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Evaluating the Energy Supply Chain in the Petrochemical Industry with the Cost Malmquist Productivity Index Approach and Fuzzy VIKOR Considering the Importance Coefficient of Input Variables

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Highlights

- Determining the important inputs and outputs of the energy supply chain in the petrochemical industry using the fuzzy VIKOR method;
- Choosing the “production of goods and services” variable as the output and the variables of machines used in production (physical capital), workers, and materials (such as fuel) consumed in production as the inputs;
- Combining the fuzzy VIKOR method (a qualitative method) and an energy efficiency assessment model (a mathematical model) to provide a better evaluation with fewer calculations;
- Providing a mathematical efficiency assessment model according to the type of input variables to reduce input costs;
- Entering desirable and undesirable output variables, including waste of petrochemical industries, in the mathematical efficiency assessment model;
- Determining the inefficient petrochemicals and helping them with their reduced efficiency by reviewing the programs of efficient petrochemicals;
- Determining the variations in total efficiency, CTC, and OEC during two consecutive years and using CMPI to compare the efficiency of the petrochemical for these two years;

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Abstract

This study was conducted to evaluate the energy supply chain in the petrochemical industry with the approach of Malmquist cost efficiency index and fuzzy VIKOR, taking into account the importance coefficient of input variables. After reviewing the literature, the inputs and outputs of the energy supply chain were first identified. Then, the influential variables in the petrochemical industry in the energy supply chain were identified and prioritized with the fuzzy VIKOR approach. Next, the weight of the input variables was calculated using the geometric mean, and the input variables were entered into the mathematical model based on their weight. Based on the input type, a mathematical model was developed to estimate input costs to ensure output and supply chain efficiency in two consecutive years. Then, the Malmquist cost index was estimated based on the model outputs. The petrochemical company with the highest Malmquist total cost index and the lowest output cost was selected as the optimal solution of the model. The value of the objective function indicates the input costs. Our inputs include two variables: the number of employees and the value of materials used in fuel reproduction. Petrochemicals 9, 7, 12, 10, 6, 5, 3, 4, 13, 11, 2, 8, 1, and 14 respectively have the lowest input costs, which is necessarily due to the efficiency of the petrochemicals; the efficiency of the petrochemicals is checked. The

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cost return is calculated from the relevant formula in the years 2021 and 2022. As seen, the yield in 2021 in petrochemicals 1, 11, 7, 13, and 14 is 1. The ratio of the outputs to the inputs is higher, so they are efficient. In petrochemicals 1, 7, 14, and 11, it is greater than 1 in 2022. Therefore, the output to input ratio is more efficient. Overall efficiency change (OEC) examines the changes in cost efficiency over the period in question and reflects the displacement value and the efficiency frontier. Evaluating the energy supply chain model in the petrochemical industry using the Malmquist productivity index can help reduce production costs, better evaluate the industry, and formulate future policies for companies active in this field.

Keywords: Energy supply chain, Energy supply chain efficiency, Fuzzy VIKOR, Supply chain input and output, Cost Malmquist index

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1. Introduction

Evaluating the energy supply chain in the petrochemical industry through the lens of the Malmquist productivity index and fuzzy VIKOR involves a multifaceted approach that integrates productivity measurement and decision-making under uncertainty. This analysis can help identify efficiencies and areas for improvement within the supply chain, which is critical given the industry's complexity and reliance on various input variables. Organizations require a planned partnership with their suppliers and customers to create a competitive advantage. Thus, determining the supply chain model in different industries can help the economic dynamics of countries (Sarkar and Seo, 2021). Nowadays, supply chain design and optimization decisions reduce supply chain costs and create a competitive advantage over other competitors. It plays a vital role in the development and sustainability of industries (Altay and Pal, 2023). It is also considered a basis for improving the cost efficiency of industries (Fallah Lajimi et al., 2020). Thus, the energy supply chain helps the petrochemical industry reduce the competitive costs of companies in the production of hazardous materials and the value of waste production of factory and electronic equipment, and increase the waste recycling capability of companies (Zhai et al., 2019). Thus, this study uses the Malmquist productivity index as a basis for reducing production costs to evaluate the energy supply chain model in the petrochemical industry. Malmquist productivity index (MPI), as a relative performance index, shows the gap between outputs and inputs under constant technology conditions at different times (Bayat et al., 2022). In this method, the productivity is measured with the linear programming method for input and output without the limitation of production technology, and the production curve is created for each input and output; the production technology is also specified (Köse and Özbuğday, 2018). The Malmquist index can be used when the prices of inputs are specified, and the decision makers seek to minimize costs. Thus, cost efficiency changes are one of the factors affecting the process of the decision-making unit over time (Mirzaeian and Fallahnejad, 2021). The fuzzy VIKOR method is a multicriteria decision-making approach that addresses uncertainty in evaluating alternatives based on conflicting criteria. It is particularly useful in environments where input variables are not precisely known, allowing for a more nuanced analysis of trade-offs (Yanget al., 2010).

According to their conditions and requirements, different countries have followed various competitive models to develop the value chain of the oil and gas industry, thereby creating more added value. Based on the experience of other countries, in line with the implementation of the value-added chain development strategy, Iran faces four models of "integration of different levels of the oil and gas industry", "relying on advanced technologies and license design", "encouraging and creating competition in the industries related to oil and gas", and "combined look at refining and petrochemical industries and creating more added value". In this regard, in the downstream part and the value chain of Iran's petrochemical industry, there was 25 million tons of production capacity for essential products in 2018, 36% of which was related to methanol production, 29% was related to ethylene production, 20% was associated with the production of ammonia, and 9% was related to the production of aromatics, including benzene, toluene, and xylene. In this context, about 63% of the feed of basic (semi-crude) products is gas, including natural gas (methane), ethane, and rich gas, and about 38% of the feed of these products is related to liquid petroleum and gas products (Bayat et al., 2022).

Cost Malmquist productivity index (CMPI) is a criterion that can be considered in evaluating supply chain dynamics. Proposed first by Xu et al. (2022), this index estimates the optimal point of productivity using the inputs and outputs of the supply chain based on environmental changes. It also determines the impact of cost control on increasing the supply chain effectiveness by combining technology and efficiency changes in different industries simultaneously (Ilyas and Rajasekar-an, 2019). The primary advantage of using the cost Malmquist index is to determine the changes in allocative efficiency and the price effect, which helps the dynamics of productivity in determining cost-decomposable resources (Walheer, 2018). The energy supply chain, as a crucial part of the competitive functions of industries, especially parent industries such as petrochemicals, plays a vital role in maintaining the competitiveness and continuous improvement of companies operating in this industry (Giampieri et al., 2020). Innovations like the cost Malmquist productivity index and fuzzy VIKOR significantly enhance the evaluation processes within the petrochemical industry's energy supply chain. By leveraging these methodologies, organizations can improve productivity assessments and make informed decisions that align with their operational goals and sustainability objectives. Thus, this study uses the cost Malmquist productivity index to evaluate the petrochemical industry in the energy supply chain and reduce supply chain costs. After analyzing the energy supply chain in the petrochemical industry, the inputs and outputs of the energy supply chain are identified and ranked. Then, the optimal efficiency point is evaluated in terms of cost.

