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Original Research

Efficiency and productivity of cancer care in Europe

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ABSTRACT

This study measures the efficiency and productivity of breast and lung cancer health care provision in Europe in order to inform related policy discussions. The included countries' relative performance is measured against a best practice production frontier computed using distance functions where inputs are used to produce an output. The distance function is well suited to identify best practice in a complex production process such as cancer care with rapid change in technologies.

Price data is not needed which is an advantage when evaluating the European health care sector where market prices often are non-existent. Input variables such as number of radiation units, number of oncologists, and oncology pharmaceuticals are used to produce survival and quality of life.

Publicly available data between 2005 and 2015 from Eurostat, OECD, WHO, and published sources are used to compute country specific efficiency and productivity results. The data reveal extensive differences in inputs and outputs and this is reflected in the performance measures. Efficient and inefficient countries occur among both wealthy and less affluent countries and it can be seen that significantly higher input use typically yields only a small increase in the outputs, both across countries and over time.

1. Introduction

An estimated 2.6 million new cases of cancer and 1.26 million cancer deaths in the European Union (EU-27), [1], not only impose a significant burden on patients but also on constrained European health care budgets. To make the most of available resources it is essential that the production of cancer care is carried out efficiently; efficient use of resources reduces waste and frees resources for use elsewhere in the production of cancer care. Efficient production does not mean increasing the resource use by working harder and running faster but rather to learn from best practice and apply this knowledge to the production of cancer care. Our goal is to identify best practice in the use of inputs in producing outcomes in a sample of European countries over the 2005–2015 period in the area of breast cancer and lung cancer care.

Other research in this area is limited. lo Storto and Goncharuk [2] used a frontier approach to evaluate the efficiency and effectiveness of 32 European countries using Eurostat data. They identified both more affluent countries like Germany, Norway, and Switzerland as inefficient together with a less affluent country like Lithuania. Towse et al. [3] utilized a Malmquist index to measure relative effectiveness and Färe et al. [4] looked at the productivity growth in health care delivery exploring a Malmquist index approach.

Here, two performance models are evaluated: (i) a static technical efficiency (Farrell) approach to assess relative efficiency at the country level in 2015, and (ii) an inter-temporal (Malmquist) productivity approach covering 2005, 2010, and 2015.

The data for this study are real world, publicly available, country level aggregate, comparable data from Eurostat, OECD, WHO, as well as published articles which are used to evaluate the country specific production of breast cancer (BC) and lung cancer (LC) care in Europe. Breast and lung cancer were chosen since they are common cancers [1], with very different mortality rates.

The results from the technical efficiency calculations yields per country efficiency scores between 0–1 with a direct interpretation: A score of one indicates that the country produces cancer care efficiently compared to the other countries in the sample, i.e. it demonstrates "best practice" that other countries can learn from. A score below one indicates inefficiency and the score gives the degree of inefficiency.

The inter-temporal productivity measurements provides the per country change in efficiency between adjacent periods, as well as the change in technology between periods. Information on the degree of efficiency and the change in efficiency and technology over time provides useful per country data to inform policy decisions to improve the country's production of health care.

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2. Methods

To measure how well a country is doing in the production of cancer care we need something to measure it against, i.e. we need a representation of the best practice technology relative to which to measure each country's performance. This best practice technology (or frontier) can be constructed from data on inputs (or resources) used to produce the outputs (or outcomes). No prices are required. The focus is on identifying deviations from best practice input use by means of an input distance function [5,6] which gauges how far a given country's observed input usage is from best practice. This function contracts observed country inputs to the best practice frontier and tells us how many resources can be saved while producing the original observed level of outputs. In addition to the distance function the approach relies on the Farrell measure of technical efficiency [7].

2.1. Efficiency

Fig. 1 provides an illustration of the input set $L(y)$, the frontier, and the input distance function. The input requirement set $L(y)$ consists of the shaded area. The frontier of the input set $I - \acute{I}$ is constructed from the data points representing country a and country b. These two countries are said to be technically efficient since they are on the frontier with an efficiency score of one. They are on the frontier since they use the fewest possible inputs to produce the same level of output y. They do this with a different mix of inputs, but there is no other country doing this more efficiently.

In contrast, consider a country c which produces the same output as a and b, but lies in the interior shaded (inefficient) area of the input set. The input distance function contracts this resource use down to $\hat{c}$ which is on the frontier. This hypothetical country $\hat{c}$ uses the same mix of inputs as c but proportionally fewer of those inputs and still produces the same level of output as c.

The Farrell input measure of technical efficiency [7], which we use in this study, is defined as the reciprocal of the input distance function [5], i.e. as: *Farrell Technical Efficiency = 1/Input Distance Function.*

For inputs inside the input set, or at the frontier, the input distance function take values greater than or equal to one and the Farrell measure takes values less than or equal to one. Hence, a Farrell measure of technical efficiency equal to one represents an efficient observation, and a value less than one represents an inefficient observation.

2.2. Productivity

Our inter-temporal measure of performance is the Malmquist input based productivity index [8], which is defined as the geometric mean of two Malmquist input based productivity indexes [9]. We choose the input based index to capture productivity change in terms of changes in

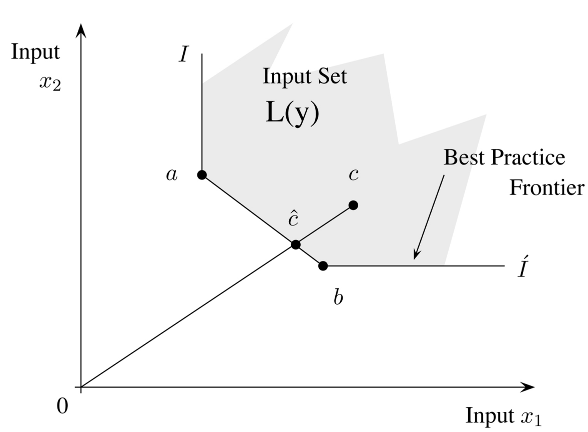

Fig. 1. The input set and the measurement of technical efficiency.

input use over time, consistent with the input-saving focus of the static Farrell efficiency analysis.

The change in productivity can be decomposed into changes in technical efficiency over time and shifts in the frontier of technology (technical change) over time. Efficiency change reflects the change in efficiency between two adjacent periods e.g. between 2010 and 2015, and technical change captures the change in the production frontier between the two adjacent periods, see appendix for details.

3. Data

The inputs should reflect the resources used to produce the output, and the output should reflect a desired outcome from the treatment. All variables need to be comparable across countries. In addition, the variables need to be clinically relevant and this was achieved by the involvement of clinical expertise and consultations with the European CanCer Organization (ECCO). There was a search for available data from websites and publications. The available variables were then discussed and quality assured with ECCO before being included in the analysis.

