Assessing national digitalization levels using cross efficiency model

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ABSTRACT

The digitalization of countries is essential since the process is related to processes of production, operation, and digitalization. Therefore, this study aims to measure the efficiency of the digitalization levels of the countries. The Data Envelopment Analysis method is an efficiency measurement tool and has different models. The CCR model, while widely used, has limitations such as zero weighting issues and discrimination power constraints. The findings showed that the CCR model considered certain factors in the calculation phase and did not take into account others. According to the result of the analysis, the Czech Republic's performance score was obtained by considering only two variables out of seven. This situation prevents accurate performance assessment. In addition, while there are 08 countries in efficient positions according to the result of the CCR model, it is not possible to rank them. Therefore, they were analyzed using the cross efficiency model. According to the result of cross efficiency model, Sweden ranks first in terms of digitalization levels, while the Netherlands is in second place and Slovenia is last. A unique ranking was obtained by considering all the variables. Therefore, the digitalization levels of countries were measured using the cross efficiency model, which can both create a unique ranking and obtain more consistent weights.

1. Introduction

The manufacturing industry has entered a new trend with the intense digitalization of industrial processes (Moreno et al., 2023). This trend is expected to support technology that can increase the efficiency of manufacturing processes and operations (Boffa & Maffei, 2023). The digitalization of countries with industries that make significant contributions to development continues rapidly. In many countries, departments have been established to carry out the digitalization process effectively and efficiently. One of these, Türkiye's Digital Transformation Office, was established in 2018 with the aim of creating a digital transformation ecosystem (Digital Transformation Office of the Presidency of Republic of Türkiye, 2023).

The report published by the Organisation for Economic Co-operation and Development (OECD), which summarizes the status of countries in digital transformation, helps countries evaluate their digital development status and create policies in response. For this purpose, it encompasses variables such as access to communication infrastructures,

services, and data, effective use of digital technologies and data, data-based innovation, good job opportunities for all, social welfare and inclusion, trust in the digital age, and market openness in digital business environments (Organisation for Economic Co-operation and Development, 2023). Using these factors obtained by the OECD, the aim of this study is to measure the digitalization efficiency of countries through the Cross Efficiency model, which is one of the Data Envelopment Analysis (DEA) models.

There are very few studies on the digitalization process in the literature. For example, Georgescu et al. (2023) evaluated the economic growth of European countries using DEA in the context of the digitalization process. The digitalization dimensions of the Digital Economy and Society Index (DESI) are taken as inputs in their studies, whereas the annual economic growth rate is taken as output. Krstić et al. (2022) analysed the digital transformation process of enterprises by measuring the efficiency of using information and communication technologies in 29 European countries between 2012 and 2020. A similar study evaluated the intensity and success of the digitalization process by measuring the effectiveness of the use of information and communication technologies in the Serbian business world between 2006 and 2019 (Petrovic et al., 2022). However, none of these studies directly measures the digitization of countries. Although there are studies measuring digitalization in various fields in the DEA literature, there is only one study that makes a holistic assessment of digitalization at the country level. In the study conducted by Keles and Alptekin (2023), the traditional output-oriented DEA model was applied. However, in their study, about half of the countries were positioned as efficient countries. Thus, the efficient countries could not be fully ranked. This case is what is known in the DEA literature as the discrimination power problem.

DEA can be used as a decision analysis tool in several areas because it classifies all units into two groups: efficient with a 100% efficiency score and inefficient with a less than 100% efficiency score. However, in real applications, Decision Makers (DMs) are typically not just interested in classifying data into efficient and inefficient; more often, they wish to rank all units under evaluation. To overcome this discrimination power problem of DEA, some approaches are improved to rank all DMUs under assessment (Aldamak & Zolfaghari, 2017). One of these approaches, cross efficiency, falls under the first group among the six groups defined by Adler et al. (2002). This approach involves the evaluation of a cross efficiency matrix, in which Decision Making Units (DMUs) are self and peer evaluated. In this study, the analysis results were obtained by applying the cross efficiency model, which was first suggested by Sexton et al. (1986), step by step. This approach ensures the complete ranking of the countries. Moreover, the digitalization levels of countries were measured using the cross efficiency model, which can both create a unique ranking and obtain more consistent weights.