2. Literature review

2.1. Theoretical framework

In a sustainable supply chain, organizations must consider profitability and competitive advantage on the one hand, and waste elimination and minimization on the other hand. Sustainable supply chain management involves an assessment of socioeconomic and environmental factors associated with the supply chain. In this regard, organizations must always pay attention to factors associated with quality social service provision, such as respect for human rights, education, health, gender equality, occupational safety, and workplace quality. In a sustainable environmental system, it is necessary to maintain the sustainable resources and be frugal in the consumption of nonrenewable energies. It is also important to keep a constant watch on the consumption of energy and water. In order to have a sustainable economic system, goods and services must be constantly produced with high quality. We must also continuously try to improve the quality of our products in order to meet all customer needs. Furthermore, we can take a huge step toward customer satisfaction by providing long-term guarantees. In many organizations, managers make their decisions for reaching organizational goals based on the progress or regression of the decision-making units. Therefore, organizations that form a supply chain are quite important in terms of the two-stage processes they have and the sustainability of economic, environmental, and social conditions.

The Malmquist productivity index is an indicator of changes in units in two consecutive periods of time. This index is defined as the ratio of differences in the unit's efficiency scores between two different points in time. Among advantages to the MPI is the fact that we can divide it into two parts, namely changes in the efficiency frontier and changes in the efficiency scores at two different times.

The work of B. Walheer (2018) reported the use of the cost Malmquist productivity index for the assessment of joint and output-specific inputs. Z. Li engaged in the prediction of financial risks in 742 Chinese companies using the MPI. Finally, D. Fern´andez used the MPI to evaluate 34 Air Separation Units (ASUs) in Europe and Asia. Considering the significance of supply chain evaluation in Iranian oil refineries, the current study uses the Malmquist productivity index for this purpose in a two-stage network consisting of suppliers and producers.

Yakovteva et al. (2012) studied three dimensions of supply chain sustainability for potato production companies in the UK. Moreover, Shafiee et al. used the BSC method to evaluate network-based supply chains, as well as the food supply chain in Iran. Later on, Nikfarjam et al. (2018) used specific forms of a hybrid model to assess a supply chain of seven DMUs. In the study conducted by Ding et al., supply chain sustainability was evaluated based on environmental factors in a case study relating to the impact of business on China's environment. Motevati Haghighi et al. used the DEA-BSC model to assess network-based models of supply chain and do research on 40 plastic recycling companies. Farzipoor Saen et al. (2013) reported a study of two stages. Fathabadi and Soufimajidpour (2019) investigated the technical efficiency and total productivity changes using the Malmquist productivity index in manufacturing industries using data envelopment analysis and stochastic frontier analysis. Variables of capital stock, including machinery and equipment, research and development, human capital, and information technology were selected as the input and the production rate as the output. Mohammad Gholiha et al. (2021) investigated the relationship between financial investment and Malmquist multiple productivity indices in a network structure in service centers. They used data envelopment analysis to design two stages of construction and operation for five consecutive years. Doroudi et al. (2022) investigated productivity using Malmquist productivity index in private insurance companies in Zanjan province. They used the data envelopment analysis and stochastic frontier analysis. In the mentioned study, the variables of insurance cost, number of personnel, and arrears value were selected as input and the variables of absorbed resources, consumptions, and number of customers were considered output variables (Hashemi et al., 2023).

2.2. Background

Numerical indexes are important in measurement of productivity and its changes. The Malmquist productivity index is one of the indices with such characteristics. The MPI is used to determine the amount of change in the productivity of all production factors. One the interesting attributes of this index is that calculating it does not require any information on the prices of production factors and products, which is often difficult or impossible to collect. This index does not aim to maximize profits or minimize costs but rather tries to make changes in the technical efficiency and influence the technology through this change. The mathematical model of the Malmquist index is defined based on a distance function, in which the productivity changes in all production factors between two data points are measured based on the distance of each point to a common technology. Distance functions can be used in measurement and analysis of efficiency and productivity. The distance function can be approached from two aspects: 1) based on inputs or production factors, which is known as the input distance function and focuses on the minimum consumption of production factors, and 2) based on outputs, which is known as the output distance function and focuses on the maximum production of outputs. Interestingly, the attribute of returns to scale in production is of great importance in the Malmquist productivity index.

In the majority of organizations, we can design and then evaluate a network based on the vectors of inputs, outputs, and intermediate measures although the type of data in these vectors, such as fuzzy, random, and binary, is of great consequence. However, after disregarding imprecise data, certain vectors in the DEA network could still be either desirable or undesirable. For instance, in the example of bottled water manufacturing companies, lack of control on the returning of plastic bottles into the production cycle could be considered an undesirable environmental factor. Furthermore, the incorrect use of water resources can be an economic, social, and environmental factor in the supply chain. Similarly, the culture of using bottled water would improve public health levels in society, thereby influencing the social factors. In the following, a two-stage network process with undesirable outputs is illustrated for a two-stage supply chain.

Gholizadeh et al. (2022) investigated the productivity fluctuations of Iran's grain production factors for different products using the Malmquist and Hicks–Moorsteen indices. Their results revealed that the changes in the three indices were mostly due to improvements in technological changes and optimal consumption of inputs. Emami Meybodi and Wahabi (2022) studied the efficiency of companies affiliated with the armed forces using the Malmquist index and the data envelopment analysis. They used the bootstrap method to correct the skewness of the results and inefficient companies and determined the efficiency and the growth rate of productivity in efficient companies using the Malmquist index. Darvish Trustee et al. (2023) presented a Malmquist productivity index based on the data envelopment analysis in the sustainable supply chain of the electricity industry. They determined the productivity level in addition to efficiency. Variables of fuel cost, the value of consumption, the capacity of substations, the length of transmission lines, production, and transmission capacity were selected as the input, and pollutant gas, subscriber damage coefficient, energy loss, and cost were considered the output variables (Keyghobadi et al., 2020).

Farashah et al. (2021) determined the factors affecting the development of the petrochemical industry and modeled the mechanism of creating capacity increase using a dynamic approach. This study needed a tool to analyze the complexities, model the industry structure to an acceptable level of detail, and include nonlinear and feedback relationships between variables. The tool should also use the built model to provide practical solutions to various stakeholders and policymakers. For this purpose, the system dynamics (SD) approach was used. The obtained results pointed out the policy solution of program improvement and budget allocation as the most effective solution to achieving the development of the petrochemical industry.