Inputs and outputs used in either BC, LC, or both:

3.1. Inputs

1. *Screening* (BC): Five year annual mean of breast cancer screening as % of women aged 50–69 years;
2. *Pulmectomy* (LC): Five year annual mean of pulmectomy per 100,000 inhabitants;
3. *Radiation* (BC, LC): Five year annual mean of radiation units per 100,000 inhabitants;
4. *Oncologists* (BC, LC): Five year annual mean of oncologists per 100,000 inhabitants;
5. *Drugs* (BC, LC): Annual cancer care drug expenditure per capita; and
6. *DDD* (BC, LC): Annual Defined Daily Dose per mortality case.

3.2. Outputs

1. *RS* (BC, LC): Age standardized 5-year relative survival; and
2. *DALYcv* (BC, LC): Life expectancy adjusted by disability adjusted life years, DALYs.

The input variables: *screening, pulmectomy, radiation, and oncologists* were obtained from Eurostat [10,11], OECD [12], and WHO [13].

Data on DDD per mortality case are obtained from the IMS Health MIDAS database and presented by Jönsson et al. [14]. The drugs included in the variable DDD in BC are: trastuzumab, lapatinib, pertuzumab, and trastuzumab emtansine, and in LC: erlotinib, crizotinib and gefitinib, as targeted drugs.

Outputs from 2005, 2010, and 2015 are used in the analysis together with inputs calculated as 5-year averages to reflect resource use to produce *RS* for 2015 [15,16], and DALYcv [17,18] for 2005, 2010, and 2015. That is, the input variables for 2005 are calculated as the average from 2001–2005, 2010 inputs as the average from 2006–2010, and 2015 inputs as the average from 2011–2015 to include the lag effect of treatment (resource use) on outcome. The constructed variable *DALYcv* is calculated as life expectancy in EU28 [17] minus disability-adjusted life years (DALY) per country and type of cancer [18].

Cancer drug expenditure data are only available for the years 2005, 2010 and 2014 and are all inflated to 2015 prices by Eurostat's annual average index for pharmaceutical products, see Jönsson et al. [19]. The *DDD* input and *RS* output are only available for the 2015 cross sectional efficiency analysis. For the time series dependent productivity analysis the *DDD* input is replaced by the *Drugs* input, collected from Jönsson et al. [19], and the *RS* output with the *DALYcv* output.

In cases of missing values, estimates based on ordinary least square (OLS) regressions and country-to-country relationships are used. Data

Table 1
Farrell technical efficiency in the production of five year relative survival (RS) in breast cancer in 2015, $N = 17$.

	RS	Screening	Radiation	Oncologists	DDD	Efficiency score
Belgium	82.7	59.00	1.20	3.91	335	0.82
Croatia	76.3	58.80	0.64	3.56	195	0.97
Czech R.	78.0	57.58	0.81	2.78	170	1.00
Denmark	81.5	82.80	1.33	2.76	390	0.65
Finland	85.7	83.16	0.98	2.96	365	0.75
France	86.1	52.66	0.91	1.29	310	1.00
Germany	83.6	55.75	0.91	3.16	335	0.92
Ireland	79.0	73.46	0.96	3.96	405	0.72
Italy	85.5	58.26	0.69	7.33	262	1.00
Netherlands	84.5	80.15	1.05	3.44	335	0.74
Poland	71.6	58.60	0.38	3.80	170	1.00
Portugal	83.3	84.20	0.66	2.46	325	0.89
Slovakia	73.9	23.41	1.20	3.58	375	1.00
Slovenia	78.7	77.02	0.58	1.33	235	1.00
Spain	82.8	79.80	0.49	3.76	335	0.99
Sweden	86.0	90.40	1.13	5.51	405	0.65
UK	79.2	76.04	0.59	3.76	335	0.86
Mean	81.1	67.71	0.85	3.50	310	0.88
Sd	4.4	16.78	0.28	1.40	77	0.13
Min	71.6	23.41	0.38	1.29	170	0.65
Max	86.1	90.40	1.33	7.33	405	1.00

Variable names: (i) RS: Five year relative survival; (ii) DDD: Defined Daily Dose.
Imputed values: 11% of the observations were missing and replaced with estimated values.

on radiation oncologists from WHO are used in the regressions to estimate missing data on oncologists, and data on mega-voltage machines from Rosenblatt et al. [20] are used to estimate missing values on radiation units, see appendix for details.

4. Results

In both breast and lung cancer a cross sectional efficiency analysis was completed with drug use measured in *DDD* as one of the inputs; and 5-year relative survival *RS* as output. These two variables were replaced with drugs measured as expenditure of cancer drugs (*Drugs*); and the converted DALY *DALYcv* as output in the productivity calculations. In addition the efficiency scores for 2005, 2010, and 2015 calculated with the variables in the productivity calculations are presented in the productivity sections. Hence, the efficiency scores for 2015 are calculated with two different sets of variables and countries.

4.1. Breast cancer

4.1.1. Efficiency 2015

The Farrell input based technical efficiency scores are presented in Table 1. Four inputs (i) Breast cancer screening; (ii) Radiation units; (iii) Oncologists; and (iv) DDD were used to produce the 5-year relative survival (RS) in 2015. The results are presented in Table 1.

There are 6 efficient countries out of the 17: Czech R., France, Italy, Poland, Slovakia, and Slovenia. France produces the highest relative survival of 86.1, and Poland the lowest of 71.6.

The least efficient countries are Sweden and Denmark with efficiency scores of 0.65. Sweden provides the most screening of all countries, is fourth from the top in number of radiation units, only Italy has more oncologists, and is an above average user of oncology drugs. So, despite producing a high relative survival Sweden is one of the most inefficient producers of breast cancer care based on these variables. If Sweden utilized its inputs more efficiently it would be able to produce the same survival with only 65% of the resources used. Compared to France, Sweden uses more of all inputs and produces the same survival. Note that despite being one of the most inefficient producers—Sweden produces higher levels of relative survival than any of the efficient countries, with the exception of France. Hence, being a patient in an inefficient country is not necessarily bad, it just means that a country like Sweden uses more than the minimal level of resources necessary to produce high survival.

Table 2
Farrell technical efficiency and Malmquist productivity change for breast cancer, 2005–2015, $N = 23$.

