efficiency* (*TC*) and *efficiency change* (*EC*), following De Borger and Kerstens [13] and Färe et al. [17]:

(3) $$M_i = \frac{D_i^{t+1}\left(x^{t+1}, y^{t+1}\right)}{D_i^t\left(x^t, y^t\right)} \sqrt{\frac{D_i^t\left(x^{t+1}, y^{t+1}\right)}{D_i^{t+1}\left(x^{t+1}, y^{t+1}\right)} \frac{D_i^t\left(x^t, y^t\right)}{D_i^{t+1}\left(x^t, y^t\right)}} = EC\,TC\,.$$

The *efficiency change*:

(4) $$EC = \frac{D_i^{t+1}\left(x^{t+1}, y^{t+1}\right)}{D_i^t\left(x^t, y^t\right)}$$

represents technical shifts towards the frontier, while the *technical change*:

(5) $$TC = \sqrt{\frac{D_i^t\left(x^{t+1}, y^{t+1}\right)}{D_i^{t+1}\left(x^{t+1}, y^{t+1}\right)} \frac{D_i^t\left(x^t, y^t\right)}{D_i^{t+1}\left(x^t, y^t\right)}}$$

captures shifts in the frontier. Let us define plant capacity utilization according to De Borger and Kerstens [13] and Sena [14] as:

(6) $$PCU(x^t, x_f^t, y^t) = \frac{D_i^t\left(x^t, y^t\right)}{D_i^t\left(x_f^t, y^t\right)}$$

the relative of the distance function with all inputs $D_i^t\left(x^t, y^t\right)$ and the distance function with only capital input x_f^t, $D_i^t\left(x_f{}^t, y^t\right)$. Since we include detrimental inputs, the capacity utilization component at this stage differs slightly from that used by De Borger and Kerstens [13] and Sena [14]; i.e., it measures efficiency changes in all variable inputs including detrimental input given the input of capital. We now decompose the efficiency change measure (see [13], [14]) into two terms:

(7) $$EC = \left(\frac{D_i^{t+1}\left(x_f^{t+1}, y^{t+1}\right)}{D_i^t\left(x_f^t, y^t\right)}\right)\frac{PCU\left(x^{t+1}, x_f^{t+1}, y^{t+1}\right)}{PCU\left(x^t, x_f^t, y^t\right)} = EC_f PUC\ .$$

The first term, EC_f, measures efficiency changes for capital only. The second term, *PUC*, captures the changes in the degree of plant capacity utilization over time, holding the level of capital constant.

In the next step, we isolate the efficiency change effect of the detrimental input following Färe et al. [7]. We introduce environmental productivity change:

(8) $$PE^s\left(x^t, x_e^t, y^t\right) = \frac{D_i^s\left(x^t, y^t\right)}{D_i^s\left(x_e^t, y^t\right)},$$

as the relative of the distance in the environmental direction and the distance taking into account all inputs (including the detrimental input) measured by technology *s* in the input space in time *t*. x_e^t represents environmental inputs. The full decomposition consists of three terms:

(9)
$$EC = \left(\frac{D_i^{t+1}\left(x_f^{t+1}, y^{t+1}\right)}{D_i^t\left(x_f^t, y^t\right)} \right) \left(\frac{D_i^{t+1}\left(x_e^{t+1}, y^{t+1}\right)}{D_i^t\left(x_e^t, y^t\right)} \right) \left[\frac{PCU(x^{t+1}, x_f^{t+1}, y^{t+1})}{PCU(x^t, x_f^t, y^t)} \frac{PE^{t+1}(x^{t+1}, x_e^{t+1}, y^{t+1})}{PE^t(x^t, x_e^t, y^t)} \frac{1}{EC} \right]$$
$$= \left(\frac{D_i^{t+1}\left(x_f^{t+1}, y^{t+1}\right)}{D_i^t\left(x_f^t, y^t\right)} \right) \left(\frac{D_i^{t+1}\left(x_e^{t+1}, y^{t+1}\right)}{D_i^t\left(x_e^t, y^t\right)} \right) \left[\frac{D_i^{t+1}\left(x^{t+1}, y^{t+1}\right)}{D_i^t\left(x^t, y^t\right)} \frac{D_i^t\left(x_f^t, y^t\right)}{D_i^{t+1}\left(x_f^{t+1}, y^{t+1}\right)} \frac{D_i^t\left(x_e^t, y^t\right)}{D_i^{t+1}\left(x_e^{t+1}, y^{t+1}\right)} \right] = EC_f EC_e PUC_e$$