Mirzaeian and Fallahnejad, (2021) analyzed the transactions of the Iranian stock market by cost Malmquist productivity index using data envelopment analysis in the presence of nonidentical prices for different DMUs in two periods. They used Farrell's CE deficiency model and Tone's CE model. Zhou et al. (2021) investigated the energy performance of the electricity industry in China using the cost Malmquist productivity index. They considered variables of energy consumption, auxiliary electricity consumption, installed capacity, and employees as the input variables and electricity generation and GDP as the output variables. They estimated the energy cost efficiency for three areas and used the Boston Consulting Group (BCG) matrix to analyze the estimated results of CMPI and compare them (Rowshanali et al., 2022).

Cho and Chen (2021) studied the impact of financial technology on China's banking industry using the cost Malmquist index. They showed that the growth rate of cost efficiency increased as the share of banks in mobile device transactions and the volume of third-party payment transactions of banks rose.

Liu et al. (2021) evaluated the growth of green productivity in the road transport industry at the provincial level using the global Malmquist–Luenberger index in China. They calculated this index based on data envelopment analysis and directional distance function and compared the fluctuations and productivity trends in the transportation industry by this index. They selected the value of highway entry, the number of operating vehicles, the number of vehicles, the number of employees, and the standard consumption of coal as the input. They also considered the variables of the volume of passenger circulation and the volume of goods circulation as the desired output and assumed the value of CO_2 emissions, the rate of traffic accidents, and the level of produced noise as the undesirable output.

Hassanpour and Karami (2022) used data envelopment analysis and the Malmquist index to calculate total factor productivity (TFP), analyze its constituent components (the growth of technical efficiency and technological changes), and compare the mean growth of productivity and efficiency. Walheer (2022) presented the global cost Malmquist index to evaluate performance in nonlinear data conditions, data measurement in different conditions, and uncertainty conditions. In the proposed method, only input and output data were required, and MI could be divided into several components; a common technology was also used under common input prices. Pourmahmoud and Bagheri (2023) evaluated healthcare systems during the coronavirus epidemic in the uncertainty conditions by the Malmquist index. The GDP per capita (nominal), the number of hospital beds per patient, the number of physicians per patient, the number of each nurse per patient, the mean number of patients, and days of exposure were selected as the input, and mean recovery and mean mortality were considered the output variables. Decomposing the MPI into efficiency changes and technical changes showed that the increase in productivity was associated with a gradual shift in the policymaking-related production frontier.

Zhu et al. (2024) presented a nonparametric mathematical model to evaluate production processes based on the cost Malmquist index for the joint production of desirable and undesirable outputs. The objective function of their proposed model was to maximize production and minimize resource costs. The variables of equity, the number of employees, the number of branches, and the value of loans were selected as the input and the variables of the value of profit, the value of noninterest income, and noncurrent loans were selected as the output variables. The bank branches were also examined and compared in terms of productivity improvement. Yaman et al. (2024) evaluated the total productivity of agricultural production factors in the provinces of Turkey using the Malmquist index. This index was used to investigate the rate of change in productivity and efficiency of production factors. The variable of agricultural gross domestic product was selected as the output variable and the total number of agricultural equipment and machines, the number of enterprises based on business records, the total arable area for agriculture, the total number of live live-stock, and electricity consumption for agricultural irrigation were selected as the input variables.

Savchina et al. (2021) analyzed the financial situation, evaluated the development prospects, and optimized the activity of one of the largest systemically important organizations of the petrochemical industry in Russia, PJSC. SIBUR Holding has paid in the conditions of macroeconomic instability. To carry out the research, the authors collected financial data from the company's financial results report and balance sheet. They choose the key indicators of performance and solvency, especially liquidity, business activity, profitability, solvency, and investment attractiveness. Further, financial risk factors affecting business expansion opportunities have received particular attention. Econometric modeling methods were used to determine the company's development prospects, which depend on the internal policy of cash flow management, accounts receivable, debt, and the external impact of inflation risk. The research results indicated that continuous cash flow, that is, the formation of a policy for managing accounts payable in crisis conditions, significantly impacted the company's further development.

3. Methodology

This study was applied in terms of purpose since it will lead to finding practical solutions in the field of increasing productivity in the energy supply chain. It is also exploratory research since it seeks to provide an effective model for the dimensions of the cost Malmquist index in the petrochemical industry through thematic analysis. As it uses a mixed method for the implementation of analyses, the analysis tool of the research is presented qualitatively and quantitatively.

3.1. Fuzzy VIKOR

This study used a mixed method based on multi-criteria methods in a fuzzy environment. The program related to fuzzy VIKOR was coded in MATLAB, and the questionnaire data were entered into the code. Then, the inputs and outputs were prioritized based on the fuzzy VIKOR method. As seen, the index with a lower Q value has a higher rank (see Tables 1 and 2).

Table 1

The results of the solution with the fuzzy VIKOR related to the input variables

Input indices	***Q***
The value of materials used in production, such as fuel	0.20962
Number of employees	0.44460
The number of machines used in production (the physical capital)	0.46416
The value of raw materials in production	0.51932
Average salary	0.52009
Financial capital	0.63158
Production capacity	0.84743

Table 2

The results of the solution with the fuzzy VIKOR related to the output variables

Output indices	***Q***
The value of the production of products and services	0.16962
GDP	0.23211
Income	0.60327
The rate of carbon dioxide emissions	0.90542

Based on the Pareto principle (20–80), one output and two inputs were selected. The variables of the value of materials consumed in production (such as fuel) and the number of employees were selected as the input, and the variable of the value of production of products and services was considered the output variables. As seen, the value of materials consumed in production is linear, and the number of employees is constant and uniform.

The coefficients of the input variables in the objective function are obtained from the inverse of dividing each coefficient by the sum of the coefficients as follows (Table 3).

