Performance Evaluation of Healthcare Systems Using Data Envelopment Analysis

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Abstract. This paper studies the context of 39 different countries' healthcare systems up to 2019 by applying the output-oriented variable return-to-scale model (VRS) of data envelopment analysis. 4 input variables (health expenditure per capita and beds, physicians, and nurses per thousand people) should result in the best 4 output results (life expectancy at birth, death rate per thousand people by communicable and non-communicable diseases, percentage of diabetes prevalence and mortality of cardiovascular diseases, cancer, diabetes or chronic respiratory disease). Efficient and super-efficient systems are identified and Mexico's system is discussed as an example.

Keywords: Linear programming · Health care logistics · Operations research

1 Introduction

It is widely and increasingly known that healthcare is an essential priority to any society. Thus, it is important to analyze and discuss how a healthcare system is performing in order to identify the most important actions to improve the services in order to reach objectives such as World Health Organization's sustainable development goals [22].

In any organization, each and every activity is aimed to transform and increase the value of an entry. Such processes may be effective if the objective is reached or efficient if the result is made using the least amount of resources. Both concepts are related to the performance of the organization.

In spite of the importance of the performance, it is not obvious to estimate. Since data envelopment analysis is a quantitative robust tool to determine the efficiency, its applications and importance are substantial. Seddhigi et al. cited a systematic review of 137 papers by Hafidz et al. who found that the most would employ data envelopment analysis for measuring efficiency in health systems [8,17].

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The measurement of efficiency is fundamental in health systems. Given its importance, there are many works related to this topic in the literature. Comparing international health systems, [16] proposes an analysis to evaluate health equity in terms of health outcomes, in international comparative analysis. At the continental level, various comparisons of health systems have been made. In [2,7,12] DEA models are used to compare the health systems of the member states of the European Union with different approaches. Similar analyses are proposed in Asia, Africa in [18,19] and the Visegrád Group [10].

However, it is more common to compare national system entities, e.g., a DEA assessment of health systems in the United States is presented in [6]. In China, [3,4,23–25] evaluate efficiency through DEA and other tools, such as regression analysis and game theory. In [5,11,14,15,20] the technique is used to compare the health systems of Portugal, the Czech Republic, Panama, Poland, and Brazil, respectively.

Considering the COVID-19 pandemic, there are some works that compare the efficiency of some international health systems considering variables that are measured worldwide: medical personnel (doctors and nurses), hospital beds, COVID-19 tests performed, cases affected, cases recovered, and cases of deaths [13].

This paper presents a comparison of the efficiency of international health systems, with a special focus on the countries of the American continent.

2 Data Envelopment Analysis

Data Envelopment Analysis compares the performance of different entities called decision-making units (DMUs) by using a set of n observations, m inputs, and s outputs of the process analyzed. These observations should be chosen wisely so they can describe the phenomena. It is recommended the number of DMU is at least 2 or 3 times the number of observations [26].

This method builds a frontier of best practices aimed to surround the non-efficient ones. This can be achieved by a straight line (constant return-to-scale, CRS) or by the linking of various points through line segments so a more approximated curve can be built (variable return-to-scale, VRS), which implies more accuracy (see Fig. 1) [9].

Since DEA is a linear programming application, even though the objective will be the same, the variables involved may be considered by two approaches, both of interest:

- Additive model (primal): determines the quantity of each observation.
- Multiplicative model (dual): determines the importance of each observation.

2.1 Additive VRS Model

DEA additive VRS model either minimizes the inputs or maximizes the outputs, only one approach can be taken while fixing the complement. Observe models (1) and (2), where both θ and ϕ are the efficiencies achieved in two different

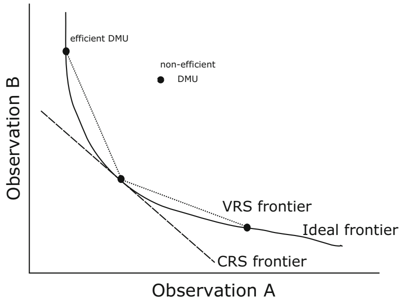

Fig. 1. Frontiers of efficiencies or good practices where de efficient DMUs are and that surround the non-efficient ones. Note the differences between the ideal, the CRS and the VRS frontier. (Own creation).