The first term, EC_f, measures as in (7) efficiency changes for capital only. The second term, EC_e, measures efficiency changes for the detrimental input, i.e., in the environmental direction. The last element, PUC_e, captures the changes in the degree of plant capacity utilization over time, holding capital levels and the detrimental input constant. Since we now exclude detrimental inputs, our capacity utilization definition compares to that used in De Borger and Kerstens [13] and Sena [14]; i.e., it measures efficiency changes in variable inputs given the input of both capital and the detrimental input.

The detrimental input may influence both efficiency change and technical change, cf. (3). We decompose the technical change element, TC, into *environmental technical change* (TC_e) and *technical changes on ordinary inputs* (TC_o):

(10)
$$TC = \sqrt{ \left(\frac{D_i^t\left(x_e^{t+1}, y^{t+1}\right)}{D_i^{t+1}\left(x_e^{t+1}, y^{t+1}\right)} \frac{D_i^t\left(x_e^t, y^t\right)}{D_i^{t+1}\left(e_e^t, y^t\right)} \right) \left[\frac{PE^t\left(x^{t+1}, x_e^{t+1}, y^{t+1}\right)}{PE^{t+1}\left(x^{t+1}, x_e^{t+1}, y^{t+1}\right)} \frac{PE^t\left(x^t, x_e^t, y^t\right)}{PE^{t+1}\left(x^t, x_e^t, y^t\right)} \right] }$$
$$= \sqrt{ \left(\frac{D_i^t\left(x_e^{t+1}, y^{t+1}\right)}{D_i^{t+1}\left(x_e^{t+1}, y^{t+1}\right)} \frac{D_i^t\left(x_e^t, y^t\right)}{D_i^{t+1}\left(e_e^t, y^t\right)} \right) \left[\frac{D_i^t\left(x^{t+1}, y^{t+1}\right)}{D_i^{t+1}\left(x^{t+1}, y^{t+1}\right)} \frac{D_i^t\left(x^t, y^t\right)}{D_i^{t+1}\left(e^t, y^t\right)} \frac{D_i^{t+1}\left(x_e^{t+1}, y^{t+1}\right)}{D_i^t\left(x_e^{t+1}, y^{t+1}\right)} \frac{D_i^{t+1}\left(x_e^t, y^t\right)}{D_i^t\left(x_e^t, y^t\right)} \right] } = TC_e TC_o$$

To summarize, the full decomposition of our Malmquist index:

(11) $$M_i = EC_f EC_e PUC_e TC_e TC_o$$

now consists of efficiency changes caused by capital, EC_f, efficiency changes caused by detrimental input changes, EC_e, efficiency changes caused by capacity utilization of traditional inputs, PUC_e, technical changes in an environmental direction, TC_e and, finally, technical changes in ordinary inputs, TC_o.

3. Data

We compute the Malmquist index on an unbalanced panel data set for the years 1992–2002 for two pollution-intensive industries: pulp and paper, and inorganic chemistry, see Table I. The data set consists of 21 and 11 plants respectively, covering about 90 per cent of the production in these manufacturing industries in 2000.[1] The input data consist of labour, intermediate inputs, energy, capital, and a detrimental input. Labour is measured in terms of working hours while the remaining inputs and outputs are measured in values (fixed 2000 prices). The firm specific capital time series are based upon fire insurance values for the first two years in the sample period, annual gross investments and depreciation:

(12) $$K_t = (1-\delta)^{t-1} K_0 + \sum_{\tau=0}^{t-1} (1-\delta)^{t-(\tau+1)} I_\tau \ ,$$

where K_t is the net capital stock in the beginning of year t. K_0 is the fire insurance value, I_τ is the gross investments in year τ, and δ is the annual depreciation rate.[2] A greenhouse gas aggregate consisting of CO_2, CH_4 and N_2O, measured in CO_2-equivalents (see [19]), represents the detrimental input.

