COMPARATIVE ANALYSIS OF THE PERFORMANCE OF RDI SYSTEMS IN CEE COUNTRIES, USING THE DATA ENVELOPMENT ANALYSIS METHOD

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DOI: 10.24818/MSWP.2026.09

Abstract: *This paper examines the efficiency of Research, Development and Innovation (RDI) systems in Central and Eastern European (CEE) countries in 2024, in a context characterized by significant differences in resource allocation and innovation performance. The topic is particularly relevant given the role of innovation in economic competitiveness and European convergence. The study focuses on the relationship between inputs and outputs, assessing how investments in RDI are translated into tangible results. To achieve this, the Data Envelopment Analysis (DEA) method is employed, enabling a comparative evaluation of relative efficiency and the identification of benchmark models. The analysis is empirical in nature and highlights the structural characteristics of RDI systems in the CEE region, as well as differences in resource utilization. It also outlines general directions for interpreting performance and development potential. Overall, the paper contributes to a better understanding of how efficiency shapes innovation outcomes and provides a useful framework for analyzing policies and strategies in the field of research and innovation.*

Keywords: technical efficiency, research, development and innovation, data envelopment analysis, CCR model, efficiency frontier, benchmarking, CEE countries, R&D investment intensity.

JEL Classification: C44, D24, O57.

1. Introduction

In the context of the knowledge-based economy, the ability of an economy to generate, disseminate and capitalize on knowledge becomes an essential factor of global competitiveness. Research, Development and Innovation (RDI or R&D&I) systems are the engine of technological progress, productivity growth and sustainable economic development. Within the European Union, the performance of these systems is constantly monitored through statistical indicators, which reflect the level of investment in research, the human resources involved, their innovative results and their economic impact. European R&D&I policies, coordinated through programs such as Horizon Europe, aim precisely to transform scientific knowledge into practical solutions that can support sustainable development, job creation and economic resilience (European Union, 2026). Within this framework, transnational cooperation and the strengthening of the European Research Area (ERA) are aimed at increasing mobility and exchange of resources between research institutions in the Member States (European Union, 2026).

The countries of Central and Eastern Europe (CEE) have undergone significant economic transformations in recent decades, moving from planned economies to market economies integrated into European space. In this process, the development of RDI systems has become a strategic priority for economic convergence and for reducing the gaps with Western European states. However, the level of efficiency in the use of R&D&I resources differs between these countries, which requires the use of analytical methods capable of comparing the relative performance of international systems.

Assessing the efficiency of RDI systems is not a straightforward process, as they involve multiple types of resources (financial, human, infrastructural) and generate diverse results (scientific publications, patents, innovative products, technology transfer) (Ștefan, et al., 2023). RDI systems can be analyzed using the GERD (Gross Expenditure on Research and Development) indicator, which reflects the total volume of R&D expenditure and is decomposed into sectors of performance, namely BERD (Business Enterprise Expenditure on R&D) for business environment, GovERD (Government Expenditure on R&D) for the public sector and HERD (Higher Education Expenditure on R&D) for higher education institutions (Piece of Mind, 2012). Overall, these components reflect how the research effort is structured at the national level and contribute to economic development and technological progress.

In this context, traditional methods of efficiency analysis based on one-dimensional indicators are insufficient. As a result, the literature has developed multidimensional tools, which allow the evaluation of efficiency based on several analysis variables. One of the most widely used methods for analyzing the relative efficiency of homogeneous units is the Data Envelopment Analysis (DEA) method. This allows the evaluation of the performance of comparable Decision Making Units (DMUs), considered peers within the analysis, by relating the results obtained to the resources used and by building the Efficiency frontier that will be the basis of the comparisons (Arunkumar, et al., 2025). The method is frequently used in various fields such as education, health, public sector, or innovation systems, due to its ability to simultaneously integrate several input and output variables (Diverse Daily, 2024).

The purpose of this research paper is to conduct a comparative analysis of the performance of RDI systems in 2024, from a group of 12 CEE countries, using the DEA method, Romania being included in the analyzed sample. By applying this analytical tool, the study aims to identify Romania's degree of efficiency in relation to other countries, in terms of the capacity to transform research resources into innovative results, as well as to highlight the existing structural differences between these international systems.

2. Theoretical foundations of the DEA method

The concept of efficiency in economic analysis is an essential dimension in the evaluation of the performance of organizations. In the classical sense, efficiency refers to the ability of an entity to transform resources – inputs, into results – outputs, in an optimal way so as to maximize production using limited resources, or to minimize costs for a given level of production (Cooper, et al., 2007). In the first economic approaches, the measurement of efficiency was often conducted by using simple ratios (usually Output/Input), an appropriate method in situations where the production process could be represented by a single input and a single output (Cooper, et al., 2007). Subsequently, with the development of modern methods of analysis, models such as Input-oriented for minimizing inputs and Output-oriented for maximizing outputs, were introduced, both based on keeping the other category of variables constant (Rabar, 2017).

In the specialized literature, Michael J. Farrell is the one who, based on the previous works of Koopmans and Debreu (1951), developed and differentiated the concepts[1] of Technical and Allocative Efficiency, later used in the decomposition of Economic Efficiency[2] (Cost Efficiency – CE) and the development of modern methods of measuring productive efficiency (Cooper, et al., 2007). Technical Efficiency (TE) refers to the ability of a production unit to achieve a maximum level of output, using a given level of input, while Allocative Efficiency (AE) reflects the optimal use of resources, according to their costs (Roman & Suciu, 2012).

However, the initial approaches had significant limitations when applied in real-world contexts characterized by the existence of multiple inputs and outputs, as neither Input-oriented, nor Output-oriented ratios were able to adequately reflect the performance of the analyzed entities (Førsund & Sarafoglou, 2000). The situation becomes even more complex if the evaluated Decision-Making Units (DMUs) are companies, public institutions, or national economies that use diversified resources and generate heterogeneous results. Under these conditions, the analyses provide an incomplete picture of performance, with the risk of missing relevant differences between units (Rabar, 2017).