Table 3

The weight of the input variables in the objective function

Input indices	*Q*	Input coefficient
The value of materials consumed in production (such as fuel)	0.20962	0.7
The number of employees	0.44460	0.3

4. Results

4.1. Mathematical model

It is assumed that there are $(DMU_j, j = 1, \ldots, n)$ numbers of production areas (groups) of the thermal power industry. Each petrochemical center is determined as a production area and each unit as a DMU. M is the number of nonnegative input $(x_{ij}^t, i = 1, \ldots, m)$, and s is the nonnegative desirable output $(y_{rj}^t, r = 1, \ldots, s)$; H is the undesirable output $(b_{zj}^t, z = 1, ..., h)$. p_i^t is the cost of uniform inputs i = 1,2, …, $q(x_i^t)$, and $(p_i^k)^t$ $(k = 1, \ldots, t_i)$ are the cost of inputs that change stepwise, i.e. $(p_i^1 < p_i^2 < \cdots < p_i^{t_i})$. In other words, p_i^k for all units is not equal to the same value. It is assumed that the costs for the inputs change in a stepwise manner, and the costs for the first input q change uniformly and are equal to the constant value p_i; the costs for inputs q + 1 to m change stepwise and are equal to the p_i^k value. If v_i^k $(k = 1, \ldots, t_i)$ is the variables corresponding to $x_i (i = 1, \ldots, m)$ in the intervals $[x_i^0, x_i^1)$ and $[x_i^1, x_i^2)$..., $[x_i^{t_{i-1}}, x_i^{t_i})$, $x_i^0 = 0$, and $x_i^{t_i} = \infty$, the cost efficiency of DMU_0 is calculated by the following method: First, $(y_0^t, p_0^t, (p_0^k)^t)$ is calculated by solving the following model. The first function is related to fixed and uniform input variables, and the second function is related to the input price variable. In other words, the model objective function is presented to reduce the input costs related to each unit in petrochemicals and thus cut the total cost, which is presented in the following form.

4.2. Model assumptions

The proposed model assumptions are as follows:

- Efficiency is examined in two periods of 2021 and 2022;
- DMUs in the area *j* seek to minimize input production costs;
- The supply chain is competitive, and the price is determined by the market;
- The input variables or the importance coefficients are entered into the target function;
- The model inputs are linear, fixed, and uniform;
- The supply chain includes several thermal power plants;
- Costs for uniform input variables are considered the same for all units;
- Costs for piecewise linear variables are not considered the same for all units;

The mathematical model variables are presented in Table 4.

Table 4

Variables of the research mathematical model (Alhamad et al., 2021)

Index of production areas (any petrochemical production of electricity)	$\boldsymbol{J} \in (\boldsymbol{j} = 1, 2, \ldots, \boldsymbol{n})$
DMU index (per unit) of thermal power industry	$\boldsymbol{k} \in (\boldsymbol{k} = 1, 2, \ldots, \boldsymbol{t_i})$
A set of periods during the planning horizon	$\boldsymbol{t} \in \{1, \boldsymbol{t}, \boldsymbol{T}\}$

The index related to each entry	$\boldsymbol{i} \in (\boldsymbol{i} = 1, 2, \ldots, \boldsymbol{m})$
Desirable output index	$\boldsymbol{r} \in (\boldsymbol{r} = 1, 2, \ldots, \boldsymbol{s})$
Undesirable output index	$\boldsymbol{h} \in (\boldsymbol{j} = 1, 2, \ldots, \boldsymbol{H})$
Input cost prices of DMU K in period *t*	$\boldsymbol{p_i^k}$
The coefficient related to the production area *j*	$\boldsymbol{\lambda_j}$
The value of input related to the thermal power generation area *j* associated with the DMU *i* in the period *t*	$\boldsymbol{x_{ij}^t}$
Variables corresponding to input $x_i (i = q + 1, \ldots, m)$ for each output in period *t*	$\boldsymbol{v_i^r}$
Input variable coefficient in the objective function	$\boldsymbol{e_i}$
The desirable value of output *r* related to the thermal electricity generation area *j* in the period *t*	$\boldsymbol{y_{rjm}^t}$
The value of undesirable output *z* related to the thermal electricity generation area *j* and DMU *i* in period *t*	$\boldsymbol{b_{ijz}^t}$

$$c^t\,(y_0^t, p_0^t, (p_0^k)^t) = \min \sum_{i=1}^{q} e_i p_i^t x_i^t + \sum_{k=1}^{t_i} \sum_{i=q+1}^{m} e_i (p_0^k)^t (v_i^k)^t \quad (1)$$

$$s.t. \quad \sum_{j=1}^{n} \lambda_j x_{ij}^t \le x_i \qquad i = 1,2,\ldots,q \quad (2)$$

$$\sum_{j=1}^{n} \lambda_j x_{ij}^t \le \sum_{k=1}^{t_i} v_i^k \qquad i = q+1,\ldots,m \quad (3)$$

$$\sum_{j=1}^{n} \lambda_j y_{rjm}^t \ge y_{r0}^t \qquad r = 1,2,\ldots,s \quad (4)$$

$$\sum_{k=1}^{t_i} \lambda_j b_{kjh}^t \le b_{mjh}^t \qquad h = 1,2,\ldots,H \quad (5)$$

$$\begin{aligned} & v_i^k \le x_i^k - x_i^{k-1} \qquad i = q+1,\ldots,m \qquad k = 1,2,\ldots,t_i - 1 \;\; 0\le \\ & \lambda_j \ge 0 \qquad j = 1,2,\ldots,n \\ & v_i^{t_i} \ge 0 \qquad i = q+1,\ldots,m \\ & x_i^{t_i} \ge 0 \qquad i = 1,\ldots,m \end{aligned} \quad (6)$$

Now, $c^t\,(y_0^{t+1}, p_0^t, (p_0^k)^t)$ is calculated by solving the following model:

$$c^t\,(y_0^{t+1}, p_0^t, (p_0^k)^t) = \min \sum_{i=1}^{q} p_i^t x_i^t + \sum_{k=1}^{t_i} \sum_{i=q+1}^{m} (p_0^k)^t (v_i^k)^t \quad (7)$$

$$s.t. \quad \sum_{j=1}^{n} \lambda_j x_{ij}^t \le x_i \qquad i = 1,2,\ldots,q \quad (8)$$

$$\sum_{j=1}^{n} \lambda_j x_{ij}^t \le \sum_{k=1}^{t_i} v_i^k \qquad i = q+1,\ldots,m \quad (9)$$

$$\sum_{j=1}^{n} \lambda_j y_{rjm}^{t+1} \ge y_{r0}^{t+1} \qquad r = 1,2,\ldots,s \quad (10)$$

$$\sum_{k=1}^{t_i} \lambda_j b_{kjh}^{t+1} \le b_{mjh}^{t+1} \qquad h = 1,2,\ldots,H \quad (11)$$

$$v_i^k \le x_i^k - x_i^{k-1} \qquad i = q+1,\ldots,m \qquad k = 1,2,\ldots,t_i - 1 \;\; 0\le \quad (12)$$

$\lambda_j \geq 0 \qquad j = 1,2, \dots, n$
$v_i^{t_i} \geq 0 \qquad i = q+1, \dots, m$
$x_i^{t_i} \geq 0 \qquad i = 1, \dots, m$

The c^{t+1} (y_0^t, p_0^{t+1}) and c^{t+1} (y_0^{t+1}, p_0^{t+1}) values are calculated similarly. Now, the following values are calculated for efficiency:

1. The linear cost efficiency of unit o at time *t* relative to frontier *t*:

$$PLCM_{t0}^{t} = \frac{c^t\ (y_0^t, p_0^t, (p_0^k)^t)}{\sum_{i=1}^{q} p_i^t x_{io}^t + \sum_{k=1}^{t_i} \sum_{i=q+1}^{m} (p_0^k)^t (v_{io}^k)^t} \tag{13}$$