[1] See [18] for further documentation regarding the data.

[2] The capital stock consists of machineries and buildings. The average depreciation rate is approximately 6 per cent per annum.

Table I: Summary statistics on industry level for variables used in the calculations of Malmquist indexes

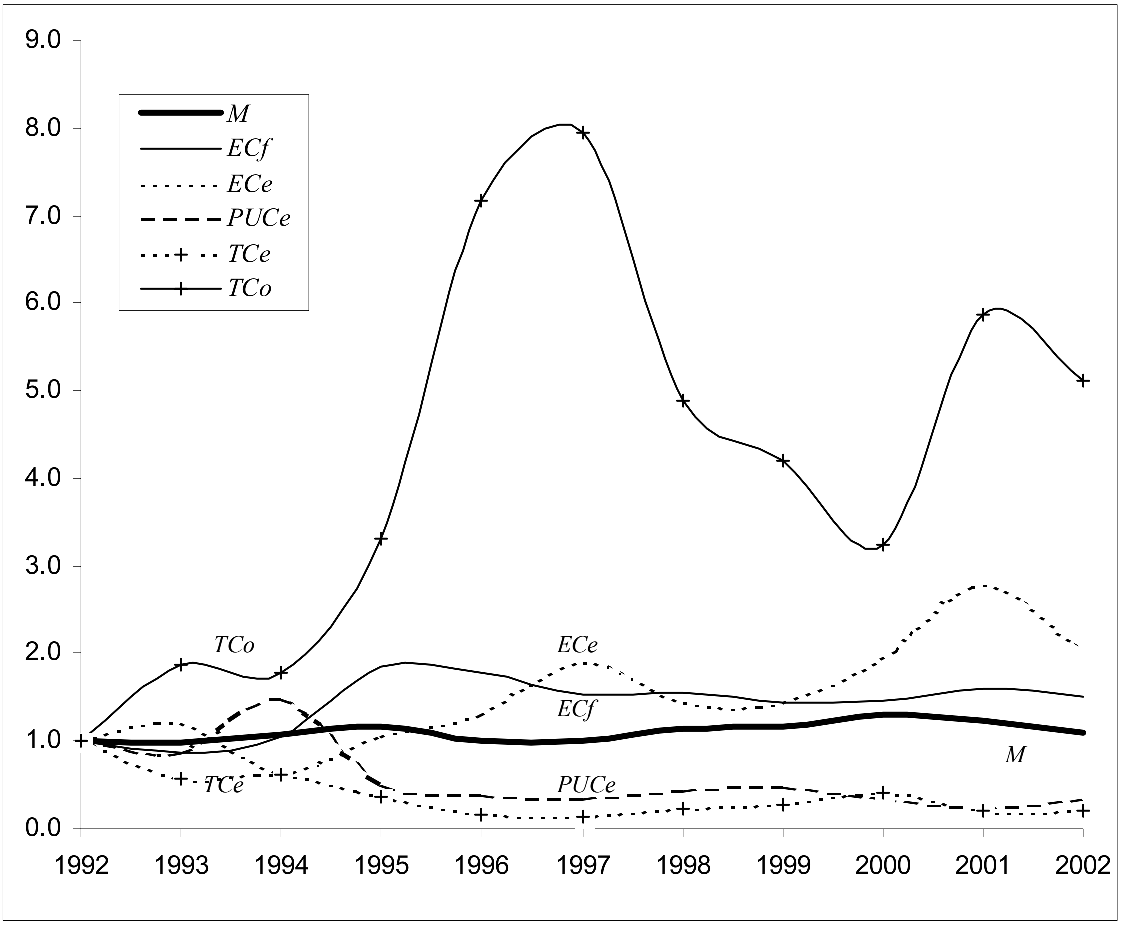
Industry	Pulp and paper				Inorganic Chemistry			
Number of observations	220				119			
	Mean	Std dev.	Min	Max	Mean	Std dev.	Min	Max
Firms	20	1.7	18	22	11	0.4	10	11
Production (mill NOK)	697	778	8	3214	300	159	73	772
Labour (mill hours)	483	391	16	1446	278	170	57	643
Intermediate inputs (mill NOK)	530	562	7	2156	198	104	32	430
Capital (1000 NOK)	1606	1809	47	7785	608	373	144	1654
Greenhouse gases (mill tonnes)	23	29	0.02	132	1.9	2.4	0.02	10