[1] In the work "The Measurement of Productive Efficiency" (1957).
[2] Also noted as Overall Efficiency – OE, according to the relationship: OE = TE x AE.

In response to these drawbacks, in 1978, Abraham Charnes, William Cooper and Edwardo Rhodes proposed the Data Envelopment Analysis method[3], a nonparametric tool based on linear programming for estimating production boundaries and evaluating the relative efficiency of the DMUs (Cooper, et al., 2007). This method has extended the concept of Technical Efficiency, from the simple input-output context, into a multivariate framework, in which the relationship between inputs and multiple outputs is simultaneously analyzed, for each evaluated DMU (Ştefan, et al., 2023).

Over time, researchers have developed 2 broad categories of methods for measuring efficiency – parametric and nonparametric. Parametric methods, such as Stochastic Frontier Analysis (SFA), involve estimating a specific production function and including statistical errors, while nonparametric methods, such as Data Envelopment Analysis, build an efficiency frontier based on existing data (Kuosmanen, 2006). One of the major advantages of the method is that it does not require the specification of a predefined production function, as is the case in parametric analysis. But in its classic form, DEA is also a deterministic method, because any deviation from the frontier is attributed to inefficiency, without explicitly separating random error, which can be a disadvantage (Rosenmayer, 2014).

The DEA method is based on the empirical construction of an efficiency frontier, based on the best performing units (DMUs) observed in the sample. Units located on this frontier are considered efficient, and those located below the frontier are considered inefficient, the Efficiency Score values being in the range (0, 1] (Diverse Daily, 2024). This score (denoted with θ) is obtained by linear programming and fulfills 2 functions – it is a proportional scaling factor, but also an indicator of Technical Efficiency (TE) (Cooper, et al., 2007).

In the analysis of relative efficiency, through DEA, an important component is the assumptions of scale returns, which influence how inputs are converted into outputs, for the compared units (Diverse Daily, 2024). The original CCR (Charnes–Cooper–Rhodes) model operates under the assumption of constant returns to scale (CRS), a condition in which outputs vary proportionally to inputs, regardless of their absolute level (Arunkumar, et al., 2025).

The Banker–Charnes–Cooper (BCC) model, later proposed in 1984, expands the framework of the CCR model, by including the convexity constraint ($\sum \lambda_j = 1$) and adopting the hypothesis of variable returns to scale (VRS), in which the proportionality condition is no longer necessary (Arunkumar, et al., 2025). Following the application of the CCR and BCC models, Technical Efficiency (TE) can be expressed as a product between Pure Technical Efficiency (PTE) and Scale Efficiency (SE) (Arunkumar, et al., 2025).

Slack variables are another key component of the DEA method, as they show residual deviations in the form of input surpluses ($S^- > 0$) and/or output deficits ($S^+ > 0$), in relation to the position of a DMU relative to the frontier. At the same time, their effective values are ≥ 0 (The SPSSAU project, 2024). Within the DEA analysis, the effectiveness of a DMU can be classified into 2 main forms – weak efficiency and strong efficiency (Cova-Alonso, et al., 2021). Weak efficiency occurs when a DMU is radially efficient ($\theta = 1$), but has slacks (S^- and/or $S^+ > 0$), indicating the existence of potential improvements in the variables, without proportionally changing them (Cova-Alonso, et al., 2021).

Strong efficiency (or Pareto-Koopmans efficiency) is achieved when a DMU is radially efficient ($\theta = 1$) and does not present slacks (S^- and $S^+ = 0$), which implies the impossibility of improving one input or output, without compromising another (Cova-Alonso, et al., 2021). On the other hand, if the DMU is not radially efficient ($\theta < 1$), then the Slack variables are no longer considered and the DMU is considered inefficient (Cova-Alonso, et al., 2021).

The development of the Data Envelopment Analysis method has also been accompanied by the gradual emergence of dedicated software tools, designed to facilitate its application in empirical analysis. In the initial phases, the implementation of DEA models was conducted through general optimization programs or programming languages, but the expansion of the use

[3] In the work "Measuring the efficiency of decision making units".

of the method led to the development of specialized "Add-In" applications for spreadsheets, or standalone software (Cook & Seiford, 2009). In parallel, integrated solutions have also been developed in statistical environments, such as the R-language packages or implementations in MATLAB, offering high flexibility and the possibility of extending models according to the analytical needs (Álvarez, et al., 2020).

Subsequently, applications freely available online were also developed, such as DEAFrontier™, an "Add-In" software for Microsoft Excel, developed by Professor Joe Zhu, which allows the implementation and resolution of DEA models, in a familiar environment to users (Zhu, 2006). The application uses Excel Solver (or alternatives, such as OpenSolver), to optimize the models and includes a wide range of DEA solutions, such as the CCR and BCC models, Scale Efficiency (SE) analysis, Slack-based, Cross-efficiency or Malmquist index models, thus providing a flexible tool for evaluating the performance of the analyzed units (DMUs) (Zhu, 2006).

In Romania, the first known works that apply DEA in various economic sectors date back to the early 2000s, in which the efficiency and productivity of national banks was analyzed, in the period 2006-2008 (Nițoi, 2009). Starting with the period 2010-2014, the method was used to assess the efficiency in the health system, in which public hospitals were analyzed (Popescu, et al., 2014). Onward, Romanian research has extended the application of the DEA method to various sectors, including in the field of education, where the efficiency of higher education institutions has been analyzed in various studies, which highlight the significant differences in performance in the period 2014-2017, between public universities in the country (Lita, 2018).

In the recent period, in an article published in 2020, the method is used to analyze the sustainability of the allocation of funds in Romanian public universities, in the period 2012-2018, highlighting both the Technical Efficiency (CRS and VRS hypotheses) and the influence of the institutional dimension on performance (Dumitrescu, et al., 2020). Also, a study published in the journal "Sustainability" (2025), presents the application of the Input-oriented DEA-CCR model, to analyze the efficiency of the tourism sector in the country, compared to other CEE states, highlighting Romania's relative positioning and the potential for improvement of this indispensable sector (Ciocoiu, et al., 2025).