2. The linear cost efficiency of unit o at time *t* + 1 relative to frontier *t*:

$$PLCM_{to}^{t+1} = \frac{c^{t+1}\ (y_0^t, p_0^{t+1}, (p_0^k)^{t+1})}{\sum_{i=1}^{q} p_i^{t+1} x_{io}^t + \sum_{k=1}^{t_i} \sum_{i=q+1}^{m} (p_0^k)^{t+1} (v_{io}^k)^t} \tag{14}$$

3. The linear cost efficiency of unit o at time *t* relative to frontier *t* + 1;

$$PLCM_{t0+1}^{t+1} = \frac{c^{t+1}\ (y_0^{t+1}, p_0^{t+1}, (p_0^k)^{t+1})}{\sum_{i=1}^{q} p_i^{t+1} x_{io}^{t+1} + \sum_{k=1}^{t_i} \sum_{i=q+1}^{m} (p_0^k)^{t+1}\ (v_{io}^k)^{t+1}} \tag{15}$$

4. The linear cost efficiency of unit o at time *t* + 1 relative to frontier *t* + 1:

$$PLCM_{t0+1}^{t+1} = \frac{c^t\ (y_0^{t+1}, p_0^t, (p_0^k)^t)}{\sum_{i=1}^{q} p_i^t x_{io}^t + \sum_{k=1}^{t_i} \sum_{i=q+1}^{m} (p_0^k)^t (v_{io}^k)^t} \tag{16}$$

The Malmquist productivity index is calculated using the following equation:

$$PLCM_0 = \left(\frac{PLCM_{t0+1}^{t+1}}{PLCM_{t0}^{t+1}} \times \frac{PLCM_{t0+1}^{t}}{PLCM_{t0}^{t}}\right)^{1/2} \tag{17}$$

It can be decomposed into the cost efficiency change and cost technical change as follows:

$$PLCM_0 = \frac{PLCM_{t0+1}^{t+1}}{PLCM_{to}^{t}} \times \left(\frac{PLCM_{t0+1}^{t}}{PLCM_{t0+1}^{t+1}} \times \frac{PLCM_{to}^{t}}{PLCM_{t0}^{t+1}}\right)^{1/2} = (OEC) \times (CTC) \tag{18}$$

where $PLCM_0 > 1$ indicates productivity growth, $PLCM_0 < 1$ denotes productivity decline, and $PLCM_0 = 1$ implies that productivity has not changed.

4.3. Solving model

The proposed model was solved by using GAMS software, and the value of *z* was calculated for values c^{t+1} $(y_0^t, p_0^{t+1}, (p_0^k)^{t+1})$, c^{t+1} $(y_0^{t+1}, p_0^{t+1}, (p_0^k)^{t+1})$, c^t $(y_0^{t+1}, p_0^t, (p_0^k)^t)$, and c^t $(y_0^t, p_0^t, (p_0^k)^t)$. The relevant indices that include the Malmquist indices of petrochemical costs were obtained in the years 2021 and 2022, and they were finally compared. Table 5 lists the results.

Table 5

The value of the objective function for the proposed models in 14 petrochemicals

Row	$y_0^t, p_0^t, (p_0^k)^t$	$y_0^{t+1}, p_0^t, (p_0^k)^t$	$y_0^t, p_0^{t+1}, (p_0^k)^{t+1}$	$y_0^{t+1}, p_0^{t+1}, (p_0^k)^{t+1}$
1	530335000	98825633.1	526217000.1	197621858
2	398752050	79715040.2	423211642.2	101036601.6
3	219475111	71412512.9	340323125.1	96212108.2
4	241000765	61659002.1	198744654.4	72420203.1
5	188451334.1	65545136.8	210400220.3	78100252.3
6	152474010	54544072.3	189659200.8	67657010.3
7	100132322.3	56444800.6	171329757.1	65121001
8	435033680.2	158426337.1	548620700.1	186788000
9	65501230.4	23121030.4	105001331.6	232121432.4
10	129032737.3	85510001.3	245003732.2	101754010.9
11	355936000.1	134132102.1	647890000.6	186000329.1
12	101326244.3	31310321.6	189385131.4	269001120
13	267155200.1	112264488.9	465740330	156845618.3
14	749098601.6	254640200.1	867453680	320436002

The value of the objective function indicates the input costs. Our inputs include two variables: the number of employees and the value of materials consumed in the reproduction of fuel. As can be seen, petrochemicals 9, 7, 12, 10, 6, 5, 3, 4, 13, 11, 2, 8, 1, and 14 have the lowest input costs, respectively, but it is necessarily because of the efficiency of the petrochemical; thus, the efficiency of the petrochemicals is checked. The input cost of each petrochemical is compared in Figure 1.