4. Results

In our input-oriented efficiency index, numbers less than one correspond to progress. For illustrative purposes, we follow Färe et al. [16] and take the reciprocal numbers so that one equals no change, a number greater than one shows progress and a number less than one shows regress.

Figure 1 presents the total decomposition of the Malmquist index, following (11). The total Malmquist index (M) in 2002 was 1.09, indicating a yearly average productivity growth of 0.9 per cent from 1992. The dominating contributor to the increasing index front was technology improvements controlled for environmental factors (TC_o). Other contributors were the more efficient use of environmental factors (EC_e) and capital (EC_f). Capital utilization controlling for capital levels and detrimental input (PUC_e) became less efficient over time, and contributed to a reduction in overall productivity.

Figure 1. Decomposition of the Malmquist index. Pulp and paper. 1992 = 1.0



Further, there has been a backwards movement in the environmental frontier technologies, i.e., lower TC_e over time. The first explanation may result from the exit of a firm with efficient technology in the environmental direction. Second, as plants depreciate, energy efficiency may fall, and emission and energy are highly correlated. Third, firms may substitute electricity with fossil fuels, but improve efficiency in other input directions. The lowest level was attained in 1996–1997. This may be explained by the relatively low prices of fossil fuels compared to electricity in 1996 when the hydropower-dominated electricity market suffered from severe inflow shortages [20]. An increase in electricity prices by almost 50 per cent from 1993 to 1997 induced the substitution of fossil fuels for electricity and increased the emission of CO_2. This is a relatively simple process in the pulp and paper industry, as electricity and fuel oils are perfect substitutes in the boilers.

Figure 2 illustrates the effect of broadening the productivity definition by including detrimental inputs. The figure shows the traditional Malmquist index excluding these inputs (*M-trad*), compared to our index *M*. As shown, the overall productivity improvements are significantly higher when the environmental dimension in the Malmquist index is excluded. When accounting for traditional inputs only, there have been frontier movements over the period 1992 to 2002. When including environmental factors, the total movement since 1992 is rather small. Our empirical illustration reveals that the choice of aspects included in the index may significantly influence the impression of technological progress, and productivity indexes excluding detrimental inputs may be misleading. The main reason in this case is weaker frontier movements in the environmental dimension.

Figure 2. Malmquist indexes, including and excluding detrimental inputs. Pulp and paper. 1992 = 1.0