cases. Note in the model (1) θ is to be minimized since is input-oriented, the inputs are variables and the outputs cannot be modified, i.e. the decision is how to set the entries to achieve a specific output. Similarly, ϕ should be maximized since it is the output-oriented model and defines the best set of outputs obtained from fixed inputs. Deciding which model to use is essential to obtain meaningful results.

$$\begin{aligned} &\theta^* = \min \theta \\ &\text{subject to:} \\ &\sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{io} \qquad i = 1, 2, ..., m \\ &\sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{ro} \qquad r = 1, 2, ..., s \\ &\sum_{j=1}^{n} \lambda_j = 1 \qquad j = 1, 2, ..., n \\ &\lambda_j \geq 0 \end{aligned} \tag{1}$$

$$\begin{aligned} &\phi^* = \max \phi \\ &\text{subject to:} \\ &\sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{io} \qquad i = 1, 2, ..., m \\ &\sum_{j=1}^{n} \lambda_j y_{rj} \geq \phi y_{ro} \qquad r = 1, 2, ..., s \\ &\sum_{j=1}^{n} \lambda_j = 1 \qquad j = 1, 2, ..., n \\ &\lambda_j \geq 0 \end{aligned} \tag{2}$$

Where θ, ϕ are the efficiencies of the input and output models respectively,

x_{ij} is the i-th input of the DMU_j,
y_{rj} is the r-th output of the DMU_j,
λ_j is the level of service achievable by the j-th DMU.

Please note that DMU_o refers to a specific DMU, so this model should be written n times so each and every DMU is compared with the rest $(o = 1, 2, ..., n)$. In addition, note that the ideal value of both θ and ϕ is 1 (efficient). In other case, we could find $\theta < 1$ or $\phi > 1$.

The value of λ_j is relevant since it represents a benchmark of service for the DMU studied. For instance, for the DMU_o with $\lambda_a = \lambda_b = 0.5(a, b \neq o)$ would not be efficient since $\lambda_o \neq 1$ and its benchmarks to improve the fastest would be DMU_a and DMU_b.

2.2 Multiplicative VRS Model

The multiplicative models aim to identify the importance of each observation. Observe models (3) and (4), input and output-oriented, respectively. A set of weights are defined, u_r is the importance of the r-th input whereas v_i is to the i-th output. Note this model has n restrictions ($j = 1, 2, ..., n$) instead of the $m + s$ restrictions the primal model has. [9] The free variables u_0, v_0 are slacks, so a zero value of them might be related to an efficient DMU.

$$\begin{aligned} \max & \sum_{r=1}^{s} u_r y_{ro} + u_0 \\ \text{s. t.:} & -\sum_{i=1}^{m} v_i x_{ij} + \sum_{r=1}^{s} u_r y_{rj} + u_0 \leq 0 \\ & \sum_{i=1}^{m} v_i x_{io} = 1 \\ & u_r, v_i \geq 0 \end{aligned} \quad (3)$$

$$\begin{aligned} \min & \sum_{i=1}^{m} v_i x_{io} + v_0 \\ \text{s. t.:} & \sum_{i=1}^{m} v_i x_{ij} - \sum_{r=1}^{s} u_r y_{rj} + v_0 \leq 0 \\ & \sum_{i=1}^{m} u_i y_{ro} = 1 \\ & u_r, v_i \geq 0 \end{aligned} \quad (4)$$

This step gives important feedback about the observations considered so corrections can be made, such as deleting or adding observations [1].

2.3 Slacks

VRS models can identify efficient DMUs. However, they could be strongly or weakly efficient (see Fig. 2). Therefore, a second stage should be implemented which is to find the slacks, that are tolerances acceptable for each DMU, reducing inputs (s_i^-) or increasing outputs (s_r^+).

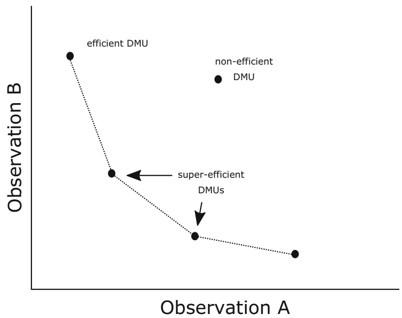

Fig. 2. Efficient and super-efficient DMUs located on the frontier. Note in this case an equilibrium of both observations A and B used are related to a super-efficient DMU. (Own creation).