The rest of the study is organized as follows. While the second section presents the theoretical background of the DEA method, the third section presents the application data, analysis steps, and findings. In the last section, the results are discussed, and suggestions for future work are provided.

2. Cross efficiency method and steps of application

DEA, based on the work of Farrell (1957), was first proposed by Charnes et al. (1978). DEA measures the relative efficiency of DMUs that produce similar outputs using similar inputs, with linear programming. According to the result of the linear programming model created for each DMU, those with an efficiency score of 1 are called efficient DMUs, while others are called inefficient DMUs. At the same time, it can offer suggestions about the

changes that inefficient DMUs should make in their factors to be efficient. DEA models have both input-oriented models and output-oriented models. The input-oriented model tries to keep the outputs constant and minimize the inputs, while the output-oriented model tries to maximize the outputs by keeping the inputs constant. Since the digitalization levels of countries are the outputs of the activities carried out in a country, each country wants to increase these outputs. Therefore, the output-oriented model was preferred in the study. This model is shown in Equation (1 - 4).

$$E_{kk} = min \sum_{i=1}^{m} v_{ik} x_{ik} \tag{1}$$

$$\sum_{r=1}^{s} u_{rk} y_{rk} = 1 \tag{2}$$

$$\sum_{i=1}^{m} v_{ij} x_{ij} - \sum_{r=1}^{s} u_{rj} y_{rj} \geq 0, \qquad j = 1, \dots, n \tag{3}$$

$$u_{rj}, v_{ij} \geq \varepsilon; r = 1, \dots, s;\ i = 1, \dots, m \tag{4}$$

m is the number of inputs, s is the number of outputs, n is the number of DMUs, x_{ij} $(i = 1, \dots, m)$ is the amount of i^{th} input of KVB_j, y_{rj} $(r = 1, \dots, s)$ is the amount of r^{th} output of KVB_j indicating in this model. In addition, the decision variables of the model are v_{ij} $(i = 1, \dots, m)$ and u_{rj} $(r = 1, \dots, s)$ representing the input weights and output weights, respectively. In order for these weights to take a value greater than zero, ε is taken as a small positive number very close to zero. However, despite this weight constraint, this model, known as the output-oriented CCR model, cannot fully rank DMUs. In such cases, it is not known which of the efficient DMUs is more efficient and which is less efficient. A cross efficient model has been proposed by Sexton et al. (1986), both to offer a better ranking and to offer peer review. The stages of the cross efficiency model are presented below.

Step 1. Decision variables u_{rj}^* and v_{ij}^* are obtained from Equation (1 - 4).

Step 2. $E_{kj} = \sum_{r=1}^{s} u_{rk}^* y_{rj} / \sum_{i=1}^{m} v_{ik}^* x_{ij}$ by calculating Equation (5). The n × n dimensional cross efficiency matrix shown in Equation (5) is obtained.

$$E_{kj} = \begin{bmatrix} E_{11} & E_{12} & \cdots & E_{1n} \\ E_{21} & E_{22} & & E_{2n} \\ \vdots & & \ddots & \vdots \\ E_{n1} & E_{n2} & \cdots & E_{nn} \end{bmatrix} \tag{5}$$

Step 3: Cross efficiency scores are obtained by applying the formulation shown in Equation (6) to the cross efficiency matrix.

$$\overline{E_j} = \frac{1}{n} \sum_{k=1}^{n} E_{kj} \tag{6}$$

The cross efficiency model evaluates how well each DMU scores when evaluated against other DMUs. It provides a more balanced view of their efficiency by considering the variables of each DMU from different perspectives, as it takes into account the various variables of each DMU. The cross efficiency model not only provides a unique ranking among DMUs, but also eliminates unrealistic weighting schemes.

This section provides a summary of theories, theoretical points, and research previously conducted. On that basis, propose research models, research hypotheses, or analytical frameworks.

3. Analysis of digitization levels of countries

When analysing the digitalization levels of countries by means of DEA, this section includes the selection of variables, descriptive statistics of the data set, and analysis results of the models.

In the literature, there is a study investigating the digitalization levels of countries with DEA, which bases the selection of variables on Keles and Alptekin (2023). Accordingly, the variables are access to the communication infrastructures, services, and data of the countries (Access; y_1), effective use of digital technologies and data (Use; y_2), data-based innovation (Innovation; y_3), good job opportunities for all (Jobs; y_4) , social welfare and inclusion (Society; y_5), trust in the digital age (Trust; y_6), and market openness in digital business environments (Market Openness; y_7). The data set and descriptive statistics used in the study are presented in Table 1.