3. Comparative study of RDI systems

In the context of efficiency analysis using Data Envelopment Analysis, the correct definition of inputs (X) and outputs (Y) variables is essential for the validity of the results. The choice of variables must respect the principle of homogeneity of DMUs, as well as the causal relationship between the resources used and the results obtained. Within a complex system like R&D&I, the process of transforming resources into innovative results is multidimensional, and the selected variables must reflect both the intensity of investments and the capacity to generate knowledge and innovation. In this perspective, table 1 summarizes both the input and output variables, as well as the DMUs used over time in the studies throughout the DEA literature, regarding the evaluation of the efficiency of RDI systems.

The comparative analysis of studies on the efficiency of Research and Development (R&D) systems highlights the fact that the performance of innovation at the level of the European Union is characterized by significant differences between states, both in terms of resources and results. The works mentioned in table 1 confirm that efficiency is not determined exclusively by the level of investments, but especially by the ability to transform inputs (expenses, personnel, financing) into concrete outputs (patents, publications, commercial results).

Studies at European level, conducted by Roman & Suciu (2012), Jurickova et al. (2019), Škrinjarić (2020) and Cabinova et al. (2024), showed that the performance of innovation systems varies significantly between Member States.

Table 1

Use of the DEA methodology in the RDI sector

No.	Authors and year of publication	Objectives studied and DEA model(s) used	DMUs	Main variables used	
				Input	**Output**
1.	(Roman & Suciu, 2012); Romania	Evaluation of R&D performance in European countries, in terms of Technical Efficiency (TE) Period: 2005-2007 Models: CCR (CRS) and BCC (VRS) Output-oriented	28 EU Member States	X1: R&D expenditure (PPS * per capita); X2: Total R&D personnel (FTE – measured in tens of thousands); X3: Employment in high-tech sectors (% of total employees)	Y1: Patent applications to the European Patent Office (EPO) per million inhabitants (No.)
2.	(Fotia & Teclean, 2019); Romania	Efficiency of innovation in selected CEE countries, through an input-output approach Period: 2007-2016 Models: CCR (CRS) and BCC (VRS) Input-oriented	Czech Republic, Hungary, Poland and Romania	X1: R&D government spending (% of GDP); X2: Total R&D personnel (FTE – measured in tens of thousands)	Y1: Patent applications to the European Patent Office (EPO) per million inhabitants (No.); Y2: High-tech exports (% of total exports)
3.	(Jurickova, et al., 2019); Czech Republic	Effectiveness of the national innovation systems of selected EU countries Period: 2005-2016 Model: CCR (CRS) Output-oriented	28 EU Member States	X1: Total researchers by sectors of performance (FTE – measured in tens of thousands); X2: Intramural R&D expenditure (GERD) by sectors of performance (million EUR)	Y1: Scientific journal articles (No.); Y2: Patent applications to the EPO by priority year (No.)
4.	(Škrinjarić, 2020); Croatia	The efficiency of the chosen European countries, in achieving the R&D objectives, by sector decomposition (private, higher education and government) Period: 2007-2017 Model: Slacks-Based Measure (SBM) Non-oriented and non-radial	29 EU Member States	X1: Intramural R&D expenditure in the higher education sector – HERD (EUR per capita); X2: Intramural R&D expenditure in the business enterprise sector – BERD (EUR per capita); X3: Intramural R&D expenditure in the government sector – GovERD (EUR per capita)	Y1: Scientific publications per million inhabitants (No.); Y2: Patent applications to the European Patent Office (EPO) per million inhabitants (No.); Y3: Total R&D personnel (% of active population, FTE); Y4: High-tech exports (% of total exports)
5.	(Cabinova, et al., 2024); Slovakia	Evolution of innovation efficiency in EU Member States and evaluation of resource use in national RDI systems Period: 2018-2021 Models: CCR (CRS) and BCC (VRS) Output-oriented	27 EU Member States	X1: Total government expenditure on education (% of GDP); X2: R&D expenditures (% of GDP); X3: Researchers in R&D (No. of researchers per million people)	Y1: Patent applications (No.); Y2: Scientific and technical journal articles (No.); Y3: High-tech exports (% of manufactured exports)

*Source: Own study based on the literature cited in the table. * Purchasing Power Standard*

The analysis made by Roman & Suciu (2012), highlights that in the period 2005-2007, some countries achieved lower technical innovation results in relation to the resources allocated, indicating marked differences in R&D performance and productivity. The results of the study made by Jurickova et al. (2019), showed that in 2016, among the countries considered technically efficient were Cyprus, Luxembourg, Malta, suggesting that systems with relatively few resources, can achieve efficient performance in terms of transforming inputs, into measurable innovation outputs (scientific articles and patents).

Research conducted by Škrinjarić (2020), confirms these discrepancies, showing that various countries fail to efficiently convert R&D expenditures, into relevant outputs such as patents or publications, reflecting variations in innovative systems. Also, an important methodological particularity in her work is the fact that the total staff involved in R&D is treated as output in the DEA model, thus highlighting the role of human capital as a relevant result of innovation performance, not just as a consumed resource.

In the case of Central and Eastern European countries, including Romania, the results indicate a positive but uneven evolution. The study conducted by Fotia & Teclean (2019), shows that the efficiency of innovation increased between 2007-2016 in the 4 countries analysed, but there are significant differences between them. Hungary being the most efficient in harnessing R&D resources, became a benchmark (reference country) in the analysis, the Czech Republic stood out for a high level of innovation efficiency, especially patents, while Poland had a lower performance, although it had a higher volume of resources (Fotia & Teclean, 2019).