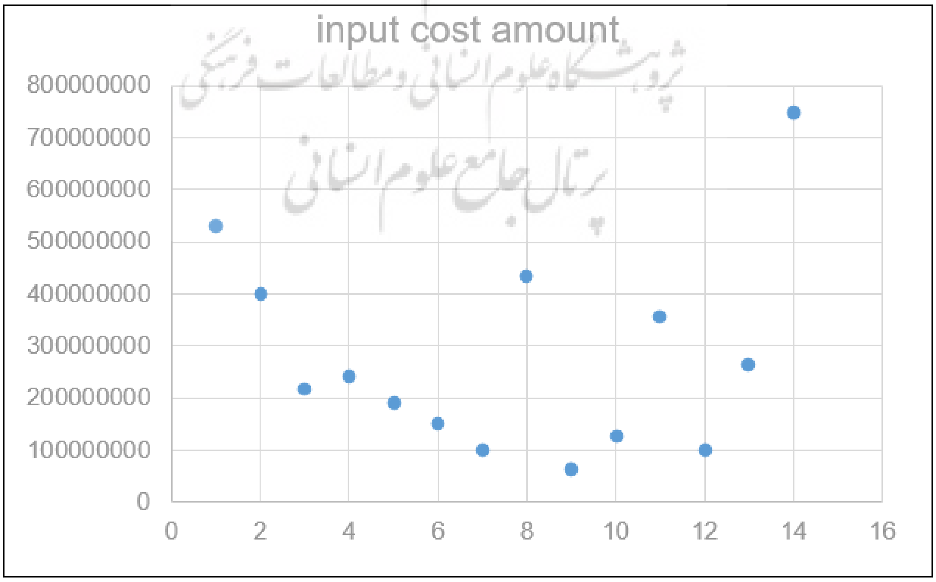

Figure 1

The value of the input cost related to each petrochemical

The cost efficiency is calculated from the relevant formula in 2021 and 2022. As can be seen, the efficiency in 2021 in petrochemicals 1, 11, 7, 13, and 14 is 1. Thus, the ratio of the outputs to the inputs is higher than 1, and they are efficient. It is equal to or larger than 1 in 2022 in petrochemicals 1, 7, 14, and 11. Thus, the ratio of the outputs to the inputs is higher, and they are efficient. In the above tables, OEC investigates the cost efficiency changes in the desired period and reflects the value of displacement and the efficiency frontier. This number indicates that the desired unit has moved away from the efficiency frontier in the desired interval or is closer to it. If this number is greater than one, it will indicate that it is close to the efficiency frontier and positive changes in efficiency over time. In other words, it shows the combined effect of input cost changes and technology changes over time. If this number is greater than one, it will indicate that technology changes have grown over time, and vice versa. The cost technology changes are positive in all units, and the efficiency changes are positive only in petrochemicals 1, 7, 14, and 11. The Malmquist index shows the changes in efficiency over time, and the changes in efficiency are positive only in petrochemicals 1, 7, 8, 11, and 14 (see Table 6).

Table 6

Indices for the proposed models in 14 petrochemicals during two years

Row	1400	1401	OEC	CTC	Malmquist index
1	1	1.142929	1.00417	1.012843	1.017071
2	0.798102	0.618701	0.6415	1.01656	0.652123
3	0.754561	0.554501	0.71118	1.000213	0.711328
4	0.713101	0.514523	0.59217	1.007456	0.59659
5	0.813454	0.626581	0.74136	1.024558	0.75957
6	0.998672	0.794545	0.77998	1.014129	0.791003
7	1	0.147383	1.15252	1.001287	1.154001
8	0.943394	0.998656	0.99399	1.011213	1.005136
9	0.605465	0.347801	0.45852	1.117645	0.512458
10	0.898678	0.617689	0.66102	1.099125	0.726545
11	1	1.128051	1.103772	1.010941	1.115849
12	0.937145	0.661939	0.630521	1.066311	0.672332
13	1	0.711705	0.659553	1.042611	0.687657
14	1	1.290001	1.06214	1.076552	1.143442

Petrochemicals are compared in Figure 2 based on the input cost and the cost Malmquist index. Now, if only the efficiency of petrochemicals is important to the decision-maker, the petrochemical with the highest Malmquist index, which is greater than one, should be selected, that is, petrochemical 7. Now, if only the input cost is important for the decision-maker, petrochemical 9 will be selected with the lowest input cost. If two criteria are important for the decision maker, petrochemical 7 will be selected.

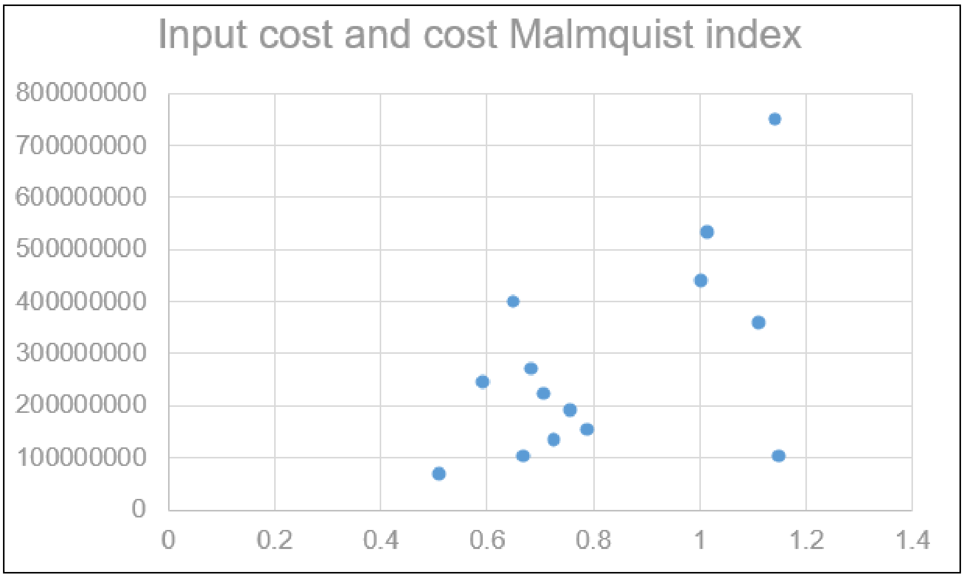

Figure 2

The input cost and the cost Malmquist index for each petrochemical

5. Conclusions and recommendations

The present study followed two purposes. After reviewing the literature related to the energy supply chain in the petrochemical industry, it identified the input and output variables using the fuzzy VIKOR method. Further, after collecting the questionnaires and solving them using MATLAB, it was found that the number of employees and the value of materials consumed in production, such as fuel, were the input, and the value of production of products and services was the output. After identifying the input and output of the study, since the variable of the value of fuel consumption was linear because of its price being determined as a fixed number by the government, the input cost changed in a stepwise manner, and the values of other variables were fixed and uniform, the cost of variables was equal to the fixed value. Based on the nature of the input variables of the research model, the objective function had two parts. Each input variable was entered into the objective function according to its weight. This model reduced the input costs related to each unit in petrochemicals and, as a result, cut the total costs. After developing the model related to the study, the model was solved in GAMS software for 14 petrochemicals, and the z value for 14 petrochemicals was obtained. In other words, the value of the objective function represented the input costs. Our inputs included the number of employees and the value of materials consumed in the fuel production.

As seen, petrochemicals 9, 7, 12, 10, 6, 5, 3, 4, 13, 11, 2, 8, 1, and 14 had the lowest input cost, respectively, but it was necessarily because of their efficiency; so the efficiency of petrochemicals was examined. The efficiency of petrochemicals 1, 11, 7, 13, and 14 was 1 in 2021. Thus, the ratio of the outputs to inputs was higher than one, so they were efficient. It was equal to or larger than 1 in petrochemicals 1, 7, 14, and 11 in 2022. Thus, the ratio of the outputs to the inputs was higher than one, so they were efficient. The changes in cost technology were positive in all units, and the efficiency changes were positive only in petrochemicals 1, 7, 8, 11, and 14. The Malmquist index showed the changes in efficiency over time, and the changes in efficiency were positive only in petrochemicals 1, 7, 8, 11, and 14. If only the efficiency of petrochemicals was important to the decision-maker, the petrochemical with the highest Malmquist index, which was greater than one, should be selected, i.e., petrochemical 7. Now, if only the input cost was important for the decision-maker, petrochemical 9 would be selected with the lowest input cost. If two criteria were important for the decision-maker, petrochemical 7 would be selected. Focusing on the concept of energy supply chain, using the cost Malmquist productivity index, and employing the qualitative interaction model for analysis were among the most important aspects of the innovation of this study. Conducting this study can help expand the theoretical literature in this field. Moreover, the innovation of this study was the link between the theoretical and applied fields in the petrochemical industry to identify the inputs and outputs of the energy supply chain. Many studies have been conducted on supply chain optimization, and some are mentioned below.