Table 1

Dataset of the Study and their Descriptive Statistics

Countries	y_1	y_2	y_3	y_4	y_5	y_6	y_7
Austria	82.500	40.400	3.420	11.000	0.450	44.300	58.800
Belgium	42.700	53.000	2.900	14.000	0.410	39.900	52.900
Czech Republic	11.800	43.800	3.960	9.200	0.430	43.700	48.500
Denmark	28.100	64.800	2.820	12.000	0.650	60.100	38.700
Estonia	31.900	57.500	2.130	16.000	0.480	41.200	41.600
Finland	33.100	75.300	1.830	15.000	0.360	64.800	29.200
France	33.900	29.400	3.600	12.000	0.570	39.900	36.400
Greece	6.500	22.400	1.750	6.700	0.350	30.000	37.700
Ireland	36.000	58.800	1.450	14.000	0.410	50.200	38.500
Italy	45.800	60.500	2.170	7.300	0.530	30.800	41.700
Latvia	23.200	28.600	1.610	12.000	0.470	29.800	40.300
Lithuania	14.500	33.600	2.980	16.000	0.400	46.300	37.200
Luxembourg	12.400	33.500	2.090	22.000	0.540	45.900	62.400
Netherlands	50.300	64.900	4.220	16.000	0.450	48.000	47.900
Norway	48.400	64.000	1.930	15.000	0.550	51.700	18.100

Countries	y_1	y_2	y_3	y_4	y_5	y_6	y_7
Portugal	12.400	34.700	1.910	8.800	0.580	46.300	50.900
Slovenia	4.500	42.700	1.930	13.000	0.510	37.500	52.100
Sweden	175.600	75.400	4.120	17.000	0.260	56.600	31.900
Mean	38.533	49.072	2.601	13.167	0.467	44.833	42.489
Min.	4.5	22.4	1.45	6.7	0.26	29.8	18.1
Max.	175.6	75.4	4.22	22	0.65	64.8	62.4
Std. Dev.	38.235	16.267	0.894	3.688	0.093	9.492	10.560

Note. The data are from "Evaluation of the digitalization efficiency of countries using data envelopment analysis" by E. U. Keles and G. I. Alptekin, 2023 (https://doi.org/10.1109/SCSP58044.2023.10146126)

DEA calculations cannot be made entirely with outputs and require at least one input. Therefore, a dummy input that has a value of 1 for all the DMUs is employed (Ramanathan, 2006; Zeydan et al., 2011).

Standardization, a method frequently used in machine learning methods, is also used in DEA. In order to keep the magnitudes of each variable at most 1, the $y_{rj} = y_{rj} / \max(y_{rj})$ transformation is applied. The input variable required for the model to be applied is taken as a dummy variable. In this way, it is assumed that all the countries included in the analysis are homogeneous and produce the same input value.

The decision variables u_1, u_2, u_3, u_4, u_5, u_6, and u_7 obtained by taking the ε value specified in Equation (4) as 10^{-6} during the analysis phase are presented in Table 2. In Table 2, weights are obtained; it is seen that in some countries, the variables are nearly zero, and not all variables are taken into account. For example, for Finland, obtaining the efficiency score by using only the social welfare and inclusion variable, eliminating the other variables is not considered a fair approach.

Table 2

Decision Variables Obtained from CCR Model

Countries	u_1^*	u_2^*	u_3^*	u_4^*	u_5^*	u_6^*	u_7^*
Austria	0.1836	0.0000	0.5976	0.0000	0.0000	0.0000	0.4558
Belgium	0.0152	0.4429	0.0000	0.0000	0.0000	0.0000	0.8080
Czech Republic	0.0000	0.0000	0.5612	0.0000	0.0000	0.0000	0.6090
Denmark	0.0000	0.0000	0.0000	0.0000	0.1491	0.9174	0.0000
Estonia	0.0000	0.4685	0.0000	0.5120	0.3259	0.0000	0.0445
Finland	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
France	0.0000	0.0000	0.6448	0.0000	0.5131	0.0000	0.0000
Greece	0.0000	0.0000	0.4737	0.0000	0.8335	0.0000	0.5871
Ireland	0.0452	0.2776	0.0000	0.0496	0.0000	0.5179	0.5535
Italy	0.2404	0.4049	0.0000	0.0000	0.3405	0.0000	0.5009