	2005	2010	2015	2005/2010			2010/2015		
	TE	TE	TE	PC	EC	TC	PC	EC	TC
Austria	0.64	0.68	0.85	0.93	1.07	0.87	0.93	1.24	0.75
Belgium	0.65	0.64	0.62	0.88	0.98	0.91	0.69	0.98	0.71
Croatia	0.75	0.83	0.75	0.83	1.11	0.75	0.64	0.91	0.71
Czech R.	0.65	0.60	0.83	0.87	0.93	0.94	0.96	1.40	0.69
Denmark	0.65	0.54	0.62	0.78	0.83	0.94	0.85	1.13	0.75
Estonia	1.00	1.00	1.00	0.64	1.00	0.64	0.73	1.00	0.73
Finland	0.56	0.56	0.67	0.97	1.00	0.96	0.91	1.20	0.76
France	1.00	1.00	1.00	0.91	1.00	0.91	0.82	1.00	0.82
Germany	0.79	0.62	0.73	0.75	0.79	0.95	0.83	1.17	0.71
Hungary	0.57	0.78	0.92	0.84	1.37	0.61	0.92	1.17	0.79
Ireland	0.70	0.62	0.63	0.86	0.88	0.97	0.76	1.01	0.75
Italy	0.36	0.52	0.58	0.89	1.42	0.63	0.89	1.13	0.79
Latvia	1.00	1.00	1.00	0.49	1.00	0.49	0.67	1.00	0.67
Lithuania	1.00	1.00	1.00	0.67	1.00	0.67	0.60	1.00	0.60
Luxembourg	0.66	0.67	0.83	0.93	1.01	0.92	0.89	1.24	0.71
Netherlands	0.51	0.49	0.61	0.94	0.96	0.97	0.92	1.25	0.74
Poland	0.92	0.98	0.98	0.84	1.06	0.79	0.74	1.00	0.74
Portugal	0.65	0.73	0.87	1.02	1.13	0.90	0.90	1.19	0.76
Slovakia	0.69	1.00	1.00	0.72	1.44	0.50	0.88	1.00	0.88
Slovenia	1.00	1.00	1.00	0.82	1.00	0.82	0.66	1.00	0.66
Spain	0.58	0.64	0.85	0.92	1.11	0.83	0.95	1.32	0.72
Sweden	0.42	0.41	0.49	0.91	0.97	0.94	0.91	1.21	0.75
UK	0.59	0.65	0.74	0.92	1.10	0.84	0.86	1.15	0.75
Mean	0.71	0.74	0.81	0.84	1.05	0.82	0.82	1.12	0.74
Sd	0.19	0.20	0.17	0.12	0.17	0.15	0.11	0.13	0.06
Min	0.36	0.41	0.49	0.49	0.79	0.49	0.60	0.91	0.60
Max	1.00	1.00	1.00	1.02	1.44	0.97	0.96	1.40	0.88

Variable names: (i) TE: Technical efficiency; (ii) PC: Productivity change; (iii) EC: Efficiency change; (iv) TC: Technical change.
Imputed values: 17% of the observations were missing and replaced with estimated values.

4.1.2. Productivity 2005—2015

The input-based Malmquist productivity change (*PC*), efficiency change (*EC*), and technical change (*TC*) for breast cancer care going from 2005 to 2010, and from 2010 to 2015 are computed under constant returns to scale and strong disposability of inputs. The results are presented in Table 2.

Four inputs (i) Breast cancer screening; (ii) Radiation units; (iii) Oncologists; and (iv) Drugs are used to produce the life expectancy adjusted by disability adjusted life years (DALYcv). A value above 1 in any of *PC*, *EC*, or *TC* indicates an improvement, a value of one indicates no change, and a value below one indicates a decline. The measures are computed from Farrell efficiency combinations of adjacent periods, see Malmquist index and its decompositions in Appendix A.

The results in Table 2 also include the Farrell technical efficiency measures (TE) for 2005, 2010, and 2015 and are computed with the same variables used to estimate productivity.

In all countries except Portugal, there was a decline in productivity (PC) going from 2005 to 2010. Nine countries had a positive change in efficiency (EC), six had no change, and seven had a negative change in efficiency between 2005 and 2010. All 23 countries had a negative change in the technology (TC) going from 2005 to 2010.

Going from 2010 to 2015 it can be seen that all countries had a decline in productivity; all countries except Belgium and Croatia had an increase in efficiency; and all countries had a negative change in the

Table 3
Farrell technical efficiency in the production of five year relative survival (RS) in lung cancer in 2015, $N = 16$.

	RS	Radiation	Oncologists	Pulmectomy	DDD	Efficiency score
Belgium	15.4	1.20	3.91	17.95	32.0	0.77
Croatia	14.8	0.64	3.56	13.40	15.6	0.93
Czech R.	11.5	0.81	2.78	11.77	20.5	0.83
Denmark	10.3	1.33	2.76	17.09	22.0	0.72
Finland	11.5	0.98	2.96	0.65	31.0	1.00
France	13.8	0.91	1.29	21.35	48.0	1.00
Germany	15.6	0.91	3.16	38.18	22.0	1.00
Ireland	11.8	0.96	3.96	9.19	16.5	0.75
Italy	14.3	0.69	7.33	16.35	25.0	0.61
Netherlands	13.4	1.05	3.44	17.72	17.0	0.85
Poland	14.4	0.38	3.80	10.46	3.0	1.00
Portugal	11.2	0.66	2.46	11.67	56.0	0.78
Slovenia	10.7	0.58	1.33	9.41	33.0	1.00
Spain	10.7	0.49	3.76	14.39	21.0	0.68
Sweden	14.7	1.13	5.51	8.86	28.0	0.70
UK	9.0	0.59	3.76	13.96	16.0	0.54
Mean	12.7	0.83	3.49	14.53	25.4	0.81
Sd	2.1	0.27	1.45	7.96	12.9	0.15
Min	9.0	0.38	1.29	0.65	3.0	0.54
Max	15.6	1.33	7.33	38.18	56.0	1.00

Variable names: (i) RS: Five year relative survival; (ii) DDD: Defined Daily Dose.
Imputed values: 11% of the observations were missing and replaced with estimated values.

technology. The decline in productivity is explained by the fact that the increase in resource use only yields a small increase in output, see appendix for data and additional details.

4.2. Lung cancer

4.2.1. Efficiency 2015

The Farrell input based technical efficiency scores are presented in Table 3. Four inputs (i) Radiation units; (ii) Oncologists; (iii) Pulmectomy; and (iv) DDD are used to produce the 5-year relative survival (RS) in 2015.

There are five efficient countries out of the 16: Finland, France, Germany, Poland, and Slovenia. The mean relative survival in breast cancer of 81.1 is very different to the mean survival in lung cancer of 12.7. Germany produces the highest survival of 15.6 and UK the lowest of 9.0. Germany use significantly more resources than the UK but this pays off with almost double the survival figure. UK is the least efficient producer of lung cancer care with an efficiency score of 0.54. Poland has the minimum number of radiation units, and a minimal drug use but still produces an above average survival.

4.2.2. Productivity 2005—2015

Four inputs (i) Radiation units; (ii) Oncologists; (iii) Pulmectomy; and (iv) Drugs are used to produce the DALYcv, see Table 4.

In all countries, except the Czech Republic and Finland, there is a decline in productivity (PC) going from 2005 to 2010. Seven countries have a positive change in efficiency (EC), seven have no change, and nine have a negative change in efficiency between 2005 and 2010. All but Finland have a negative change in the technology (TC) going from 2005 to 2010.

Going from 2010 to 2015 it can be seen that all countries but the Czech Republic see a decline in productivity. Twelve countries have an increase in efficiency, six have no change, and five have a decline in efficiency and all countries have a negative change in the technology between 2010 and 2015.

Table 4
Farrell technical efficiency and Malmquist productivity change for lung cancer, 2005–2015, $N = 23$.