Observe models (5) and (6), input and output-oriented, respectively. In both cases, the objective is to maximize the slacks. Note the efficiencies are fixed [26].

$$\begin{aligned} \max \quad & \sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+ \\ \text{s. t.:} \quad & \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = \theta^* x_{io} \\ & \sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{ro} \\ & \sum_{j=1}^{n} \lambda_j = 1 \\ & \lambda_j \geq 0 \end{aligned} \tag{5}$$

$$\begin{aligned} \max \quad & \sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+ \\ \text{s. t.:} \quad & \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = x_{io} \\ & \sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = \phi^* y_{ro} \\ & \sum_{j=1}^{n} \lambda_j = 1 \\ & \lambda_j \geq 0 \end{aligned} \tag{6}$$

If certain DMU results to have $\theta, \phi = 1$ and $s_i^{-*} = s_r^{+*} = 0$ for all i and r, we can say it is super-efficient.

3 Application

The selected model is the output-oriented VRS in order to obtain the best results by using a fixed set of inputs. The data processing was done through an own written R script, based on Hosseinzadeh et al.'s code [9], which uses the package 'lpSolve' to solve for every DMU. The script results were also verified with the R package 'deaR'.

3.1 Data

The observations chosen for the 39 healthcare systems are shown in Table 1. The data selected was the most recently reported by each country between the years 2016 and 2019 [21], since the changes are not drastic and the model does not allow empty spaces (see Table 2).

Table 1. Observations chosen for evaluating the performance of a healthcare system.

Observation	Alias	Description
Inputs	Health kUSD	Health expenditure in 1000 USD per capita
	Beds	Hospital beds per thousand people
	Physicians	Physicians per thousand people
	Nurses	Nurses and midwives per thousand people
Outputs	Life Exp	Life expectancy at birth
	Disease Deaths	Diseases deaths per thousand (from communicable and non-communicable deaths)
	MCCDR	Mortality from cardiovascular diseases, cancer, diabetes or chronic respiratory diseases (percentage)
	Diabetes	Percentage of diabetes prevalence

Table 2. Data set built for healthcare systems evaluation. Note some of the outputs are negative since they should be minimized instead of maximized.