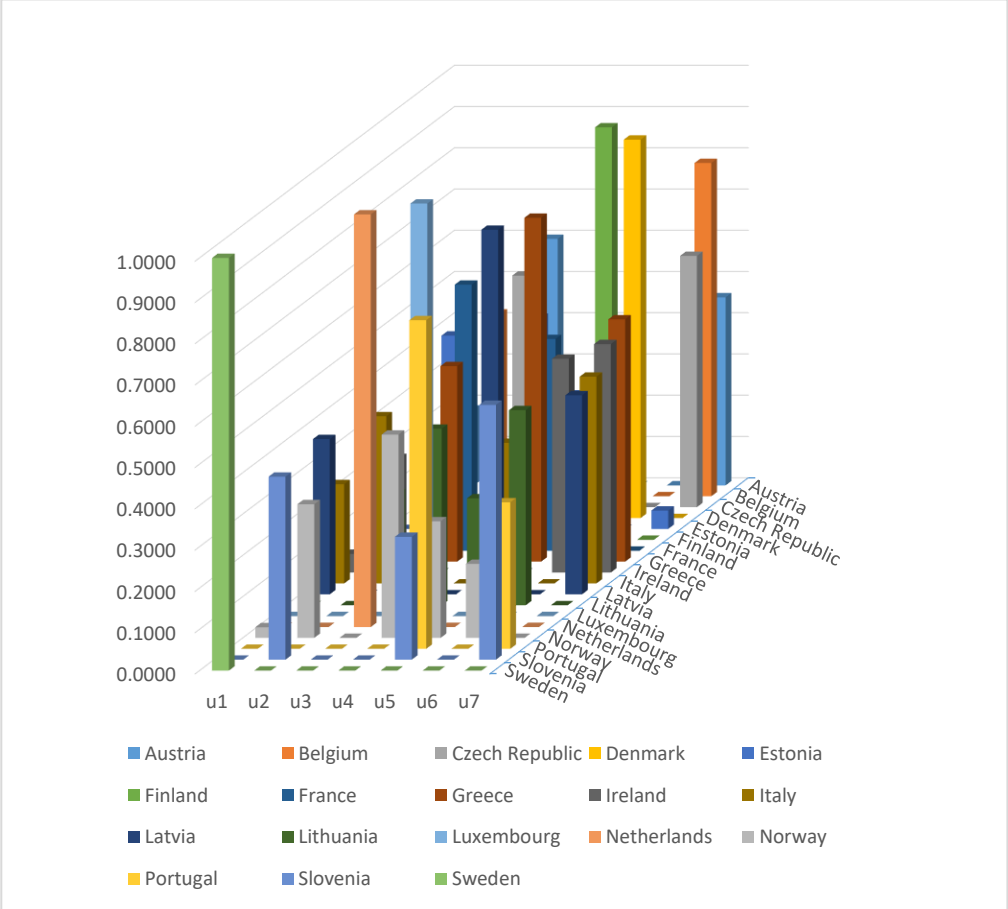
Countries	u_1^*	u_2^*	u_3^*	u_4^*	u_5^*	u_6^*	u_7^*
Latvia	0.3761	0.0000	0.0000	0.0000	0.8835	0.0000	0.4822
Lithuania	0.0000	0.0000	0.2718	0.4277	0.2590	0.4725	0.0000
Luxembourg	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
Netherlands	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
Norway	0.0258	0.3239	0.0000	0.4925	0.2825	0.1794	0.0000
Portugal	0.0000	0.0000	0.0000	0.0000	0.7963	0.0000	0.3548
Slovenia	0.0000	0.4434	0.0000	0.0000	0.2977	0.0000	0.6172
Sweden	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Note. Data analysis result of the research

Figure 1 shows the distribution of weights used in obtaining the efficiency scores of the countries. A variable may be heavily weighted in some countries and have a lower weight in others. In such cases, a fair distribution approach is not possible for every country. Therefore, in the cross efficiency model, a cross efficiency matrix is obtained by considering all the weights for each DMU. The resulting cross efficiency matrix is presented in Table 3.