Authors Cabinova et al. (2024) noted that Member States can be classified into 5 distinct efficiency groups, depending on how they use innovation resources, which underlines that some of them outperform the same number of inputs, while others continue to be inefficient in their national RDI systems. Based on the scaling method and DEA scores (BCC-O), regarding the CEE countries, Czech Republic is ranked in the above-average group (no. 2), Estonia, Poland, Hungary, Latvia, Slovakia and Slovenia in the medium-efficiency group (no. 3), Bulgaria and Lithuania in the below-average group (no. 4), and Croatia in the group of inefficient economies (no. 5) (Cabinova, et al., 2024).

As for Romania, although it is making some progress according to the DEA analyses carried out by Fotia & Teclean (2019) and Škrinjarić (2020), it lags behind the other economies analyzed, especially in terms of the ability to transform investments into results such as patents or high-tech exports. According to the authors Roman & Suciu (2012), the very low rate of knowledge production in Romania in the period 2005-2007, indicated a reliance on the replication of existing technologies. But in the recent period, according to the DEA analyses applied by Jurickova et al. (2019) and Cabinova et al. (2024), an evolution has been identified, Romania is among the countries classified as technically efficient in the European Union, in terms of transforming innovation resources into measurable outputs.

The DEA method often shows that countries or organizations with limited resources can achieve satisfactory results, while others with higher investments are less efficient. The present analysis continues this line of research, by clarifying the selected model and the rationale behind this choice. The research methodology is based on the application of the Data Envelopment Analysis (DEA) method, used to assess the relative efficiency of Research, Development and Innovation (RDI) systems, from a group of 12 countries in Central and Eastern Europe (CEE), Romania being the main point of interest of the analysis.

Statistical data related to the analyzed variables were collected from the official Eurostat and OECD databases for 2024. Subsequently, they were centralized and processed into DEAFrontier™, developed by Joe Zhu, used for the application of the selected DEA model and the evaluation of the Technical Efficiency (TE) of the 12 DMUs. Thus, the methodology used allows the identification of differences between CEE states, in terms of the capacity to transform the resources allocated to RDI activities, into measurable innovative outputs. The Input-oriented DEA-CCR model is used, based on the assumption of constant returns of scale (CRS) and which aims to identify the minimum level of resources necessary to obtain a certain level of output.

Basically, the relative efficiency of RDI systems is evaluated by the ability to reduce the consumption of resources (X), without diminishing the level of innovative results (Y). The relationship between variables can be conceptualized as follows in table 2.

Table 2

Main variables used in the present paper

Objective studied	DMUs	Sources	Input	Description	Sources	Output	Description
Efficiency of RDI systems (2024)	12 CEE countries	(Eurostat; OECD, 2026a)	X1: R&D expenditures by sectors of performance (% of GDP)	It measures the overall intensity of investments in the RDI sector, at macroeconomic level.	(European Patent Office, 2026)	Y1: Patent applications to the EPO by country of applicants and inventors (No.)	The main output of technological innovation.
		(Eurostat; OECD, 2026b)	X2: Gross Domestic Expenditure on R&D (GERD) at national level (million EUR)	It expresses the total volume of expenditure incurred for RDI activities.	(Eurostat; OECD, 2026d)	Y2: R&D personnel by sectors of performance (% of active population, FTE *)	Structural output of RDI systems – specialized human resource.
		(Eurostat; OECD, 2026c)	X3: Business Enterprise Expenditure on R&D (BERD) by activity and type of expenditure (million EUR)	It measures the involvement of the private sector in RDI activities.			

*Source: Data compiled by the author, taken from EUROSTAT. * Full-Time Equivalent*

Within the chosen DEA model, the inputs presented in table 2 are defined as factors of innovation production and the outputs as direct and indirect results of this process. Therefore:

INPUTS

Variable X1 – R&D expenditures by sectors of performance relative to GDP, is included as an input, as it captures the relative intensity of investments, allowing the comparison of performance between RDI systems and reflects the priority given to research within economic policies. Variable X2 – Gross Domestic Expenditure on R&D (GERD) is used as input, because it provides an aggregate measure of the financial resources allocated to RDI systems, highlighting their effective capacity to support national research activities. Variable X3 – Business Enterprise Expenditure on R&D (BERD) is also considered an input, as it reflects the direct involvement of the private sector in the innovation process, helping to orient research towards applied results and economic competitiveness.

OUTPUTS

The variable Y1 – No. of patent applications at the European Patent Office (EPO) is treated as output, being a standard indicator of innovative performance, which highlights the ability of RDI systems to generate relevant and transferable technological results in the economy. Variable Y2 – Personnel involved Full-Time Equivalent in R&D is included as output, because in the macroeconomic context, it reflects the cumulative result of investments and expresses the ability of systems to support specialized human capital, which in turn contributes to all patents issued. According to Ziarul Financiar (2025a), the RDI sector had 50,579 employees in 2024, up 5.1 % compared to 2023, of which 45.3 % (22,921 people) were women. Table 3 presents the related data extracted from the statistical sources mentioned:

Table 3

Statistical data for 2024 in CEE countries

Countries (DMUs)	Input Variables			Output Variables	
	X1: R&D expenditures by sectors of performance (% of GDP)	*X2: Gross Domestic Expenditure on R&D (GERD) at national level (million EUR)*	*X3: Business Enterprise Expenditure on R&D (BERD) by activity and type of expenditure (million EUR)*	*Y1: Patent applications to the EPO by country of applicants and inventors (No.)*	*Y2: R&D personnel by sectors of performance (% of active population, FTE)*
Bulgaria	0.77	804.857	524.12	53	0.90
Czech Republic	1.82	5,847.024	3,783.383	252	1.69
Croatia	1.35	1,160.008	636.107	41	0.95
Estonia	1.99	791.064	472.228	74	1.39
Greece	1.54	3,655.331	2,001.481	107	1.50
Latvia	0.92	372.643	135.996	36	0.79
Lithuania	1.04	825.347	335.918	73	1.00
Poland	1.41	11,955.521	7,567.626	692	1.15
Romania	**0.46**	**1,624.214**	**1,043.183**	**63**	**0.45**
Slovakia	0.98	1,278.787	767.835	62	0.95
Slovenia	2.16	1,458.002	1,012.104	156	1.78
Hungary	1.31	2,696.840	2,038.333	139	1.24