	2005	2010	2015	2005/2010			2010/2015		
	TE	TE	TE	PC	EC	TC	PC	EC	TC
Austria	0.64	0.69	0.84	0.94	1.09	0.86	0.99	1.21	0.82
Belgium	0.57	0.54	0.51	0.85	0.94	0.91	0.75	0.95	0.80
Croatia	0.88	0.95	0.76	0.90	1.08	0.83	0.63	0.80	0.79
Czech R.	0.54	0.58	0.84	1.00	1.00	0.93	1.13	1.45	0.77
Denmark	0.65	0.53	0.55	0.75	0.81	0.92	0.85	1.04	0.82
Estonia	1.00	1.00	1.00	0.65	1.00	0.65	0.73	1.00	0.73
Finland	1.00	1.00	1.00	1.11	1.00	1.11	0.98	1.00	0.98
France	0.66	0.68	1.00	0.92	1.04	0.89	0.82	1.46	0.56
Germany	0.61	0.55	0.57	0.69	0.90	0.77	0.83	1.04	0.80
Hungary	0.49	0.55	0.74	0.76	1.11	0.68	0.94	1.34	0.70
Ireland	1.00	0.85	0.74	0.77	0.85	0.91	0.76	0.87	0.87
Italy	0.63	0.63	0.63	0.90	0.99	0.91	0.90	1.01	0.89
Latvia	1.00	1.00	1.00	0.55	1.00	0.55	0.68	1.00	0.68
Lithuania	1.00	1.00	1.00	0.82	1.00	0.82	0.66	1.00	0.66
Luxembourg	0.71	0.74	0.84	0.97	1.05	0.92	0.91	1.13	0.80
Netherlands	0.52	0.52	0.55	0.92	0.99	0.93	0.91	1.07	0.85
Poland	1.00	1.00	1.00	0.88	1.00	0.88	0.85	1.00	0.85
Portugal	0.83	0.87	0.92	0.98	1.05	0.93	0.90	1.06	0.85
Romania	1.00	0.98	1.00	0.81	0.98	0.83	0.82	1.02	0.81
Slovenia	1.00	1.00	1.00	0.84	1.00	0.84	0.70	1.00	0.70
Spain	0.91	0.88	0.85	0.88	0.96	0.92	0.83	0.97	0.85
Sweden	0.64	0.65	0.70	0.92	1.01	0.91	0.92	1.08	0.86
UK	1.00	0.87	0.79	0.80	0.87	0.92	0.77	0.91	0.85
Mean	0.79	0.79	0.82	0.85	0.99	0.86	0.84	1.06	0.80
Sd	0.20	0.19	0.17	0.12	0.08	0.11	0.12	0.16	0.09
Min	0.49	0.52	0.51	0.55	0.81	0.55	0.63	0.80	0.56
Max	1.00	1.00	1.00	1.11	1.11	1.11	1.13	1.46	0.98

Variable names: (i) TE: Technical efficiency; (ii) PC: Productivity change; (iii) EC: Efficiency change; (iv) TC: Technical change.
Imputed values: 17% of the observations were missing and replaced with estimated values.

5. Discussion

Estimating efficiency and productivity of breast and lung cancer in a sample of countries in Europe with publicly available data from Eurostat, OECD, WHO, and published articles reveals that there are inefficiencies and negative productivity change in many European countries.

Policy relevance requires that estimates of efficiency and productivity are based on clear definitions and on inputs and outcomes that are meaningful to all stakeholders, including clinicians and patients. For example, inputs should be measured in relevant units to provide an understanding of what drives efficiency and productivity. In addition, the method should allow for a multitude of outcome measures, defined as relevant by patients, as e.g. both survival and quality of life.

Our application at the country levels shows that the studied countries can be separated as efficient and inefficient in a systematic manner. We used two different outcome measures, five-year relative survival and a reduction in burden of cancer in terms of quality-adjusted life years (DALY). Results were similar with the two different outcomes.

The application to breast cancer and lung cancer show both similarities and differences. Efficient countries include both countries with good outcomes, for example France and Italy in breast cancer and France and Germany in lung cancer, and countries with less good outcomes but with less input use. It is also interesting to note that input of cancer medicines gives similar results when measured as value (euro per capita) or volume (DDD/case of the specific cancer).

The measurement of productivity provides insights in both the change in the frontier, and how individual countries move in relation to the frontier. There are notable differences among countries, for example the significant increase in efficiency in the Czech Republic (BC, LC), Spain (BC), and France (LC) between 2010 and 2015, but also the significant decline in productivity on the efficient but low outcome countries Latvia (BC, LC) and Lithuania (BC, LC). The observed decline in technical change has been observed in other health care productivity studies, and is rooted in the increased resource use over time, for example doctors and nurses, needed to sustain the prevailing level of activities.

Technical change in medicine is mainly incremental, and more resources are needed in order to improve outcomes over time. However, there are also jumps or shifts in the technology, for example when a curative treatment is introduced. In such cases resource use may be significantly reduced, with the same or even better outcome. We have not seen any such shifts in breast and lung cancer management during the studied period. It should, however, be remembered that our approach does not focus on costs and cost-savings, for examples changes in salaries of doctors and prices of medicines, but on the real resources used for producing outcomes.

A limitation of this study is the dependency on available official EU-level data. Detailed data on resource use and relevant health outcomes is limited. There are many initiatives to collect real world data on resource use, patient treatment pathways and outcome, which will support future studies like this. Studies on the national level limit the number of observations and thus the level of detail of the analysis. However, frontier analysis can be applied to any level of decision-making units, e.g. regions or specific providers. It is also possible to apply this analysis at the patient level, for which increasingly relevant outcome data is systematically collected.

Medical research and innovations in diagnosis and treatment creates an increasing number of potential options to improve outcomes at any given level of resources. Studies of efficiency in real practice will be increasingly important to inform policy makers, patients, and the general public on how well the health care system can produce value for patients.

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Acknowledgements

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Appendix A. Formal methods of efficiency and productivity measurement

Following [6], let x be a vector of $n = 1, \ldots, N$ non-negative inputs producing a vector of $m = 1, \ldots, M$ non-negative outputs y. The relationship between inputs producing outputs is modeled by the input requirement set which represents all input vectors x able to produce at least output vector y. That is:

$$L(y) = \{x\colon x \text{ can produce } y\}. \tag{1}$$

The input distance function is defined in terms of the input requirement set as:

$$D_i(y, x) = \max\{\lambda > 0\colon x/\lambda \in L(y)\}, \tag{2}$$

and the isoquant (frontier) as:

$$\text{Isoq } L(y) = \{x\colon x \in L(y), D_i(y, x) = 1\}, \tag{3}$$

i.e. the *Isoq* $L(y)$ is the lower boundary of the input set, where $D_i(y, x) = 1$ which means that those are the minimum input bundles that can produce observed output y.

