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Green Efficiency Metrics using Meta-frontier and DEA Models

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Introduction

In the pursuit of sustainable development, measuring green efficiency how effectively industries balance economic output with environmental responsibility has become essential. As global industries face mounting pressure to reduce emissions, optimize resource use and shift toward low-carbon operations, tools that can accurately evaluate their environmental and operational performance are increasingly vital. Traditional productivity assessments often overlook environmental externalities, failing to capture the real impact of industrial activities on ecosystems.

To address this gap, Green Total-Factor Productivity (GTFP) has emerged as a key metric, combining resource inputs, economic outputs and environmental indicators like pollution and emissions. Two prominent analytical methods used to measure GTFP and green efficiency are the Meta-Frontier approach and Data Envelopment Analysis (DEA). These models allow for comparative efficiency assessments across heterogeneous units or regions, accounting for differing technologies, environmental standards and resource constraints. By leveraging these models, policymakers and industrial stakeholders gain robust insights into sustainability performance, helping drive greener industrial transitions and more equitable benchmarking systems [1].

Description

Data Envelopment Analysis (DEA) is a non-parametric technique that evaluates the relative efficiency of Decision-Making Units (DMUs), such as firms, factories, or regions, by comparing multiple inputs (e.g., labor, energy, capital) to multiple outputs (e.g., products, services) and undesirable outputs (e.g., emissions, waste). In green DEA models, undesirable outputs are included to reflect environmental performance more accurately. This makes DEA particularly valuable for assessing eco-efficiency, as it can measure how well entities convert inputs into desirable outputs while minimizing environmental harm. When applied to resource-intensive industries such as mining, quarrying, or metal manufacturing, DEA helps identify leaders in green efficiency and flag areas needing improvement. One major advantage of DEA is its flexibility it doesn't assume a fixed functional relationship between inputs and outputs, making it suitable for complex, real-world industrial systems. Moreover, it facilitates peer-to-peer benchmarking, allowing less efficient units to learn from best-performing counterparts. However, DEA's limitation is its sensitivity to sample selection and its inability to handle differences in technological environments across regions or sectors.

To overcome such limitations, the Meta-Frontier approach is used in tandem with DEA. The Meta-Frontier model allows comparison among groups with different technologies by constructing a common frontier that envelopes group-specific frontiers. This is particularly useful when analyzing green productivity across regions, sectors, or countries that operate under varying environmental regulations and technological maturity levels. For example, a metal manufacturing plant in one region may have access to advanced emission-reducing technologies, while another in a different area may operate with older infrastructure. A conventional DEA model might unfairly penalize the latter, whereas the Meta-Frontier framework accounts for such heterogeneity, allowing for fairer and more accurate performance assessment. Additionally, this model can quantify the Technology Gap Ratio (TGR), which indicates how far a specific unit is from the optimal (meta) frontier, helping policymakers design tailored interventions. By combining DEA with the Meta-Frontier approach, analysts gain a multidimensional perspective on industrial sustainability one that respects regional diversity while promoting accountability and continuous improvement [2].

Conclusion

Green efficiency metrics derived from DEA and Meta-Frontier models provide a comprehensive, fair and actionable framework for evaluating environmental performance in complex industrial settings. These tools support informed decision-making by identifying best practices, highlighting inefficiencies and enabling technology benchmarking across heterogeneous units. As industries transition toward greener operations, adopting these models can help align economic growth with environmental responsibility, ensuring that sustainability goals are met without compromising productivity or equity.

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Conflict of Interest

None.

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