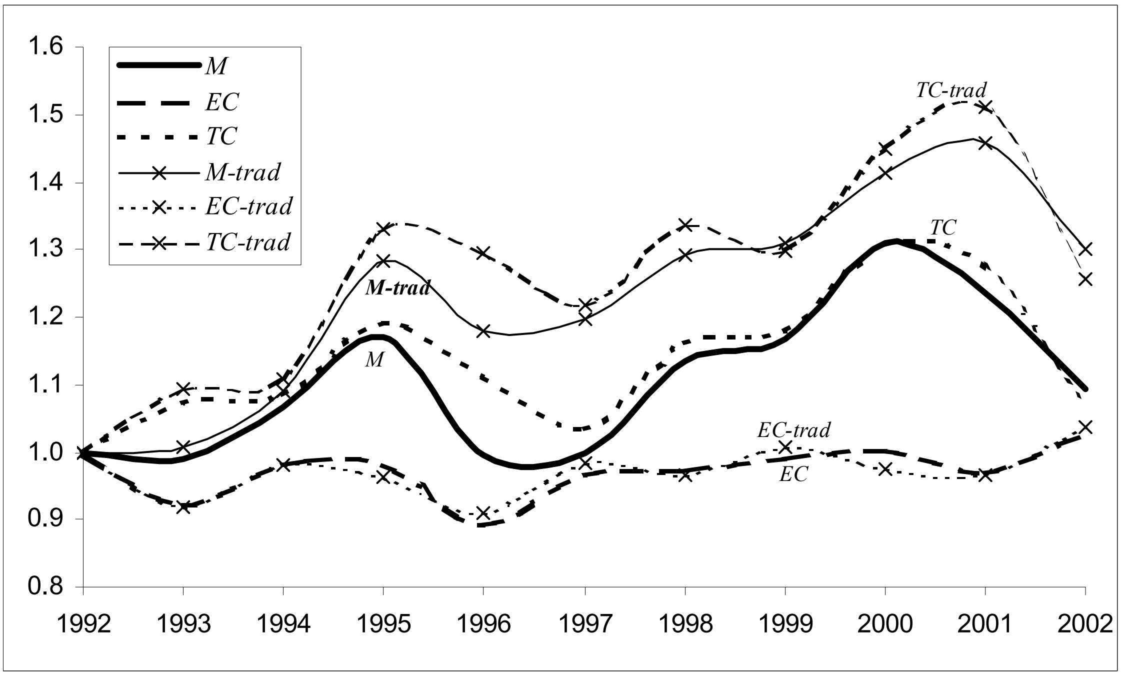
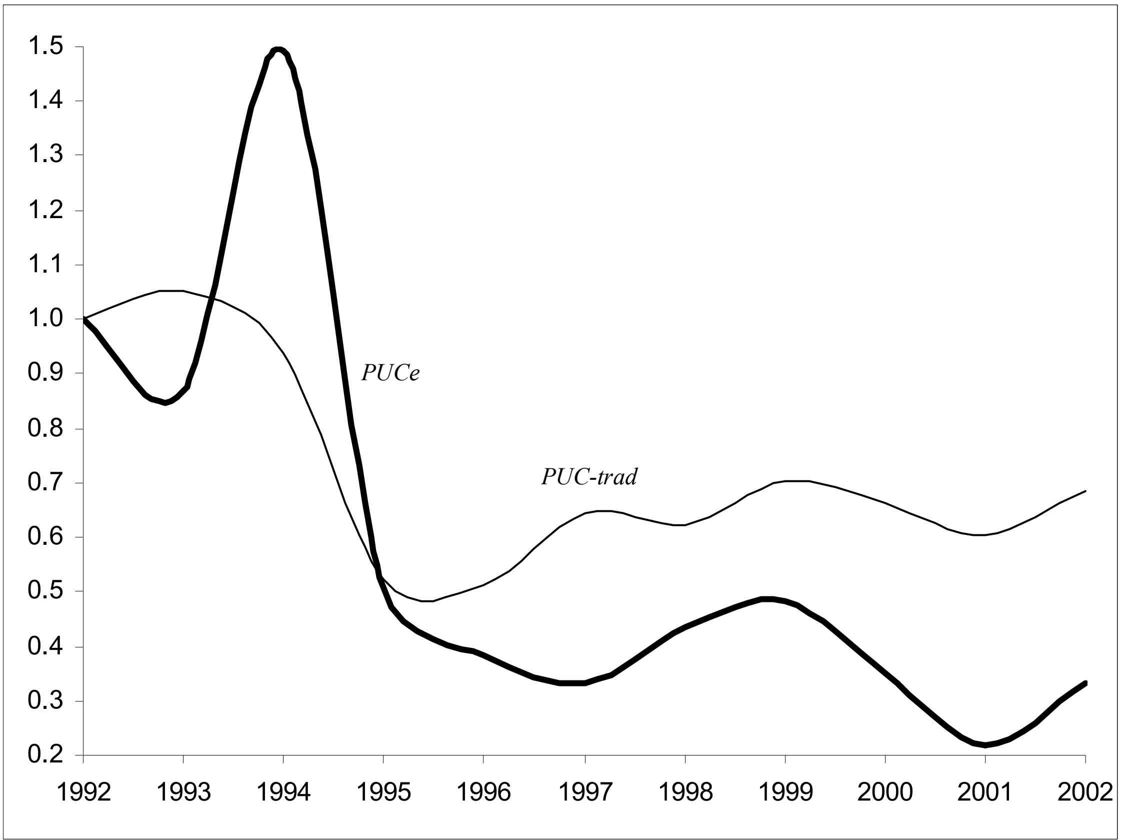