Source: Data compiled by the author, taken from EUROSTAT

The data in table 3 show a significant variation in the intensity and structure of RDI investments between CEE countries in 2024. Some countries, such as Slovenia, the Czech Republic and Estonia, have levels of R&D expenditures relative to GDP above the average of many regional economies, while Romania and Bulgaria are below the 1 % of GDP threshold, which is among the lowest levels in the European Union (Eurostat, 2025a). At the same time, the number of patent applications reflects discrepancies in the capacity to generate technological results (with a relatively high volume in Poland and the Czech Republic compared to smaller CEE countries), suggesting differences in the efficiency of innovation systems and their integration into global technology markets.

This diversity reflects the common challenge of CEE countries to stimulate private investment in R&D to get closer to the EU's target of 3 % of GDP in R&D spending, a target that remains unmet in many countries in the region (Eurostat, 2025a). Equally, the differences in the structure of expenses and specialized human capital indicate key areas for improvement, in order to capitalize on innovative results and increase economic competitiveness.

The methodological approach included the definition of the analyzed decision units (DMUs), the selection of statistical indicators, the construction of the database, the application of the DEA model and the interpretation of the results obtained through efficiency scores (θ), slacks, λ values and types of scale yields. These aspects will be analyzed in detail in the section below, where the link between the inputs invested and innovative performance obtained will be assessed.

4. Results and discussion

Following the application of the Input-oriented CCR model, the efficiency scores of the evaluated units (CEE countries) were determined, the results being presented in table 4.

As not all DMUs (CEE countries) in the sample operate at the constant scale of production (according to the CRS hypothesis), the Sum of the Lambda vector coefficients ($\sum \lambda$) in table 4 is used to determine the type of scale yields and the θ Score to identify the technically efficient countries that will serve as reference units. Therefore, with $\sum \lambda = 1$ and Score $\theta = 1$, Bulgaria, Latvia, Lithuania, Poland, and Slovenia define by Constant Returns to Scale – the efficiency frontier. Being frequently used as reference countries for other states, they confirm their role as models of good practice in the region. In contrast, most of the inefficient countries – Croatia, Czech Republic, Estonia, Greece, Slovakia and Hungary – are characterized by Decreasing Returns to Scale (DRS), suggesting that the current level of resources is relatively high in relation to the results achieved and that a better allocation of resources could lead to an increase in TE.

Table 4

Efficiency groups and optimal λ values

DMU No.	**Countries (DMUs)**	**General Score of Efficiency (θ)**	**Reference Countries (benchmarks) and Optimal λ Values**					
			∑ λ	*RTS **	*No. of reference countries*	*DMU No.*	*Reference Countries (DMUs)*	*Optimal λ* [4]
1.	Bulgaria	1.000	1.000	Constant	1.	1.	Bulgaria	1.000
2.	Czech Republic	0.851	1.810	Decreasing	2.	8.	Poland	0.244
						1.	Bulgaria	1.566
3.	Croatia	0.671	1.037	Decreasing	3.	7.	Lithuania	0.322
						6.	Latvia	0.143
						1.	Bulgaria	0.572
4.	Estonia	0.940	1.581	Decreasing	2.	11.	Slovenia	0.142
						6.	Latvia	1.439
5.	Greece	0.841	1.658	Decreasing	2.	8.	Poland	0.030
						1.	Bulgaria	1.628
6.	Latvia	1.000	1.000	Constant	1.	6.	Latvia	1.000
7.	Lithuania	1.000	1.000	Constant	1.	7.	Lithuania	1.000
8.	Poland	1.000	1.000	Constant	1.	8.	Poland	1.000
9.	**Romania**	**0.891**	**0.484**	**Increasing**	**2.**	**8.**	**Poland**	**0.058**
						1.	**Bulgaria**	**0.425**
10.	Slovakia	0.833	1.053	Decreasing	2.	8.	Poland	0.010
						1.	Bulgaria	1.043
11.	Slovenia	1.000	1.000	Constant	1.	11.	Slovenia	1.000
12.	Hungary	0.844	1.348	Decreasing	2.	8.	Poland	0.106
						1.	Bulgaria	1.243

*Source: Author with DEAFrontier™ based on statistical data. * Return to Scale*

According to Eurostat (2025b), there are significant differences between the 5 CEE countries that define the frontier, in terms of the level and structure of investments. Poland stands out for its relatively large size of the RDI system and for the high volume of both investments and outputs. Although Bulgaria has a low level of R&D expenditure intensity (below 1 % of GDP), it manages to make relatively efficient use of available resources (Eurostat, 2025b). Most inefficient countries are thus compared both to Poland, as a model of scale and innovative performance, and to Bulgaria, as a model of efficiency under conditions of limited resources.

In the case of intermediate countries, such as Croatia, extensive combinations of benchmarks arise (Bulgaria, Latvia and Lithuania), because RDI systems in the CEE region are heterogeneous and a single country cannot fully reflect their Input-Output structure. The Baltic states, Latvia and Lithuania, have stood out in the last decade for the accelerated dynamics of investment in R&D, with some of the largest increases in public allocations for research at EU level, which indicates a structural adaptation and the increasingly efficient use of inputs (Eurostat, 2025b). Slovenia on the other hand, differs by a more balanced profile, characterized by a high intensity of RDI expenditure (~ 2 % of GDP), but also by the significant involvement of the private

[4] Optimal Lambdas: intensity coefficients that show the combination of efficient units and form the reference for a DMU.

sector, which positions it as a model of effective correlation between consistent inputs and innovative results (Eurostat, 2025b).