Figure 1

Distribution of DEA Model Weights for Each Country



Note. Data analysis result of the research

Table 3

Cross Efficiency Matrix Obtained by Equation (4)

Countries	**Austria**	**Belgium**	**Czech Republic**	**Denmark**	**Estonia**	**Finland**	**France**	**Greece**	**Ireland**	**Italy**	**Latvia**	**Lithuania**	**Luxembourg**	**Netherlands**	**Norway**	**Portugal**	**Slovenia**	**Sweden**
Austria	1.000	1.188	1.078	1.406	1.565	1.972	1.233	1.887	1.908	1.516	1.830	1.411	1.308	1.000	2.193	1.526	1.519	1.000
Belgium	1.000	1.006	1.135	1.138	1.144	1.222	1.555	1.622	1.187	1.118	1.454	1.478	1.000	1.000	1.637	1.164	1.086	1.155
Czech Republic	1.000	1.141	1.029	1.367	1.492	1.947	1.233	1.713	1.809	1.479	1.694	1.355	1.160	1.000	2.374	1.370	1.344	1.197
Denmark	1.369	1.518	1.394	1.000	1.442	1.000	1.437	1.980	1.243	1.793	1.888	1.338	1.292	1.277	1.165	1.268	1.543	1.161
Estonia	1.337	1.152	1.406	1.000	1.035	1.017	1.338	2.081	1.120	1.231	1.435	1.281	1.000	1.000	1.000	1.385	1.203	1.018
Finland	1.463	1.624	1.483	1.078	1.573	1.000	1.624	2.160	1.291	2.104	2.174	1.400	1.412	1.350	1.253	1.400	1.728	1.145
France	1.139	1.304	1.059	1.059	1.420	1.774	1.000	1.839	1.834	1.333	1.621	1.297	1.341	1.000	1.372	1.334	1.434	1.198
Greece	1.000	1.122	1.043	1.000	1.215	1.608	1.025	1.514	1.441	1.151	1.302	1.265	1.000	1.009	1.386	1.054	1.113	1.382
Ireland	1.024	1.069	1.137	1.000	1.149	1.000	1.395	1.628	1.096	1.265	1.494	1.270	1.000	1.000	1.281	1.128	1.155	1.000
Italy	1.000	1.056	1.198	1.000	1.106	1.189	1.305	1.687	1.167	1.038	1.374	1.465	1.058	1.000	1.230	1.133	1.127	1.000
Latvia	1.000	1.175	1.262	1.000	1.192	1.581	1.101	1.591	1.334	1.089	1.243	1.441	1.000	1.141	1.254	1.029	1.124	1.273
Lithuania	1.188	1.218	1.204	1.000	1.183	1.085	1.131	1.850	1.243	1.550	1.500	1.112	1.000	1.000	1.099	1.289	1.303	1.000
Luxembourg	2.000	1.571	2.391	1.833	1.375	1.467	1.833	3.284	1.571	3.014	1.833	1.375	1.000	1.375	1.467	2.500	1.692	1.294
Netherlands	1.234	1.455	1.066	1.496	1.981	2.306	1.172	2.411	2.910	1.945	2.621	1.416	2.019	1.000	2.187	2.209	2.187	1.024
Norway	1.333	1.196	1.421	1.000	1.072	1.000	1.319	2.073	1.126	1.341	1.467	1.240	1.000	1.028	1.000	1.373	1.249	1.000
Portugal	1.148	1.266	1.266	1.000	1.233	1.674	1.123	1.580	1.409	1.147	1.263	1.449	1.000	1.234	1.309	1.016	1.103	2.033
Slovenia	1.035	1.038	1.136	1.000	1.095	1.184	1.337	1.596	1.161	1.050	1.357	1.418	1.000	1.000	1.315	1.091	1.062	1.209
Sweden	2.128	4.112	14.881	6.249	5.505	5.305	5.180	27.015	4.878	3.834	7.569	12.110	14.161	3.491	3.628	14.161	39.022	1.000
Mean	1.244	1.401	2.033	1.424	1.543	1.629	1.519	3.306	1.652	1.611	1.951	1.951	1.875	1.217	1.564	2.079	3.444	1.172

Note. Data analysis result of the research

The CCR score results obtained by Equation (1 - 4), and the cross efficiency score results and rankings are presented in Table 4. Accordingly, eight out of 18 OECD countries are in an efficient position according to the CCR results. The ranking of inefficient countries is: Belgium, Portugal, Czech Republic, Estonia, Italy, Slovenia, Ireland, Lithuania, Latvia, and Greece. Nevertheless, these efficient countries cannot be ranked in relation to one another. The cross efficiency model, which may perform a unique ranking and produce more consistent weights, is therefore recommended.