Mirzaeian and Fallahnejad (2021) investigated the cost Malmquist productivity index using data envelopment analysis. In the qualitative section of their study, they identified the influential inputs and outputs in the petrochemical industry by an interactive model. Our results were consistent with those of Mirzaeian and Fallahnejad (2021), using nonparametric modeling and the Malmquist productivity index to minimize the cost. However, in addition to measuring the productivity, we employed the fuzzy VIKOR model to analyze the productivity in Iran's petrochemical industry. They selected the value of consumed materials and production capacity as the input variable and the value of production of products and services as the output variable, which is in line with our study; however, their selected input variable is not in line with this study. Yaman et al. (2024) estimated the dynamics of cost productivity and its determinants in the healthcare system of OIC member countries using the cost Malmquist productivity index and short bootstrap regression. They also used the short bootstrap regression to identify the factors determining the change in cost productivity and estimate the model during the study period. However, in this study, the DEA method was used to estimate the model and determine the optimal point of productivity. Furthermore, the fuzzy VIKOR method was used to identify the factors determining productivity and analyze the results. The output variables obtained by them (the production rate, adjusted inflation, and gross domestic product) are not in line with our study. However, their input variables, namely the variables of the number of machines used in production (the physical capital), the number of employees, and the value of materials consumed in production, agree with this study.

Zhu et al. (2024) studied the energy cost performance of the thermal power industry in China using the cost Malmquist productivity approach. They used the Boston Consulting Group (BCG) matrix to analyze the results of the Malmquist index. However, we used the fuzzy VIKOR method to analyze the results of the Malmquist index, and the input and output of the energy supply chain in the petrochemical industry were determined through interviews with experts. In addition to the variables of this study, they selected average salary and production capacity as the input variables; their output variables also agree with ours.

Given the recent inflation and economic pressures, most managers believe that preventing the imposition of additional costs and reducing the organization's costs are of particular importance. Thus, this study aimed to identify significant inputs and outputs in the energy supply chain and prevent possible losses caused by the lack of management in the relevant industry. One of the study limitations was that this model is only used in competitive conditions, cannot be used in noncompetitive conditions, and does not provide accurate and reliable results in noncompetitive conditions.

It is recommended that petrochemical companies should take measures to improve efficiency by holding educational and motivational classes and establishing quality standards to enhance the efficiency of technology and technical knowledge. The organization should have short-term and long-term plans to deal with risks related to macroeconomics, including price fluctuations, exchange and interest rate fluctuations, and economic stagnation since they cause the most damage to the supply chain. A look at the production situation of the aromatic chain complexes of petrochemical industries indicates that these units are producing gas condensates in the most difficult sanctions without deficit and lack of feed, meeting domestic needs and exporting products. Sanctions have put the most pressure on petrochemicals. They can reduce the number of additional machines and employees and increase production by adding some new equipment and machinery or packages to overcome the barriers of increasing capacity; it is cost-effective in terms of energy consumption. Minimizing the time of annual repairs, identifying the cases resulting in production stoppage or production reduction in the past years, and strengthening the maintenance and repair team of petrochemical units are vital. Based on their needs, the companies should attract the country's most capable human resources, especially in mechanics and electronics, with the highest intelligence, creativity, perseverance, and courage necessary to strengthen the repair unit; they should not be satisfied with the existing personnel. Further, local prejudices and political pressures should not be allowed in the recruitment of specialists because it has caused irreparable damage to the country's petrochemical industry; recruiting a person with a low level of knowledge and learning ability will be associated with irreparable financial and life consequences. Thus, attention should be paid to recruiting personnel in this sensitive industry, especially for specialized units, and petrochemical companies should take measures toward technical knowledge.

Data analysis showed that using these two methods makes it possible to identify the weak points of the supply chain and provide solutions for its improvement. Further, it is suggested that petrochemical industries should continuously use these tools to monitor their performance so that they can remain competitive in the market. Combining the Malmquist cost efficiency index with the fuzzy VIKOR method can help enhance the performance of the energy supply chain in the petrochemical industry. This approach not only helps identify weak points, but also enables better decision-making.

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7. Declaration of interest

None.

Nomenclature

CMPI	Cost Malmquist productivity index
CTC	Cost-to-Change
DEA	Data Envelopment Analysis
DMUs	Decision Making Units
MPI	Malmquist productivity index
OEC	Overall Efficiency Change

References

Alhamad K, M'Hallah R, Lucas C. (2021). A Mathematical Program for Scheduling Preventive Maintenance of Cogeneration Plants with Production. Mathematics. 9(14):1705. DOI: 10.3390/math9141705

Altay, N., and Pal, R. (2023). Coping in supply chains: a conceptual framework for disruption management. The International Journal of Logistics Management, 34(2): 261–279. DOI: 10.1108/IJLM-05-2021-0305

Bayat, A., Rahbar, F., Vatani, A., and Razavi, S. A. (2022). An Analysis of the Value Chains of the Petrochemical Industry with a Focus on the New Approach of Petro-Refinery. Petroleum Business Review, 6(4): 115–132. DOI: 10.22050/pbr.2023.365275.1283

Cho, T. Y., and Chen, Y. S. (2021). The impact of financial technology on China's banking industry: An application of the metafrontier cost Malmquist productivity index. The North American Journal of Economics and Finance, 57(1): 101414–27. DOI: 10.1016/j.najef.2021.101414

Darvish Trustee, MH., Moatamdei, M., and Vahedi, O. (2023). Presenting a Malmquist productivity index based on the network data envelopment analysis in the sustainable supply chain of the electricity industry. Journal of Quality and Productivity of Iran's Electricity Industry, 12(3):44–52. http://ieijqp.ir/article-1-927-fa.html

Doroudi, H., Abchar, B., and Bigdeli, E. (2022). Productivity analysis using Malmquist index in private insurance companies of Zanjan province, Financial Economics Quarterly Journal, 16(58): 109–127. https://www.sid.ir/paper/958124/en

Emami Meybodi, A., and Wahabi, M. (2022). "Efficiency calculation in companies affiliated to the armed forces using data envelopment analysis", Quarterly Journal of National Defense Economy and Sustainable Development, 7(25): 9–37. https://eghtesad.sndu.ac.ir/article_2427.html?lang=en

Fallah Lajimi, H., Jafari Soruni, Z., and Hoseini Dolatabad, A. (2020). Designing a Mathematical Optimizing Model of the Integrated Supply Chain Network at Strategic and Tactical Levels. Industrial Management Journal, 12(4): 545–577. DOI: 10.22059/imj.2021.312894.1007797

Farashah VH., Sazvar Z., and Hosseini SH. (2021). A dynamic model to formulate effective capacity expansion policies in Iranian petrochemical Industry to complete the value chain. Energy Policy. 148(1): 111992–99. DOI: 10.1016/j.enpol.2020.111992

Farzipoor Saen R, et al. (2013). Developing a linear stochastic two-stage data envelopment analysis model for evaluating sustainability of supply chains: a case study in welding industry. International Journal of Production Economics, 141(1):302–314.