Country	Health kUSD	Beds	Physicians	Nurses	Life Exp	Disease Deaths	MCCDR	Diabetes
Argentina	1.12790723	4.99	3.9901	2.5996	76.667	−7.169884	−15.7	−5.9
Austria	5.32643701	7.27	5.1697	7.0899	81.7926829	−8.8881403	−10.4	−6.6
Belgium	4.91270068	5.62	3.0709	19.4614	81.7463415	−8.9185082	−10.6	−4.6
Bolivia	0.22359789	1.29	1.5901	1.5589	71.513	−6.1735856	−17.9	−6.8
Brazil	0.84838885	2.09	2.1643	10.119	75.881	−5.7764304	−15.5	−10.4
Canada	4.99490234	2.55	2.6102	9.9438	82.0487805	−7.1881473	−9.6	−7.6
Chile	1.45560791	2.06	2.5912	13.3248	80.181	−5.7684861	−10	−8.6
China	0.50105939	4.31	1.9798	2.6621	76.912	−6.6159779	−15.9	−9.2
Colombia	0.51315869	1.71	2.1848	1.3309	77.287	−4.8409828	−9.7	−7.4
Cuba	0.98693732	5.33	8.4218	7.5614	78.802	−8.4620948	−16.6	−9.6
Denmark	6.21676855	2.43	4.0099	10.3195	81.202439	−8.9730103	−10.8	−8.3
Ecuador	0.51624799	1.39	2.0368	2.5059	77.01	−4.5341484	−11	−5.5
Finland	4.51567725	3.61	3.8118	14.7374	81.7853659	−9.2469853	−9.6	−5.6
France	4.69007227	5.91	3.2672	11.4707	82.5780488	−8.521616	−10.6	−4.8
Germany	5.47220215	8	4.2488	13.2352	80.9414634	−10.77549	−12.1	−10.4
Greece	1.5668999	4.2	5.4789	3.6331	81.9390244	−11.242621	−12.5	−4.7
Hungary	1.08180286	7.01	3.4075	6.9157	76.0219512	−12.749754	−22.1	−6.9
Iceland	6.53093213	2.87	4.0778	16.2132	82.5609756	−5.9496626	−8.7	−5.8
Ireland	5.4890708	2.97	3.3125	16.0996	82.302439	−6.0536993	−9.7	−3.2
Italy	2.98899585	3.14	3.9774	5.7401	83.197561	−10.095046	−9	−5
Japan	4.26658691	12.98	2.4115	12.1531	84.3563415	−10.554673	−8.3	−5.6
Korea, Rep.	2.54281812	12.43	2.3608	7.3009	83.2268293	−5.1721349	−7.3	−6.9
Luxembourg	6.22708398	4.51	3.009	12.1744	82.4463415	−6.4827734	−9.7	−5
Mexico	0.51960547	0.98	2.3827	2.3961	75.054	−5.4436178	−15.6	−13.5
Netherlands	5.30653467	3.17	3.6054	11.1839	82.0121951	−8.2926811	−10.3	−5.4
Norway	8.2390957	3.53	2.9164	18.2248	82.9073171	−7.17453	−8.7	−5.3
Paraguay	0.40039273	0.83	1.3544	1.6604	74.254	−4.9237504	−16	−9.6
Poland	0.97873566	6.54	2.3788	6.8926	77.8560976	−10.341985	−17	−6.1
Portugal	2.21517358	3.45	5.124	6.9746	80.6829268	−10.377485	−11	−9.8
Singapore	2.82363818	2.49	2.2936	6.2432	83.497561	−4.7863234	−9.5	−5.5
Spain	2.73632324	2.97	3.8723	5.7295	83.4853659	−8.4812551	−9.6	−6.9
Sweden	5.98170605	2.14	3.984	11.8164	82.9585366	−8.1667783	−8.4	−4.8
United Arab Emirates	1.81734766	1.38	2.5278	5.7271	77.972	−1.2805499	−18.5	−16.3
United Kingdom	4.31542773	2.5	2.8117	8.1723	81.204878	−8.6682466	−10.3	−3.9
United States	10.6238496	2.87	2.612	14.548	78.7878049	−8.1298925	−13.6	−10.8
Uruguay	1.59004822	2.43	5.0794	1.9412	77.911	−8.7780898	−16.5	−7.3
Australia	5.42534033	3.84	3.6778	12.5508	82.9	−6.3017123	−8.6	−5.6
Russian Federation	0.60900916	7.12	4.0139	8.5429	73.0839024	−12.396768	−24.2	−6.1
Saudi Arabia	1.48459338	2.24	2.6117	5.4763	75.133	−2.8229543	−20.9	−15.8

3.2 Results

The next tables summarizes the results obtained. Table 3 shows super-efficient healthcare systems, which means that resulted in values $\phi = 1, \sum \text{Slacks} = 0$. Both Tables 3 and 6, for super-efficient and inefficient DMUs respectively, show the weights related to each observation, shoeing which aspects deserve to be enhanced and how remarkable the improvement would be.

Table 3. Weights of super-efficient healthcare systems. All these DMUs had $\phi = 1$ and $\sum Slacks = 0$.