The slightly lower level of Technical Efficiency for Romania (θ = 0.891) corresponds to the data provided by Eurostat in 2024, as it had the lowest budget allocation for R&D in the EU (~ € 19 per capita), which reflects the underutilized resources for the national RDI system (Ziarul Financiar, 2025b). Data from the National Institute of Statistics (INS) show that in 2024, ~ RON 8.08 billion were allocated for R&D activities, both from the private sector (0.30 % of GDP) and from the public sector (0.16 % of GDP), which suggests that the RDI sector is mainly financed from private sources (AGERPRES, 2025). At the same time, out of the total expenses (RON 8.08 billion), RON 7.34 billion represented current expenses (90.9 %), and more than 50 % of these were destined to personnel expenses, which shows that human resources remain the main pillar of the research sector in Romania (Ziarul Financiar, 2025a).

However, the Increasing Returns to Scale (IRS) indicate a development potential for Romania, in the sense that the expansion of investments in R&D sector could generate more than proportional increases in outputs. The analysis of employees by categories of occupations conducted by INS showed that 63.6 % (32,163 people) were researchers, the rest being auxiliary and technical personnel. As regards the level of professional training, 38.8 % had doctoral/postdoctoral studies, 48.9 % bachelor's/master's or postgraduate studies, and 12.3 % had another level of training (exclusively higher), indicating a significant share of highly qualified personnel (AGERPRES, 2025). And the establishment of Poland and Bulgaria as reference units outlines the essential strategic directions for Romania, highlighting the need to align innovation policies with models of more efficient use of resources and capitalization of RDI results.

The results indicate the need for collaboration between the public and private sectors in order to increase the efficiency of international RDI systems. From a public policy perspective, it is essential to direct resources towards areas with high potential for innovation and technology transfer, while implementing continuous performance evaluation mechanisms. Basically, higher investments in human capital generate few innovative results, compared to reference countries. Table 5 transposes the necessary adjustments related to the inputs, in order to achieve performance.

Table 5 summarizes for each CEE country, the current levels of resources allocated to R&D and how much should be adjusted to achieve the Technical Efficiency calculated by the DEA model. The 5 countries – Bulgaria, Latvia, Lithuania, Poland and Slovenia define the frontier; therefore, they do not have to adjust their resources, presenting an allocation of inputs harmonized with the outputs of RDI systems. However, within the Input-oriented model, for the countries with a Score θ < 1, the Target values are lower than the Actual ones, indicating a relatively inefficient use of resources compared to the reference units. This suggests that the same results can be achieved with fewer inputs, making it easier to reallocate surpluses to centers of excellence and projects capable of generating patents and measurable technological results.

In the case of Romania, the Target values reflect a need for a more pronounced adjustment of Gross Domestic Expenditure (GERD) and Business Enterprise Expenditure (BERD), given that total R&D Expenditure accounted in 2024, for only 0.46 % of GDP and 72.8 % of employees in the field carried out Full-Time (FTE) activity, compared to the actual number of hours worked (AGERPRES, 2025).

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Table 5

Actual and Target levels of Input variables according to DEA-CCR model

Countries (DMUs)	**General Score of Efficiency (θ)**	**Actual Values**			**Target Values**		
		X1: R&D expenditures by sectors of performance (% of GDP)	*X2: Gross Domestic Expenditure on R&D (GERD) at national level (million EUR)*	*X3: Business Enterprise Expenditure on R&D (BERD) by activity and type of expenditure (million EUR)*	*X1: R&D expenditures by sectors of performance (% of GDP)*	*X2: Gross Domestic Expenditure on R&D (GERD) at national level (million EUR)*	*X3: Business Enterprise Expenditure on R&D (BERD) by activity and type of expenditure (million EUR)*
Bulgaria	1.000	0.77	804.857	524.120	0.77	804.857	524.120
Czech Republic	0.851	1.82	5,847.024	3,783.383	1.54	4,180.248	2,668.974
Croatia	0.671	1.35	1,160.008	636.107	0.90	779.485	427.442
Estonia	0.940	1.99	791.064	472.228	1.63	743.673	339.721
Greece	0.841	1.54	3,655.331	2,001.481	1.29	1,668.161	1,079.789
Latvia	1.000	0.92	372.643	135.996	0.92	372.643	135.996
Lithuania	1.000	1.04	825.347	335.918	1.04	825.347	335.918
Poland	1.000	1.41	11,955.521	7,567.626	1.41	11,955.521	7,567.626
Romania	**0.891**	**0.46**	**1,624.214**	**1,043.183**	**0.40**	**1,041.308**	**665.364**
Slovakia	0.833	0.98	1,278.787	767.835	0.81	955.565	620.148
Slovenia	1.000	2.16	1,458.002	1,012.104	2.16	1,458.002	1,012.104
Hungary	0.844	1.31	2,696.840	2,038.333	1.10	2,263.761	1,451.138

Source: Author with DEAFrontier™ based on statistical data

Table 6

Potential rates of improvement in the efficiency of RDI systems in CEE countries (DEA-CCR)

Countries (DMUs)	**Input Variables**			**Input Slacks (CRS)**		
	X1: R&D expenditures by sectors of performance	*X2: Gross Domestic Expenditure on R&D (GERD) at national level*	*X3: Business Enterprise Expenditure on R&D (BERD) by activity and type of expenditure*	*X1: R&D expenditures by sectors of performance (% of GDP)*	*X2: Gross Domestic Expenditure on R&D (GERD) at national level (million EUR)*	*X3: Business Enterprise Expenditure on R&D (BERD) by activity and type of expenditure (million EUR)*
Bulgaria	0.00%	0.00%	0.00%	0.000	0.000	0.000
Czech Republic	−15.38%	−28.50%	−29.45%	0.000	799.247	553.065
Croatia	−33.33%	−32.80%	−32.80%	0.000	0.000	0.000
Estonia	−18.09%	−5.99%	−28.05%	0.239	0.000	104.217
Greece	−16.23%	−54.36%	−46.05%	0.000	1,408.189	604.670
Latvia	0.00%	0.00%	0.00%	0.000	0.000	0.000
Lithuania	0.00%	0.00%	0.00%	0.000	0.000	0.000
Poland	0.00%	0.00%	0.00%	0.000	0.000	0.000
Romania	**−13.04%**	**−35.88%**	**−36.21%**	**0.000**	**406.055**	**264.233**
Slovakia	−17.34%	−25.27%	−19.23%	0.000	110.409	19.905
Slovenia	0.00%	0.00%	0.00%	0.000	0.000	0.000
Hungary	−16.03%	−16.05%	−28.80%	0.000	12.954	269.655

Source: Author with DEAFrontierTM based on statistical data

Table 6 shows both the relative reduction percentages of inputs and the absolute volumes of slack that can be eliminated by most CEE countries for optimal efficiency.