Table 4

Comparison of CCR Model Scores and Cross Efficiency Scores

Countries	***Score$_{CCR}$***	***Rank$_{CCR}$***	***Score$_{Cross}$***	***Rank$_{Cross}$***
Austria	1	1	1.244	3
Belgium	1.006	9	1.401	4
Czech Republic	1.029	11	2.033	15
Denmark	1	1	1.424	5
Estonia	1.035	12	1.543	7
Finland	1	1	1.629	10
France	1	1	1.519	6
Greece	1.514	18	3.306	17
Ireland	1.096	15	1.652	11
Italy	1.038	13	1.611	9
Latvia	1.243	17	1.951	13
Lithuania	1.112	16	1.951	13
Luxembourg	1	1	1.875	12
Netherlands	1	1	1.217	2
Norway	1	1	1.564	8
Portugal	1.016	10	2.079	16
Slovenia	1.062	14	3.444	18
Sweden	1	1	1.172	1

Note. Data analysis result of the research

4. Conclusion and discussion

In this study, the aim is to measure the digitalization levels of the countries with DEA and to rank the countries. The digitalization levels of the countries were measured using the output-oriented CCR model using seven different variables obtained from the data compiled by the OECD. However, since the CCR model finds about half of the countries efficient, it is not possible to rank these efficient countries within each other. Therefore, it is preferred to use the cross efficiency model, which can perform both a unique ranking and obtain more consistent weights.

There are two different basic DEA models: an input-oriented model and an output-oriented model. Since the structure of the input and output-oriented models is different while the first one takes values less than one, the second one takes values greater than one. According to the CCR model result, the countries that are in an efficient position include Denmark, Austria, Finland, France, Netherlands, Norway, Sweden, and Luxembourg. However, the CCR model is not sufficient to understand which of these countries is in the first place. If Table 4 is examined in detail, it is seen that the efficiency score of eight countries is 1. These countries, which are in an efficient position, would not know which is better or worse. However, the cross-efficiency model can give the answer to this question easily. Therefore, the cross efficiency model offers a more consistent ranking of results. Accordingly, Sweden ranks first in terms of digitalization levels, while Slovenia ranks last. According to the cross efficiency results, the Netherlands ranked second and Austria ranked third, followed by Belgium, Denmark, France, and Estonia. They are followed by Norway, Italy, Finland, Ireland, Luxembourg, Latvia, Lithuania, Czech Republic, Portugal, and Greece. According to the report (Digital Economy and Society Index, 2024), published by the European Commission and assessing the digital performance and competitiveness of countries, Finland, Denmark, the Netherlands, and Sweden remain the EU frontrunners. In addition, according to Małkowska et al. (2021), Denmark, Estonia, Netherlands, Finland, Sweden, United Kingdom are among the high performers. This shows that the results of the literature and analysis are compatible.

DEA models are considered to be a perfect method to measure the digitalization processes of countries or companies and to identify their deficiencies. At the same time, research that can be considered as a future research topic will compare the digitalization levels of not only OECD countries, but all countries. Moreover, apart from Sexton et al. (1986), models such as Andersen and Petersen (1993), Wang and Jiang (2012), Toloo (2015), Toloo and Salahi (2018), Özsoy et al. (2021) also provide a unique ranking of DMUs. Another study in which these models are evaluated together is considered for a future study. There are also limitations to the model used in the study. This study is limited to OECD countries only. Therefore, the dataset is limited to the dataset shared by OECD. Finally, the effect of environmental variables such as cultural or political differences on efficiency scores was also excluded from the scope of the study.

SCIENTIFIC CONTRIBUTION

The manuscript presents statistically and practically significant findings with new datasets using cross efficiency.

AUTHOR CONTRIBUTIONS

CRediT: **Volkan Soner Özsoy**: Conceptualization, Methodology, Writing - Original Draft, Review & Editing, Software, Investigation, Formal Analysis, Supervision, Validation, Visualization.

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All authors declare that they have no conflict of interest.

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