DMU	v_1	v_2	v_3	v_4	u_1	u_2	u_3	u_4	v_0
Bolivia	0	0	0.62889126	0	0.02335976	0	0.00688633	0.08047957	0
Chile	0.02937194	0.01087341	0	0.00036444	0.01250012	0	0	0.00026421	0.92999067
China	0.03617291	0	0.02164895	0	0.01300187	0	0	0	0.93901463
Colombia	0	0.0057436	0.44380464	0.01544373	0.01912439	0	0.0492852	0	0
Ecuador	0.00226697	0	0.49039164	0	0.02832821	0.20865524	0	0.04281484	0
Greece	0.04172753	0	0.02714084	0.00072401	0.01633238	0	0	0.07197	0.78328481
Iceland	0	0.15699239	0.13473732	0	0.10483232	0.17871106	0.75767679	0	0
Ireland	0	0.00074946	0	0.00034392	0.01246554	0	0	0.00810757	0.99223709
Italy	0	0.0159608	0.18009223	0.04069341	0.06434565	0	0.30723874	0.31765058	0
Japan	0	0	0.41467966	0	0.0166026	0	0.03099295	0.02558798	0
Korea, Rep.	0	0	0.42358523	0	0.01591407	0	0.02678758	0.01868521	0
Norway	0	0.03817635	0.26707947	0.00473678	0.05881405	0	0.32063066	0.20502419	0
Paraguay	0	0	0.20652898	0	0.01523049	0	0.00818278	0	0.72027715
Singapore	0.02692634	0	0.40284694	0	0.02351959	0.13809514	0.03188004	0	0
Spain	0.01710778	0.00015162	0.00080757	0	0.01197815	0	0	0	0.94961011
Sweden	0	0.01295001	0.14612027	0.03301715	0.05220772	0	0.2492823	0.2577301	0
United Arab Emirates	0	0	0.39560092	0	0.02078241	0.12336022	0.02499875	0	0
United Kingdom	0.01866848	0	0.32700414	0	0.01958365	0	0	0.15135586	0

Tables 4 and 5 show the efficiencies determined, the sum of the slacks found (which should be zero), the closest countries as a benchmark, and the factor of each benchmark.

Table 4. Efficiencies, slacks and benchmarks for Americas' inefficient healthcare systems.

DMU	Efficiency	SumSlacks	Benchmark	Factor
Argentina	1.03747931	8.15158435	Colombia	0.49867127
			Ecuador	0.03457781
			Greece	0.40793435
			Singapore	0.05881656
Brazil	1.02963524	18.9580786	Colombia	0.58704971
			Ecuador	0.26395383
			Korea, Rep.	0.03503501
			Singapore	0.11396145
Canada	1.01771742	11.1529506	Japan	0.00571973
			Singapore	0.99428027
Cuba	1.00731737	22.5032809	Colombia	0.55038427
			Greece	0.44961573
Mexico	1.00008846	6.65982428	Ecuador	0.20139955
			Paraguay	0.73093454
			United Arab Emirates	0.06766591
United States	1.06017258	30.6846495	Japan	0.03622498
			Singapore	0.96377502
Uruguay	1.0078195	12.0471215	Colombia	0.73490574
			Greece	0.26509426

Table 5. Efficiencies, slacks and referents for other non-efficient countries.

DMU	Efficiency	SumSlacks	Benchmark	Factor
Australia	1.00180085	2.9509122	Iceland	0.23388361
			Korea, Rep.	0.13938215
			Singapore	0.27149325
			Sweden	0.35524099
Austria	1.02294997	7.66540688	Japan	0.21178156
			Spain	0.78821844
Belgium	1.01903834	12.8123944	Ireland	0.36547358
			Japan	0.28165612
			Singapore	0.3528703
Denmark	1.02712625	16.176426	Singapore	0.82857143
			Sweden	0.17142857
Finland	1.02205634	15.6082404	Japan	0.10676835
			Singapore	0.89323165
France	1.0100877	4.87862012	Ireland	0.2968796
			Japan	0.31244021
			Singapore	0.3906802
Germany	1.03715256	19.9449911	Japan	0.52526215
			Singapore	0.47473785
Hungary	1.0460887	27.2097128	Colombia	0.54367037
			Greece	0.36637247
			Korea, Rep.	0.08995716
Luxembourg	1.0117648	6.93016513	Ireland	0.19979053
			Japan	0.18342236
			Singapore	0.61678711
Netherlands	1.01875637	12.5774589	Ireland	0.0022555
			Japan	0.06472043
			Singapore	0.93302406
Poland	1.00978297	18.7353922	Colombia	0.23593181
			Ecuador	0.501223
			Greece	0.07117163
			Korea, Rep.	0.19167357
Portugal	1.02596818	9.23842065	Greece	0.45875483
			Singapore	0.17555925
			Spain	0.36568592
Russian Federation	1.0618778	36.6087166	Colombia	0.55230794
			Ecuador	0.35777893
			Greece	0.08991314
Saudi Arabia	1.04366239	13.3423767	Colombia	0.33825606
			Korea, Rep.	0.06134861
			Singapore	0.06348956
			United Arab Emirates	0.53690578

Table 6. Observation weights for inefficient healthcare systems.