The Farrell input measure of technical efficiency is defined as the reciprocal of the input distance function i.e. as:

$$TE_i(y, x) = 1/D_i(y, x) \tag{4}$$

Since for feasible input vectors, i.e. $x \in L(y)$, the input distance function takes values $D_i(y, x) \geqq 1$, the Farrell measure is $TE_i(y, x) \leqq 1$, with efficiency $TE_i(y, x) = 1$, which corresponds to $x \in$ *Isoq* $L(y)$, i.e. efficiency in the Farrell sense is relative to the best practice frontier represented by the isoquant.

The decomposed input based Malmquist productivity index expressed in Farrell measures is defined as:

$$^{t}\text{PC}_i^{t+1} = \underbrace{\frac{\text{TE}_i^{t+1}(y^{t+1}, x^{t+1})}{TE_i^{t}(y^{t}, x^{t})}}_{\text{EC}} \cdot \underbrace{\left[\frac{TE_i^{t}(y^{t+1}, x^{t+1})}{TE_i^{t+1}(y^{t+1}, x^{t+1})} \cdot \frac{TE_i^{t}(y^{t}, x^{t})}{TE_i^{t+1}(y^{t}, x^{t})}\right]^{1/2}}_{\text{TC}}, \tag{5}$$

where EC stands for *Efficiency Change* and TC for *Technical Change*. The efficiency change part of the index reflects the change in efficiency between two adjacent periods (t, and $t + 1$), and technical change captures the change in the production frontier between the two adjacent periods.

Appendix B. Malmquist quantity index

In this section we introduce a Malmquist input quantity index in order to aggregate multiple input quantities into a single index number. We use this index to evaluate what we call 'marginal rate of return' to using 'more' inputs. By 'more' we mean a higher value of the input quantity index.

Recall the input distance function evaluated at time t

$$D_i^t(y^t, x^t) = \sup\{\lambda: x^t/\lambda \in L^t(y^t)\}, \tag{6}$$

where 'sup' (supremum) is a generalization of maximum. A Malmquist input quantity index is defined as

$$\mathrm{PC}_i^t(y_k^t, x_k^t, x_k^{t+1}) = \frac{D_i^t(y_k^t, x_k^{t+1})}{D_i^t(y_k^t, x_k^t)}, \quad k = 1, \ldots, K, \tag{7}$$

where the input requirement sets and the base input vector are from the period t. The change in the input quantity index is from t to period $t+1$. In our examples we estimate the change in quantity index from $t = 2005$ and $(t+1) = 2010$ as well as from $t = 2010$ and $(t+1) = 2015$ for the countries $k = 1, \ldots, K$.

We compute the indexes using Farrell technical efficiency measures which are the reciprocals of the distance functions. Values of our quantity indexes greater than one signal that inputs increased from t to $t+1$, values less than one are associated with declines in input used between t and $t+1$. As mentioned above, we use our quantity indexes to construct what we call 'marginal rate of return' to changes in input. We take the ratio of period $t+1$ output to period t output, y_k^{t+1}/y_k^t, $k = 1, \ldots, K$ and divide that by the quantity index for the same time change for each country. This ratio of changes in outputs divided by quantity index of changes in inputs is our measure of 'marginal rate of return' (MRR). If the MRR is greater than one, the return to inputs is increasing, we interpret values less than one as declining MRR.

Linear programming is used to construct the piecewise linear technology frontier and compute the $k = 1, \ldots, K$ country specific efficiency scores relative to that technology. This is done under constant returns to scale and strong disposability of inputs using N inputs and M outputs. Each country is associated with an intensity variable z which serves the purpose of shrinking or expanding individual observed activities to construct the unobserved hypothetical observations (e.g. $\hat{c}$ in Fig. 1).

The following LP problem is solved for each country $k = 1, \ldots, K$ to compute the Farrell input measure of technical efficiency:

$$\begin{aligned} TE_i(y^k, x^k|C, S) = &\min_{\lambda,z} \lambda \\ \text{s. t. } &\sum_{k=1}^{K} z^k y_m^k \geqq y_m^k, \quad m = 1, \ldots, M \\ &\sum_{k=1}^{K} z^k x_n^k \leqq \lambda x_n^k, \quad n = 1, \ldots, N \\ &z^k \geqq 0, \quad j = 1, \ldots, K \end{aligned} \tag{8}$$

The measure is bounded by zero and unity, C stands for constant returns to scale, and S for strong disposability of inputs.

B.1 Breast cancer

In Fig. A.1 it can be seen how the increase in the four inputs (i) Screening; (ii) Radiation units; (iii) Oncologists; and (iv) Drugs, only yield a limited increase in the output DALYcv. That is, Fig. A.1 illustrates the diminishing rate of return in the production of breast cancer care over time.

In Table A.1 the marginal rate of return is computed with a Malmquist input quantity index as described above. Values less than one indicates a declining marginal rate of return, confirming the visual result of Fig. A.1

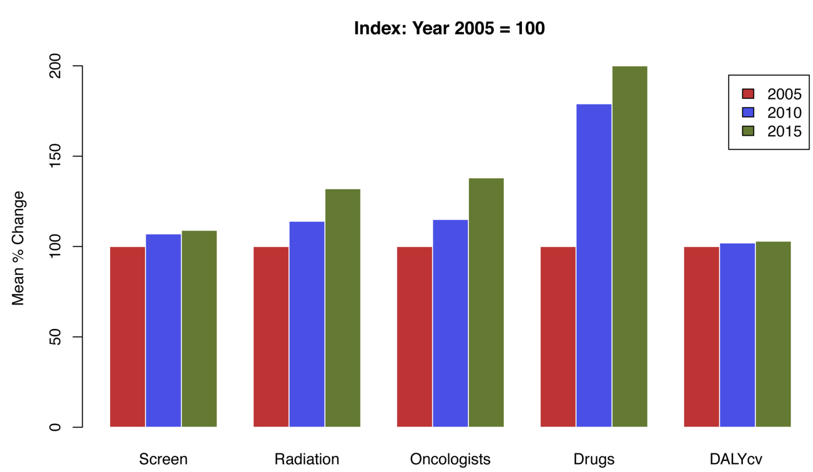

Fig. A.1. Diminishing rate of return in the production of breast cancer care.

Table A.1
Breast cancer marginal rate of return (MRR) using a Malmquist quantity index, $N = 23$.

	2005/2010	2010/2015
Austria	0.85	0.76
Belgium	0.90	0.78
Croatia	0.69	0.66
Czech R.	0.88	0.67
Denmark	0.93	0.77
Estonia	0.51	0.65
Finland	0.96	0.78
France	0.90	0.77
Germany	0.91	0.72
Hungary	0.57	0.76
Ireland	0.97	0.75
Italy	0.60	0.79
Latvia	0.31	0.54
Lithuania	0.44	0.53
Luxembourg	0.91	0.74
Netherlands	0.97	0.75
Poland	0.75	0.73
Portugal	0.88	0.77
Slovakia	0.43	0.85
Slovenia	0.67	0.52
Spain	0.80	0.68
Sweden	0.94	0.77
UK	0.83	0.77
Mean	0.77	0.72
Sd	0.19	0.09
Min	0.31	0.52
Max	0.97	0.85

B.2 Lung cancer

In Fig. A.2 it can be seen how the increase in the four inputs (i) Radiation units; (ii) Oncologists; (iii) Pulmectomy; and (iv) Drugs, only yield a limited increase in the output DALYcv. That is, Fig. A.2 illustrates basically the same diminishing rate of return in the production of lung cancer as was seen in breast cancer.