Based on the results in the previous table (5), the relative values to the left of table 6 reflect the potential input reduction rates calculated using formula 1.

$$\Delta\% = \frac{\mathrm{Vf} - \mathrm{Vi}}{\mathrm{Vi}} * 100 \qquad (1)$$

Vf represents the Target value determined by the DEA model, while Vi is the Actual value (Mathwords, 2026). Therefore, the 5 reference countries still do not require adjustments, which suggests that the current allocation of their resources is the optimal one. The other countries – Croatia, Czech Republic, Estonia, Greece, Romania, Slovakia and Hungary, according to the model used, present the need for reductions in inputs, especially on R&D expenditures by sectors of performance (% of GDP), which signals a relative over-utilization of resources compared to the frontier. In addition, the absolute Slack Input (S^{-}) values to the right of table 6 indicate resource surpluses that can still be eliminated after the percentage adjustment to achieve full efficiency. In particular, Czech Republic, Greece and Romania highlight large volumes of Slack in Gross Domestic Expenditure (GERD) and Business Enterprise Expenditure (BERD), reflecting a pronounced potential for efficiency in the allocation of resources for RDI systems, compared to efficient countries.

These results clearly show that most CEE countries can improve the efficiency of resource allocation by reducing inputs to RDI systems both proportionally and in absolute terms, in order to approach the efficiency frontier set by the DEA model. Also based on the absolute Slack values, but also according to the Radial Efficiency, the forms of efficiency – weak or strong of the CEE countries for the year 2024, can be determined as follows in table 7.

Table 7

Establishing the forms of efficiency of RDI systems in CEE countries according to DEA-CCR

DMU No.	Countries (DMUs)	General Score of Efficiency (θ)	Radial Efficiency	Input Slacks (CRS)
1.	Bulgaria	1.000	$\theta = 1$	$S^{-} = 0$
2.	Czech Republic	0.851	$\theta < 1$	$S^{-} > 0$
3.	Croatia	0.671	$\theta < 1$	$S^{-} = 0$
4.	Estonia	0.940	$\theta < 1$	$S^{-} > 0$
5.	Greece	0.841	$\theta < 1$	$S^{-} > 0$
6.	Latvia	1.000	$\theta = 1$	$S^{-} = 0$
7.	Lithuania	1.000	$\theta = 1$	$S^{-} = 0$
8.	Poland	1.000	$\theta = 1$	$S^{-} = 0$
9.	**Romania**	**0.891**	$\boldsymbol{\theta < 1}$	$\boldsymbol{S^{-} > 0}$
10.	Slovakia	0.833	$\theta < 1$	$S^{-} > 0$
11.	Slovenia	1.000	$\theta = 1$	$S^{-} = 0$
12.	Hungary	0.844	$\theta < 1$	$S^{-} > 0$

Source: Author with DEAFrontier™ based on statistical data

Within the DEA analysis, the θ score not only has a technical role of proportional (radial) scaling of variables, for the design of a DMU on the efficiency frontier, but also an important interpretative role in differentiating between weak and strong efficiency (Pareto-Koopmans). Based on table 7, the 5 CEE countries – Bulgaria, Latvia, Lithuania, Poland and Slovenia, with an Efficiency Score of 1 and a Slack Input of 0, do not require proportional adjustments on inputs as they may affect outputs. Therefore, they can be considered efficient in the full sense of the DEA model, reflecting strong efficiency. In contrast, the Czech Republic, Estonia, Greece, Slovakia, Hungary and Romania have a Score θ below 1 and a Slack Input > 0, which signals inefficiency, in that there is both a possible radial reduction in inputs and surpluses of resources that are not used efficiently.

Returning to the situation in Romania, according to INS data presented by AGERPRES (2025), even though human and financial resources in the RDI sector have increased, their impact on innovative results remains limited, compared to countries on the efficiency frontier. The investment structure is dominated by low capital expenditure and mainly geared towards equipment (71 %) and financing is mainly concentrated in the private (53.6 %) and public (28.4 %) sectors (AGERPRES, 2025). In this context, the capacity to convert resources into innovation and economic performance remains relatively low (~ 11 %), according to Score θ equal to 0.891.

However, a particular case is the situation of Croatia, given that it has a Score θ below 1, but does not exhibit Input Slack, meaning that there are no excess inputs that can be reduced after the radial adjustment. According to the DEA-CCR model, Croatia's efficiency problem stems exclusively from the performance of the outputs, with a Slack Output of ~ 17 % related to the variable Y1 – No. of patent applications at the European Patent Office (EPO). This result is in line with the European Innovation Scoreboard (2024), which indicates for Croatia a level of 17.6 % of the EU average for patents related to the environmental technologies.

Private sector involvement in R&D activities needs to be stepped up for most CEE countries, as it helps to increase the BERD component and turn innovations into commercial products. Given the types of efficiency highlighted, it is necessary to move to table 8 to assess whether they have been maintained or fluctuated, in the period 2020-2024.