DMU	Weights							
	Inputs				Outputs			
	Health kUSD	Beds	Physicians	Nurses	Life Exp	Disease Deaths	MCCDR	Diabetes
Argentina	0	0	0	0.02570587	0.01515057	0.0088022	0	0.01668436
Australia	0	0.00789764	0	0	0.01702046	0.01102571	0.03971106	0
Austria	0	0	0	0.00165773	0.01222603	0	0	0
Belgium	0	0.00096819	0	0	0.01261314	0	0	0.00675607
Brazil	0.03412508	0.00044001	0.02442616	0	0.01317853	0	0	0
Canada	0	0.00099778	0	0	0.01218787	0	0	0
Cuba	0.05602357	0	0	0	0.01269003	0	0	0
Denmark	0	0.01896581	0	0	0.0123149	0	0	0
Finland	0	0.00100099	0	0	0.01222713	0	0	0
France	0	0.00095942	0	0	0.01249891	0	0	0.00669489
Germany	0	0.00101143	0	0	0.01235461	0	0	0
Hungary	0.03793714	0	0.00644098	0	0.0131541	0	0	0
Luxembourg	0	0.00096229	0	0	0.01253633	0	0	0.00671493
Mexico	0.01033877	0.06343291	0	0	0.01332374	0	0	0
Netherlands	0	0.00097018	0	0	0.01263907	0	0	0.00676996
Poland	0.03760151	0	0.00738879	0	0.01295185	0	0	0.00137383
Portugal	0.019857	0.00329722	0	0	0.0123942	0	0	0
United States	0	0.00103908	0	0	0.01269232	0	0	0
Uruguay	0	0	0	0.02593583	0.01283516	0	0	0
Russian Federation	0.06664677	0	0	0	0.01386061	0	0	0.0021291
Saudi Arabia	0.03705213	0.00024966	0	0	0.01371963	0.01090953	0	0

4 Conclusion

Observing both the value of the efficiency and the sum of the slacks, it is noticeable that the context of Mexico is not so privileged, since the system is already collapsed due to the economical situation of this country.

It might be feasible to increase Mexico's attention to the healthcare systems of Ecuador, Paraguay, and United Arab Emirates, as Table 4 shows. Particularly, the health expenditure and beds per thousand people could be enhanced so an improvement in the life expectancy at birth is noticeable. Similar inferences for any of the countries studied can be made from these results.

5 Discussion

This analysis may be more robust if more indicators are considered and could show more representative information as the data is more recent. In future analysis, not only could more countries be added but it could also be possible to take into account more observations related to the World Health Organization's sustainable development goals [22] such as the equality of the services given all economic strata or the total of population health-covered.