In Table A.2 the marginal rate of return is computed with the same Malmquist input quantity index as in breast cancer. And just as in breast cancer the marginal rate of return in lung cancer over time is diminishing (to a slightly less degree than in breast cancer).

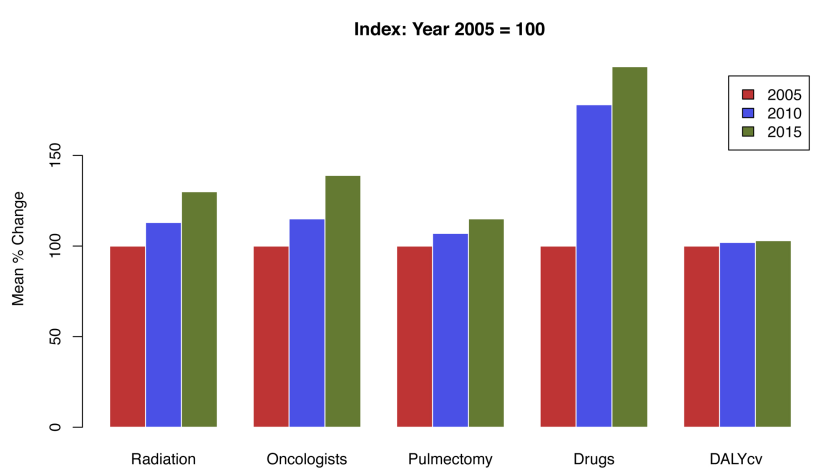

Fig. A.2. Diminishing rate of return in the production of lung cancer care.

Table A.2
Lung cancer marginal rate of return (MRR) using a Malmquist quantity index, $N = 23$.

	2005/2010	2010/2015
Austria	0.83	0.81
Belgium	0.88	0.76
Croatia	0.81	0.79
Czech R.	0.94	0.79
Denmark	0.91	0.82
Estonia	0.50	0.65
Finland	0.73	0.85
France	0.83	0.53
Germany	0.73	0.81
Hungary	0.62	0.67
Ireland	0.89	0.86
Italy	0.91	0.89
Latvia	0.36	0.54
Lithuania	0.72	0.53
Luxembourg	0.93	0.83
Netherlands	0.92	0.86
Poland	0.83	0.81
Portugal	0.92	0.87
Romania	0.72	0.77
Slovenia	0.68	0.52
Spain	0.92	0.87
Sweden	0.89	0.87
UK	0.93	0.87
Mean	0.80	0.76
Sd	0.15	0.12
Min	0.36	0.52
Max	0.94	0.89

Appendix C. Time series data

The time series data used to compute the Malmquist productivity change, efficiency change, technical change, and the corresponding Farrell technical efficiency scores are presented in Table A.3 for breast cancer, and in Table A.4 for lung cancer.

Table A.3
Farrell technical efficiency scores with corresponding breast cancer data 2005, 2010, and 2015.

	TE	Screen	Rad.	Onc.	Drug	DALYcv	TE	Screen	Rad.	Onc.	Drug	DALYcv	TE	Screen	Rad.	Onc.	Drug	DALYcv
	2005	2005	2005	2005	2005	2005	2010	2010	2010	2010	2010	2010	2015	2015	2015	2015	2015	2015
Austria	0.64	71.90	0.45	2.61	25.09	71.40	0.68	73.02	0.49	2.99	48.72	73.20	0.85	72.70	0.49	3.56	60.53	73.40
Belgium	0.65	55.00	1.02	1.63	22.81	68.80	0.64	60.20	1.11	1.91	41.14	70.50	0.62	59.00	1.20	3.91	44.39	71.30
Croatia	0.75	56.45	0.24	2.61	5.70	70.50	0.83	60.60	0.28	2.99	14.07	71.20	0.75	58.80	0.64	3.56	16.14	71.50
Czech R.	0.65	28.55	0.90	2.33	11.41	71.40	0.60	45.16	0.87	2.57	20.57	74.10	0.83	57.58	0.81	2.78	15.13	75.00
Denmark	0.65	75.06	0.60	1.90	21.67	68.30	0.54	75.55	1.05	2.20	41.14	70.00	0.62	82.80	1.33	2.76	49.43	72.10
Estonia	1.00	40.00	0.15	2.08	2.28	71.10	1.00	50.40	0.24	2.54	7.58	74.20	1.00	53.04	0.36	3.59	7.06	74.10
Finland	0.56	87.46	0.88	2.11	21.67	71.90	0.56	85.18	0.88	2.44	33.56	73.10	0.67	83.16	0.98	2.96	40.35	74.20
France	1.00	41.75	0.76	0.94	33.07	69.90	1.00	51.64	0.83	0.98	50.88	71.50	1.00	52.66	0.91	1.29	50.44	72.40
Germany	0.79	48.71	0.76	1.34	18.25	69.20	0.62	54.38	0.83	2.15	48.72	70.60	0.73	55.75	0.91	3.16	59.52	71.10
Hungary	0.57	40.66	0.26	4.53	11.41	70.50	0.78	47.25	0.36	5.09	22.73	72.50	0.92	45.70	0.45	3.40	23.20	72.40
Ireland	0.70	77.95	0.70	1.51	23.95	71.70	0.62	76.08	0.84	2.13	34.64	74.50	0.63	73.46	0.96	3.96	41.36	74.20
Italy	0.36	59.95	0.45	7.06	19.39	70.40	0.52	59.96	0.58	7.88	35.73	71.70	0.58	58.26	0.69	7.33	40.35	72.00
Latvia	1.00	6.24	0.15	3.17	1.14	71.10	1.00	20.25	0.34	3.40	3.25	71.70	1.00	34.30	0.40	3.32	7.06	72.60
Lithuania	1.00	8.92	0.70	1.46	2.28	72.40	1.00	22.40	0.52	1.58	3.25	73.70	1.00	38.82	0.73	2.40	6.05	73.20
Luxembourg	0.66	60.98	0.61	2.38	11.41	73.00	0.67	63.58	0.61	2.73	15.16	73.50	0.83	60.94	0.73	3.32	10.09	75.00
Netherlands	0.51	81.48	0.89	2.49	20.53	69.00	0.49	82.40	0.97	2.86	34.64	71.00	0.61	80.15	1.05	3.44	39.34	71.90
Poland	0.92	51.58	0.28	2.03	4.56	74.20	0.98	56.69	0.32	2.35	8.66	75.30	0.98	58.60	0.38	3.80	11.10	75.50
Portugal	0.65	88.48	0.60	1.90	23.95	71.70	0.73	86.34	0.60	1.94	24.90	73.00	0.87	84.20	0.66	2.46	22.19	73.90
Slovakia	0.69	12.96	0.87	2.62	7.98	73.60	1.00	21.38	1.07	3.00	23.82	74.60	1.00	23.41	1.20	3.58	27.24	74.00
Slovenia	1.00	86.94	0.40	0.60	13.69	70.40	1.00	85.10	0.54	0.66	28.15	72.40	1.00	77.02	0.58	1.33	32.28	72.80
Spain	0.58	82.14	0.39	3.21	21.67	73.50	0.64	81.24	0.44	3.64	38.97	74.80	0.85	79.80	0.49	3.76	36.32	75.20
Sweden	0.42	97.42	0.96	3.61	20.53	71.50	0.41	93.52	1.05	4.50	31.40	73.80	0.49	90.40	1.13	5.51	35.31	74.80
UK	0.59	75.24	0.39	2.95	12.55	69.30	0.65	76.42	0.47	3.31	25.98	72.20	0.74	76.04	0.59	3.76	37.32	73.00
Mean	0.71	58.08	0.58	2.48	15.52	71.08	0.74	62.12	0.66	2.86	27.72	72.74	0.81	63.33	0.77	3.43	30.97	73.29
Sd	0.19	25.98	0.27	1.30	8.53	1.56	0.19	20.81	0.28	1.44	14.03	1.49	0.16	17.18	0.28	1.19	16.48	1.31
Min	0.36	6.24	0.15	0.60	1.14	68.30	0.41	20.25	0.24	0.66	3.25	70.00	0.49	23.41	0.36	1.29	6.05	71.10
Max	1.00	97.42	1.02	7.06	33.07	74.20	1.00	93.52	1.11	7.88	50.88	75.30	1.00	90.40	1.33	7.33	60.53	75.50