Figure 3 illustrates our second point, the specification of the plant capacity utilization as part of the efficiency changes. The *PUC-trad* illustrates that capacity utilization has become less efficient over time, when measuring capacity utilization along the traditional inputs. The PUC_e shows that capacity utilization taking also environmental inputs into consideration gets even worse over time. The PUC_e index element is only one half of the *PUC-trad* index element. This indicates that environmental considerations are less exercised under upswings.

Figure 3. Plant capacity utilization, controlling for detrimental inputs (*PUC_e*), and measured in the traditional way (*PUC-trad*). Pulp and paper. 1992 = 1.0



Finally, to investigate the generality of the results, we compare these results with those obtained for the inorganic chemistry industry, see Figures 4 and 5. In this industry, the traditional Malmquist index increases less than the index including detrimental inputs—opposite to the case of the pulp and paper industry. The traditional technical change element is lower than the technical change element including detrimental inputs —again the opposite was found for pulp and paper. This could reflect the different substitution possibilities in these two industries. The traditional efficiency change is approximately equal to the efficiency change including detrimental inputs—as for the pulp and paper industry. The capacity utilization measure taking into account detrimental inputs are less than the traditional one—the same as the paper and pulp industry. A conclusion appears to be that when considering efficiency changes, the inclusion of detrimental inputs may work in both ways. When including environmental considerations in capacity utilization, it appears that the environment loses when capacity utilization increases.

Figure 4. Malmquist indexes, including and excluding detrimental inputs. Inorganic chemistry. 1992 = 1.0