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References

1. Bonilla, M., Casasús, T., Medal, A., Sala, R.: Un Análisis de la Eficiencia de los Puertos Españoles. VI Jornada de ASEPUMA, Ud Valencia, Departamento de Economía Financiera y Matemática: Santiago de Compostela (97), 9 (1998)
2. Briestensky, R., Kljucnikov, A.: "The impact of DRG-based management of healthcare facilities on amenable mortality in the European union. Prob. Perspect. Manag. **19**(2), 264–275 (2021). https://doi.org/10.21511/ppm.19(2).2021.22. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85109032676&doi=10.21511%2fppm.19%282%29.2021.22&partnerID=40&md5=102d0d2b3371321e4074cb303e6f5a25. Cited By 0
3. Chai, P., Wan, Q., Kinfu, Y.: Efficiency and productivity of health systems in prevention and control of non-communicable diseases in China, 2008–2015. Eur. J. Health Econ. **22**(2), 267–279 (2021). https://doi.org/10.1007/s10198-020-01251-3. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85098692749&doi=10.1007%2fs10198-020-01251-3&partnerID=40&md5=3bc310b679b925cba13246c31bdf019a. Cited By 0
4. Chen, Z., Chen, X., Gan, X., Bai, K., Baležentis, T., Cui, L.: Technical efficiency of regional public hospitals in China based on the three-stage DEA. Int. J. Environ. Res. Public Health **17**(24), 1–17 (2020). https://doi.org/10.3390/ijerph17249383. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85097940247&doi=10.3390%2fijerph17249383&partnerID=40&md5=e913fd7d29d2994fbde6653560a66498. Cited By 0
5. Cordero, J., García-García, A., Lau-Cortés, E., Polo, C.: Assessing panamanian hospitals' performance with alternative frontier methods. Int. Trans. Oper. Res. (2021). https://doi.org/10.1111/itor.13013. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85107204634&doi=10.1111%2fitor.13013&partnerID=40&md5=a5614354ec137d87b8a5ef893dc6132c. Cited By 0
6. Darabi, N., Ebrahimvandi, A., Hosseinichimeh, N., Triantis, K.: A DEA evaluation of U.S. STATES' healthcare systems in terms of their birth outcomes. Expert Syst. Appl. **182** (2021). https://doi.org/10.1016/j.eswa.2021.115278. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85107660523&doi=10.1016%2fj.eswa.2021.115278&partnerID=40&md5=b8f3cb48a329b94c6469d01c92a99b1c. Cited By 0
7. Dincă, G., Dincăp, M., Andronic, M.: The efficiency of the healthcare systems in EU countries - a DEA analysis. Acta Oeconomica **70**(1), 19–36 (2020). https://doi.org/10.1556/032.2020.00002. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85089176349&doi=10.1556%2f032.2020.00002&partnerID=40&md5=ada2b82b7953ecdfa36ec6650957e1d8. Cited By 3
8. Hafidz, F., Ensor, T., Tubeuf, S.: Efficiency measurement in health facilities: a systematic review in low- and middle-income countries. Appl. Health Econ. Health Policy **16**(4), 465–480 (2018). https://doi.org/10.1007/s40258-018-0385-7
9. Hosseinzadeh Lotfi, F., Ebrahimnejad, A., Vaez-Ghasemi, M., Moghaddas, Z.: Data Envelopment Analysis with R. In: Studies in Fuzziness and Soft Computing, vol. 386. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-24277-0. http://link.springer.com/10.1007/978-3-030-24277-0
10. Lacko, R., Markovič, P., Šagátová, S., Hajduová, Z.: Evaluation and development of environmental and health efficiency: Case of v4 countries. Ekonomicky casopis **68**(10), 1040–1056 (2020). https://doi.org/10.31577/ekoncas.2020.10.04. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85099049479&doi=10.315

77%2fekoncas.2020.10.04&partnerID=40&md5=2e62fa928153929d82157ac27221ce48. Cited By 0
11. Miszczynska, K., Miszczyński, P.: Measuring the efficiency of the healthcare sector in Poland – a window-DEA evaluation. Int. J. Prod. Perform. Manag. (2021). https://doi.org/10.1108/IJPPM-06-2020-0276. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85103404006&doi=10.1108%2fIJPPM-06-2020-0276&partnerID=40&md5=6ba82e76e0113a91dd764dbe8d130907. Cited By 0
12. Mitropoulos, P.: Production and quality performance of healthcare services in EU countries during the economic crisis. Oper. Res. **21**(2), 857–873 (2021). https://doi.org/10.1007/s12351-019-00483-3. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85081212915&doi=10.1007%2fs12351-019-00483-3&partnerID=40&md5=4a591d9780af0bc0b8211b1247e01d0e. Cited By 3
13. Mourad, N., Habib, A., Tharwat, A.: Appraising healthcare systems' efficiency in facing COVID-19 through data envelopment analysis. Decis. Sci. Lett. **10**(3), 301–310 (2021). https://doi.org/10.5267/j.dsl.2021.2.007. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85106921537&doi=10.5267%2fj.dsl.2021.2.007&partnerID=40&md5=0503bfbcf5438b789c143511b114df22. Cited By 0
14. Peixoto, M., Musetti, M., Mendonça, M.: Performance management in hospital organizations from the perspective of principal component analysis and data envelopment analysis: the case of federal university hospitals in Brazil. Comput. Ind. Eng. **150** (2020). https://doi.org/10.1016/j.cie.2020.106873. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85092105354&doi=10.1016%2fj.cie.2020.106873&partnerID=40&md5=317a648c569e18bdbedf72cf7c022e05. Cited By 2
15. Pereira, M., Ferreira, D., Figueira, J., Marques, R.: Measuring the efficiency of the Portuguese public hospitals: a value modelled network data envelopment analysis with simulation. Expert Syst. Appl. **181** (2021). https://doi.org/10.1016/j.eswa.2021.115169. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85105546492&doi=10.1016%2fj.eswa.2021.115169&partnerID=40&md5=a56fedf4cb9be0b8a8ea06b2c773481c. Cited By 0
16. Schenkman, S., Bousquat, A.: From income inequality to social inequity: impact on health levels in an international efficiency comparison panel. BMC Public Health **21**(1) (2021). https://doi.org/10.1186/s12889-021-10395-7. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85104017932&doi=10.1186%2fs12889-021-10395-7&partnerID=40&md5=41f5bd5fb581517805522e4a4171f068. Cited By 0
17. Seddighi, H., Nosrati Nejad, F., Basakha, M.: Health systems efficiency in Eastern Mediterranean region: a data envelopment analysis. Cost Effectiveness Resour. Allocat. **18**(1), 1–8 (2020). https://doi.org/10.1186/s12962-020-00217-9
18. Singh, S., Bala, M., Kumar, N., Janor, H.: Application of DEA-based malmquist productivity index on health care system efficiency of Asian countries. Int. J. Health Plan. Manag. (2021). https://doi.org/10.1002/hpm.3169. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85104241429&doi=10.1002%2fhpm.3169&partnerID=40&md5=6c2738b303ea271233d40cff35a90140. Cited By 0
19. Top, M., Konca, M., Sapaz, B.: Technical efficiency of healthcare systems in African countries: an application based on data envelopment analysis. Health Policy Technol. **9**(1), 62–68 (2020). https://doi.org/10.1016/j.hlpt.2019.11.010. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85076592553&doi=10.1016%2fj.hlpt.2019.11.010&partnerID=40&md5=9290dd4249f562548f2b89698589ab6d. Cited By 8