Variable names: (i) TE: Farrell technical efficiency score; (ii) Screen: Screening (input); (iii) Rad.: Radiation units (input); (iv) Onc.: Oncologists (input); (v) Drug: Drug expenditure (input); and (vi) DALYcv: Converted DALY (output).

Table A.4
Farrell technical efficiency scores with corresponding lung cancer data 2005, 2010, and 2015.

	TE	Rad.	Onc.	Pulm.	Drug	DALYcv	TE	Rad.	Onc.	Pulm.	Drug	DALYcv	TE	Rad.	Onc.	Pulm.	Drug	DALYcv
	2005	2005	2005	2005	2005	2005	2010	2010	2010	2010	2010	2010	2015	2015	2015	2015	2015	2015
Austria	0.64	0.45	2.61	19.06	25.09	68.50	0.69	0.49	2.99	18.82	48.72	69.00	0.84	0.49	3.56	15.69	60.53	69.71
Belgium	0.57	1.02	1.63	15.63	22.81	63.90	0.54	1.11	1.91	16.65	41.14	65.07	0.51	1.20	3.91	17.95	44.39	66.53
Croatia	0.88	0.24	2.61	11.39	5.70	62.62	0.95	0.28	2.99	12.25	14.07	63.36	0.76	0.64	3.56	13.40	16.14	63.98
Czech R.	0.54	0.90	2.33	15.16	11.41	64.39	0.58	0.87	2.57	15.09	20.57	66.58	0.84	0.81	2.78	11.77	15.13	68.64
Denmark	0.65	0.60	1.90	13.22	21.67	62.50	0.53	1.05	2.20	15.52	41.14	64.12	0.55	1.33	2.76	17.09	49.43	65.68
Estonia	1.00	0.15	2.08	13.96	2.28	66.49	1.00	0.24	2.54	14.92	7.58	68.63	1.00	0.36	3.59	16.16	7.06	68.52
Finland	1.00	0.88	2.11	1.22	21.67	69.97	1.00	0.88	2.44	0.73	33.56	70.75	1.00	0.98	2.96	0.65	40.35	71.74
France	0.66	0.76	0.94	22.86	33.07	66.03	0.68	0.83	0.98	23.50	50.88	67.08	1.00	0.91	1.29	21.35	50.44	67.71
Germany	0.61	0.76	1.34	30.75	18.25	65.95	0.55	0.83	2.15	33.93	48.72	66.89	0.57	0.91	3.16	38.18	59.52	67.20
Hungary	0.49	0.26	4.53	28.15	11.41	57.24	0.55	0.36	5.09	27.55	22.73	56.35	0.74	0.45	3.40	28.56	23.20	57.43
Ireland	1.00	0.70	1.51	5.00	23.95	69.80	0.85	0.84	2.13	7.13	34.64	71.90	0.74	0.96	3.96	9.19	41.36	72.01
Italy	0.63	0.45	7.06	14.14	19.39	66.10	0.63	0.58	7.88	15.10	35.73	67.92	0.63	0.69	7.33	16.35	40.35	68.80
Latvia	1.00	0.15	3.17	11.29	1.14	65.90	1.00	0.34	3.40	12.15	3.25	67.35	1.00	0.40	3.32	13.29	7.06	68.39
Lithuania	1.00	0.70	1.46	8.40	2.28	67.82	1.00	0.52	1.58	9.15	3.25	69.39	1.00	0.73	2.40	10.43	6.05	68.94
Luxembourg	0.71	0.61	2.38	11.90	11.41	68.17	0.74	0.61	2.73	12.78	15.16	70.12	0.84	0.73	3.32	13.95	10.09	71.19
Netherlands	0.52	0.89	2.49	14.94	20.53	64.19	0.52	0.97	2.86	16.10	34.64	65.04	0.55	1.05	3.44	17.72	39.34	66.12
Poland	1.00	0.28	2.03	8.65	4.56	63.27	1.00	0.32	2.35	9.41	8.66	64.44	1.00	0.38	3.80	10.46	11.10	65.47
Portugal	0.83	0.60	1.90	9.77	23.95	69.90	0.87	0.60	1.94	10.58	24.90	70.47	0.92	0.66	2.46	11.67	22.19	70.80
Romania	1.00	0.45	1.44	8.13	2.28	66.29	0.98	0.50	1.57	8.87	11.91	66.55	1.00	0.40	2.58	12.31	14.12	66.28
Slovenia	1.00	0.40	0.60	11.15	13.69	63.82	1.00	0.54	0.66	10.79	28.15	65.98	1.00	0.58	1.33	9.41	32.28	66.05
Spain	0.91	0.39	3.21	8.94	21.67	67.65	0.88	0.44	3.64	10.56	38.97	68.90	0.85	0.49	3.76	14.39	36.32	69.40
Sweden	0.64	0.96	3.61	7.94	20.53	69.54	0.65	1.05	4.50	7.89	31.40	71.27	0.70	1.13	5.51	8.86	35.31	72.78
UK	1.00	0.39	2.95	7.29	12.55	66.51	0.87	0.47	3.31	9.84	25.98	68.15	0.79	0.59	3.76	13.96	37.32	69.17
Mean	0.79	0.56	2.43	13.00	15.27	65.94	0.79	0.64	2.80	13.88	27.21	67.19	0.82	0.73	3.39	14.90	30.39	67.94
Sd	0.19	0.26	1.32	6.78	8.83	2.94	0.18	0.26	1.47	6.92	14.38	3.27	0.17	0.28	1.20	7.14	16.83	3.18
Min	0.49	0.15	0.60	1.22	1.14	57.24	0.52	0.24	0.66	0.73	3.25	56.35	0.51	0.36	1.29	0.65	6.05	57.43
Max	1.00	1.02	7.06	30.75	33.07	69.97	1.00	1.11	7.88	33.93	50.88	71.90	1.00	1.33	7.33	38.18	60.53	72.78

Variable names: (i) TE: Farrell technical efficiency score; (ii) Rad.: Radiation units (input); (iii) Onc.: Oncologists (input); (iv) Pulm.: Pulmectomy (input); (v) Drug: Drug expenditure (input); and (vi) DALYcv: Converted DALY (output).