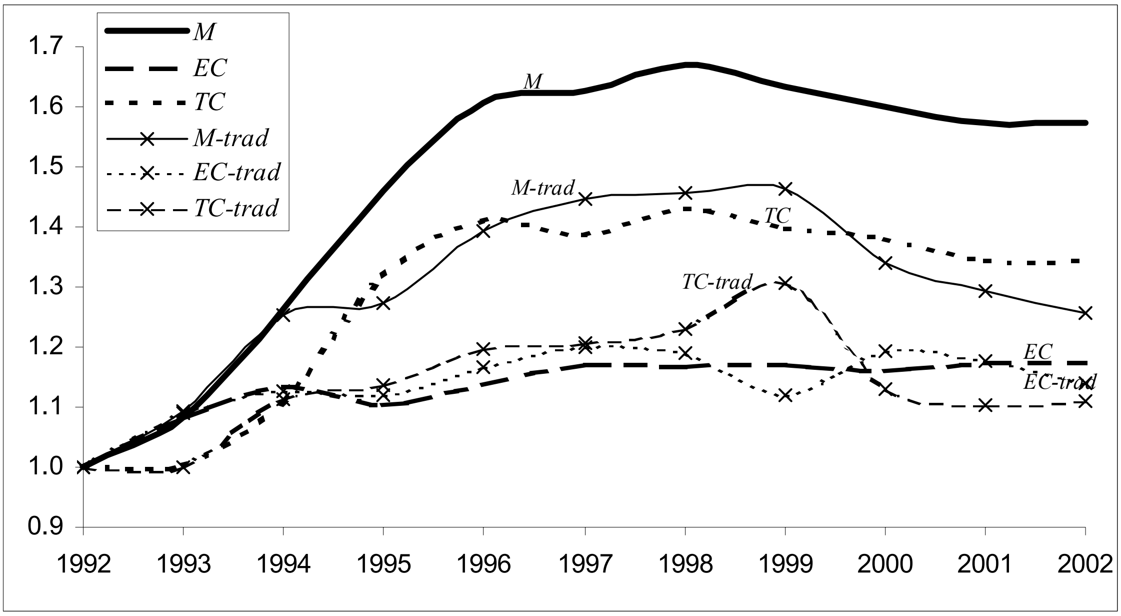
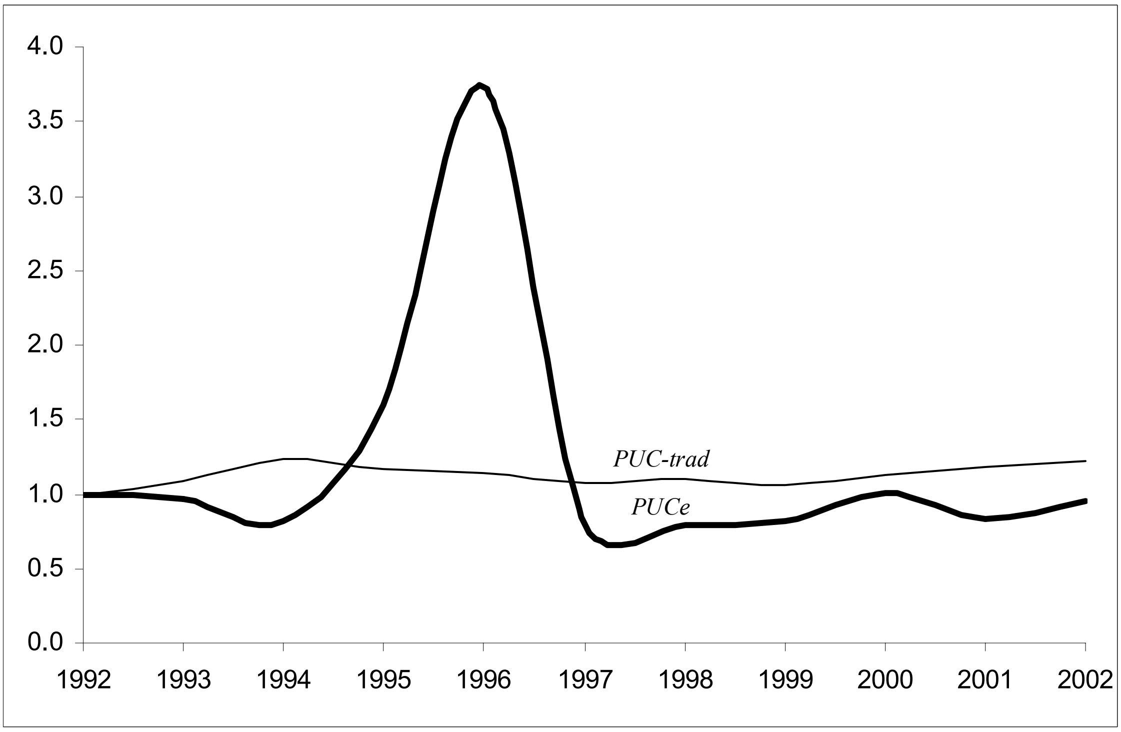


Figure 5. Plant capacity utilization, controlling for detrimental inputs (PUC_e), and measured in the traditional way (*PUC-trad*). Inorganic chemistry. 1992 = 1.0



5. Summary

Efficiency gains disregarding detrimental inputs may be misleading as a productivity measure, as shown in numerous studies in the literature. When measuring efficiency, capacity utilization is also important, as Johansen proved in his seminal work [12]. In our paper, we combine earlier developments of the Malmquist productivity index, including detrimental inputs, with the decomposition of technical efficiency changes into contributions from environmental factors, capacity utilization and other traditional factors. Hence, our capacity utilization element is wider than that used in the earlier literature as it also takes into account the capacity for producing negative externalities.

Our empirical analysis illustrates that the choice of inputs significantly influences the overall productivity measure and its decomposition into efficiency changes and technical changes. We also demonstrate that the empirical importance of capacity utilization with respect to all inputs differs significantly from that obtained employing a definition including traditional inputs only. The importance of the new elements is ambiguous, except from the effect on the capacity utilization element. The influence on this element appears to be more in line with ex ante assumptions; the environment loses when plants implement maximize profit along with business cycles.

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