20. Vrabková, I., Vaňková, I.: Efficiency of human resources in public hospitals: an example from the Czech Republic. Int. J. Environ. Res. Public Health **18**(9) (2021). https://doi.org/10.3390/ijerph18094711. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85104794289&doi=10.3390%2fijerph18094711&partnerID=40&md5=d196ba0c724695b904b1547d4f90eb64. Cited By 0
21. World Data Bank: Health Nutrition and Population Statistics—DataBank. https://databank.worldbank.org/source/health-nutrition-and-population-statistics
22. World Health Organization: World Health Statistics - Monitoring Health For The SDGs. World Health Organization, p. 1.121 (2016)
23. Yaya, S., Xi, C., Xiaoyang, Z., Meixia, Z.: Evaluating the efficiency of China's healthcare service: a weighted DEA-game theory in a competitive environment. J. Clean. Prod. **270** (2020). https://doi.org/10.1016/j.jclepro.2020.122431. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85087743297&doi=10.1016%2fj.jclepro.2020.122431&partnerID=40&md5=5dce288ebf0b59042c3552195b76a585. Cited By 3
24. Yu, J., Liu, Z., Zhang, T., Hatab, A., Lan, J.: Measuring productivity of healthcare services under environmental constraints: evidence from China. BMC Health Serv. Res. **20**(1) (2020). https://doi.org/10.1186/s12913-020-05496-9. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85088425147&doi=10.1186%2fs12913-020-05496-9&partnerID=40&md5=91a7ccfe76ba0ca38d7016c6fb033455. Cited By 2
25. Zhang, T., Lu, W., Tao, H.: Efficiency of health resource utilisation in primary-level maternal and child health hospitals in Shanxi province, China: a bootstrapping data envelopment analysis and truncated regression approach. BMC Health Serv. Res. **20**(1) (2020). https://doi.org/10.1186/s12913-020-5032-y. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85081199838&doi=10.1186%2fs12913-020-5032-y&partnerID=40&md5=4327aa0194a9e3ad5ec827138cb4db18. Cited By 6
26. Zhu, J.: Quantitative Models for Performance Evaluation and Benchmarking. In: International Series in Operations Research & Management Science, vol. 213. Springer, Cham (2014). https://doi.org/10.1007/978-3-319-06647-9. http://link.springer.com/10.1007/978-3-319-06647-9