Table 8

Evolution of the General Efficiency Scores (θ) of RDI systems in CEE countries (2020-2024)

DMU No.	**Countries (DMUs)**	**2020**	**2021**	**2022**	**2023**	**2024**
1.	Bulgaria	1.000	1.000	1.000	1.000	1.000
2.	Czech Republic	0.826	0.819	0.799	0.908	0.851
3.	Croatia	0.769	0.745	0.657	0.706	0.671
4.	Estonia	0.800	1.000	1.000	0.918	0.940
5.	Greece	0.910	1.000	0.990	1.000	0.841
6.	Latvia	1.000	1.000	1.000	1.000	1.000
7.	Lithuania	0.917	1.000	1.000	1.000	1.000
8.	Poland	1.000	1.000	1.000	1.000	1.000
9.	**Romania**	**0.907**	**0.829**	**0.819**	**0.791**	**0.891**
10.	Slovakia	0.903	0.836	0.731	0.795	0.833
11.	Slovenia	1.000	0.909	0.928	0.879	1.000
12.	Hungary	0.802	0.753	0.807	0.844	0.844

Source: Author with DEAFrontier™ based on statistical data

Overall, the results in table 8 highlight structural differences between RDI systems in the CEE region, indicating that performance is conditioned not only by the volume of resources, but also by their ability to exploit them efficiently. A group of countries (peers) are emerging with consistently high efficiency such as Bulgaria, Latvia and Poland, which remain on the efficiency frontier throughout the analyzed period, confirming a stable and efficient use of RDI resources. Lithuania and Slovenia are approaching this profile, frequently reaching maximum efficiency, which indicates a progressive strengthening of innovation systems.

In contrast, countries such as the Czech Republic, Estonia and Greece show oscillating developments, alternating between periods of high efficiency and decreases, which suggests difficulties in maintaining a constant performance. Croatia and Slovakia also have relatively low and unstable levels of efficiency, indicating persistent dysfunctions in the use of resources. And Hungary shows a moderate evolution, with a slight trend of improvement, but without reaching the efficiency frontier.

In the case of Romania, the evolution of θ Scores indicates a downward trend in the period 2020-2023 followed by a recovery in 2024, which reflects an unstable use of resources for the RDI system. Although the level of efficiency of this DMU remains relatively close to the frontier, it is lower than that of the reference countries, suggesting the existence of Technical Efficiency losses.

This dynamic between RDI systems suggests both the presence of structural dysfunctions in the period under review and a potential for recent improvement which could be strengthened through policies aimed at increasing resource efficiency and alignment with good regional practices. Some of the observed dysfunctions can also be associated with the impact of recent external crises, COVID-19 pandemic and the Russia-Ukraine conflict, which have generated significant disruptions on research activities, collaborations and the economic environment.

5. Conclusions

The analysis of the efficiency of the Research, Development, and Innovation systems in the countries of Central and Eastern Europe highlights the existence of significant structural differences between states, both in terms of the level of resources allocated and their capacity to capitalize on them. The results obtained by applying the Input-oriented DEA-CCR model confirm that the performance of innovation systems is not determined exclusively by the volume of investments, but especially by the efficiency with which they are transformed into concrete results, patents or specialized human capital.

Thus, Bulgaria, Latvia, Lithuania, Poland and Slovenia stand out for their strong efficiency, setting the frontier of efficiency and can be considered benchmarks for the implementation of good practices in the region. On the other hand, most countries in the region experience inefficiencies associated with decreasing scale yields (DRS), which indicates the existence of dysfunctions in the use of available resources. This result suggests that simply increasing expenditure on RDI is not enough, requiring a reconfiguration of the way they are distributed and managed. The good practice models identified offer clear directions, as Poland stands out for its ability to generate a high volume of outputs, Bulgaria for its efficiency in the use of limited resources and Slovenia for its balance between public funding and private sector involvement. In addition, the dynamics of the Baltic States reflect a rapid structural adaptation and an efficient orientation of investments towards innovative results.

A distinct aspect highlighted by the analysis is the case of Croatia which, although it does not exhibit Input Slack, registers Output Slack, indicating a particular problem of inefficiency. This means that even after the proportional adjustment of inputs, the RDI system fails to generate the potential level of innovative results. In economic terms, Croatia uses resources without significant excesses, but its performance is limited by a low capacity to convert them into outputs, suggesting the need for measures aimed at increasing research productivity and the impact of innovation, not just optimizing resource consumption.

In the case of Romania, the results indicate an efficiency relatively close to the frontier, but insufficient to place it among the performing countries. The main advantage is the existence of increasing scale yields (IRS), which signals a high potential for development. Increasing investment in RDI could lead to significant improvements in output. However, the extremely low level of funding, the limited involvement of the private sector and the low capacity to harness innovative results are major obstacles. In addition, the existence of Slacks at the input level indicates that existing resources are not being used efficiently, which emphasizes the need for structural reforms.

However, the results must be interpreted in the context of methodological limitations. The exclusive use of the Input-oriented CCR model, based on the CRS hypothesis, narrows the perspective of the analysis and does not fully capture the complexity of the innovation process. In this respect, the use of alternative models such as Output-oriented or SBM (Slack-Based Measure) models, could provide a more detailed assessment of inefficiencies.

This research paper contributes to the literature by applying the DEA model to recent data for 2024, providing an up-to-date comparative picture of the efficiency of RDI systems in CEE countries. At the same time, it integrates relevant indicators both from the perspective of financial resources and human capital, highlighting the complex relationship between inputs and outputs. The identification of reference countries and target levels of input provides important practical directions for informing public policies and development strategies in the field of innovation.

To strengthen innovation ecosystems in CEE countries, it is recommended that the public sector increase the funding of RDI schemes, while focusing on resource efficiency, targeting strategic areas and stimulating technology transfer between universities, research institutes and companies. In parallel, the private sector should increase its own investments in R&D, but also actively engage in applied innovation projects, contributing to capitalizing on the knowledge and technologies developed. Close collaboration through Public-Private Partnerships can bring more opportunities, including facilitating the adoption of efficient innovation models, developing technologies with practical applicability, increasing competitiveness, and reducing gaps with Western European countries.

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