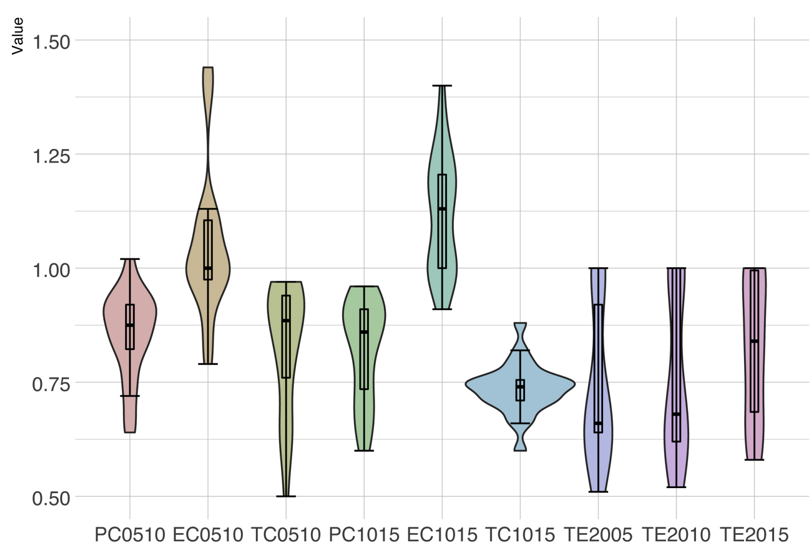

Fig. A.3. Breast cancer—Malmquist index (PC), efficiency change (EC), technical change (TC), and Farrell technical efficiency (TE).

The violin plot in Fig. A.3 is a box plot with an added vertical density plot showing the probability density of the data at different values. The box plot part illustrates the median with a vertical line inside the box, the upper and lower limits of the box indicates the third and first quartiles, and the whiskers indicates 1.5 times the first and third quartiles. The violin part shows the full distribution of the data with its peaks and amplitudes.

Fig. A.4

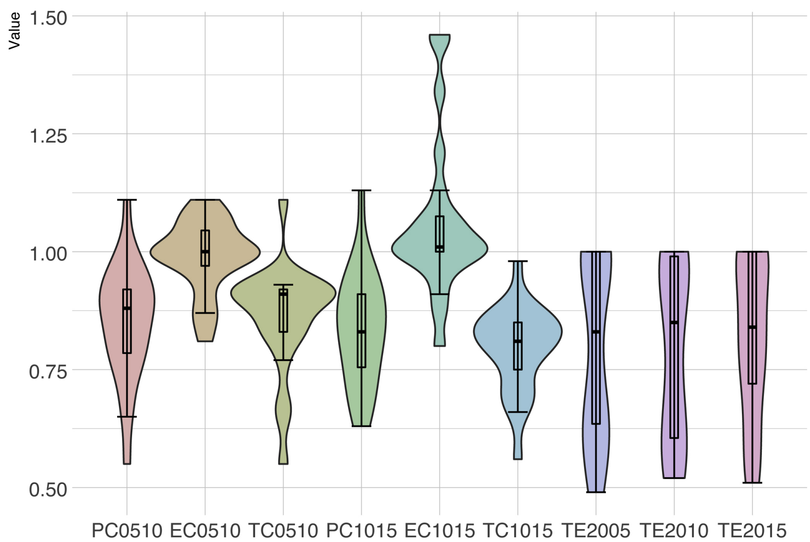

Fig. A.4. Lung cancer—Malmquist index (PC), efficiency change (EC), technical change (TC), and Farrell technical efficiency (TE).

Appendix D. Imputation of missing data

For variables where data from a certain country was missing (for a certain year) alternative ways of estimation were conducted. When possible an ordinary least square (OLS) regression was used to estimate the missing values with data from an alternative source or from the relationship between years. If alternative sources were not available to run a regression, a country-to-country relationship was used.

For the variable breast cancer screening missing data for the years 2010 and 2005 were imputed by using separate regressions from the countries that had observations in both periods 2015 and 2010, and 2010 and 2005 respectively. For 2010 this method was used Austria, Poland, Portugal, Spain and Sweden. For 2005 this was done for Austria, Croatia, Denmark, Germany, Latvia, Lithuania, Poland, Portugal, Spain and Sweden.

For the variable radiation units per 100,000 inhabitants in 2015 the alternative source Rosenblatt's data on mega-voltage machines [19] was used to estimate data on radiation units (creating a regression including 22 European countries that had observations in both sources). This was used for Belgium, France, Germany, Netherlands, Portugal and Sweden. For the years 2010 and 2005 we created separate regressions including the countries that had observations in both periods 2015 and 2010, and 2010 and 2005 respectively. For 2010 this method was used for Belgium, France, Germany, Netherlands, Portugal and Sweden. For 2005 this was used for Belgium, Croatia, France, Germany, Netherlands, Poland, Romania, Spain and Sweden.

For the variable oncologists per 100,000 inhabitants in 2015 the alternative source WHO's data on radiation oncologists [13] was used to estimate data on oncologists (creating a regression including 23 European countries that had observations in both sources). This was used for Austria, Croatia, Hungary, Luxemburg, Netherlands, and Slovakia. For the years 2010 and 2005 we created separate regressions including the countries that had observations in both periods 2015 and 2010, and 2010 and 2005 respectively. For 2010 this method was used for Austria, Croatia, Luxemburg, Netherlands and Slovakia. For 2005 this was used for Austria, Croatia, Denmark, Germany, Latvia, Lithuania, Poland, Portugal, Spain and Sweden.

For the variable pulmectomy per 100,000 inhabitants in 2015 a country-to-country relationship was used for missing data: data for the Netherlands was based on the Netherlands/Denmark relationship in 2010, while for Latvia 2015, the data on pulmectomy was estimated as the mean of Lithuania and Estonia. For the years 2010 and 2005 we created separate regressions including the countries that had observations in both periods 2015 and 2010, and 2010 and 2005 respectively. For 2010 this method was used for (Belgium, Croatia, Estonia, Italy, Latvia, Luxemburg, Poland and Portugal. For 2005 this was used for Belgium, Croatia, Estonia, Italy, Latvia, Lithuania, Luxemburg, Poland, Portugal and Romania.

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