Fathabadi A, Soufimajidpour M. (2019). Investigating technical efficiency and total productivity changes in manufacturing industries using Malmquist productivity index: An application of data envelopment analysis and stochastic frontier analysis. Journal of Manufacturing Science and Engineering, 141(4):041008.

Fernández D, Rivas M, Morais P, García-Sánchez F, González-Álvarez R. (2017). Productivity and energy efficiency assessment of existing industrial gases facilities via data envelopment analysis and the Malmquist index: Evaluation of 34 Air Separation Units in Europe and Asia. Energy, 141:1–12

Gholizadeh, H., Nassabian, S., Moghaddasi, R., and Amini, A. (2022). Experimental analysis of productivity fluctuations in Iranian grain production factors. Agricultural Economics Research, 14(1): 170–182. DOI: 10.30495/jae.2022.25238.2177

Giampieri, A., Ling-Chin, J., Ma, Z., Smallbone, A., and Roskilly, A. P. (2020). A review of the current automotive manufacturing practice from an energy perspective. Applied Energy, 261(1): 114074–86. DOI: 10.1016/j.apenergy.2019.114074

Hashemi, Y., Hajian, M. M., and Aghaei, G. (2023). The Prerequisites for International Sales of Natural Gas in the Iran Energy Exchange. Petroleum Business Review, 7(4): 35–58. DOI: 10.22050/pbr.2023.394112.1297

Hassanpour, B., and Karami, A. (2022). Sources of Productivity Growth in Cereals Cultivation in Selected Provinces in Iran: Improving Farm Management or Technological Progress?. Journal of Agricultural Economics Researches, 14(2): 65–84. https://jae.marvdasht.iau.ir/article_5664.html

Ilyas, A. M., and Rajasekaran, S. (2019). An empirical investigation of efficiency and productivity in the Indian non-life insurance market. Benchmarking: An International Journal, 26(7): 2343–2371. DOI: 10.1108/BIJ-01-2019-0039

Keyghobadi, A. R., Ebadi, A., Yeganegi, M. R., and Motadel, M. R. (2020). The Analysis of Sustainable Supply Chain Risks Based on the FMEA Method in the Oil and Gas industry and Factors Affecting Risk Management. Petroleum Business Review, 4(1): 95–116. DOI: 10.22050/pbr.2020.115177

Köse, E. G., and Özbuğday, F. C. (2018). The Productivity of Turkey's Agricultural Production on Provincial Basis. Ekonomik Yaklasim, 29(109): 55–64. DOI: 10.5455/ey.16701

Li Z, Wang Y, Li X. (2017). Dynamic prediction of financial distress using Malmquist DEA: Evidence from 742 Chinese firms. Research in International Business and Finance, 42:864–877

Liu, H., Yang, R., Wu, D., and Zhou, Z. (2021). Green productivity growth and competition analysis of road transportation at the provincial level employing Global Malmquist-Luenberger Index approach. Journal of cleaner production, 279(1): 123677–86. DOI: 10.1016/j.jclepro.2020.123677

Mirzaeian, F., and Fallahnejad, R. (2021). Cost Malmquist Productivity Index Based on Piecewise Linear Cost Function in Data Envelopment Analysis. Industrial Management Journal, 13(2): 300–328. DOI: 10.22059/imj.2021.322204.1007841

Mohammad Gholiha, A., Hosseinzadeh Lotfi, F., Shahriari, M., and Vaez-Ghsemi, M. (2021). The Relationship between Financial Investment and Malmquist Productivity Index Based on Data Envelopment Analysis in Network Structure (Case Study: Tehran Metro Stations). Journal of Investment Knowledge, 10(40): 103–118. https://jik.srbiau.ac.ir/article_18227.html?lang=en

Nikfarjam A, et al. (2018). Assessing the supply chain efficiency of seven DMUs using a hybrid model. Journal of Supply Chain Management, 44(3):23–34

Pourmahmoud, J., and Bagheri, N. (2023). Uncertain Malmquist productivity index: An application to evaluate healthcare systems during COVID-19 pandemic. Socio-economic planning sciences, 87(1): 101522–30. DOI: 10.1016/j.seps.2023.101522

Rowshanali, A., Hejazi, R., Ranjbar, M. H., Abedini, B., and Rostamijaaz, H. (2022). Interpretive Ranking of Inertia Characteristics in the Auditing Profession to Enhance the Auditors' Independence in Petrochemical Industry. Petroleum Business Review, 6(4): 61–85. DOI: 10.22050/pbr.2022.338057.1260

Sarkar, M., and Seo, Y. W. (2021). Renewable energy supply chain management with flexibility and automation in a production system. Journal of Cleaner Production, 324(1): 129149–56. DOI: 10.1016/j.jclepro.2021.129149

Savchina, O., Bratanov, A., Konovalova, N., and Saksonova, S. (2021). Evaluation of financial condition and performance optimization of the petrochemical industry organization in the context of increased financial risks. Universal Journal of Accounting and Finance, 9(5), 1169–1183. DOI: 10.13189/ujaf.2021.090526

Walheer, B. (2018). Disaggregation of the cost Malmquist productivity index with joint and output-specific inputs. Omega, 75(1): 1–12. DOI: 10.1016/j.omega.2017.01.012

Walheer, B. (2022). Global Malmquist and cost Malmquist indexes for group comparison. Journal of Productivity Analysis, 58(1): 75–93. DOI: 10.1007/s11123-022-00640-5

Xu, S., Fang, L., and Govindan, K. (2022). Energy performance contracting in a supply chain with financially asymmetric manufacturers under carbon tax regulation for climate change mitigation. Omega, 106(1): 102535–48. DOI: 10.1016/j.omega.2021.102535

Yakovleva N, et al. (2012). Measuring the sustainability of the food supply chain: A case study of potato production companies in the UK. Journal of Cleaner Production, 32:1–8

Yaman, H., Sungur, O., and Dulupçu, M. A. (2024). Measuring the agricultural total factor productivity of provinces in turkey using Malmquist index. Erciyes Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi, (67): 191–196. DOI: 10.18070/erciyesiibd.1345345

Yang, Y. L., Sheng, T. C., and Huang, M. H. (2010). Estimating the cost Malmquist productivity index in the Taiwan biotech and biopharmaceutical industry. Taiwan Economic Review, 37(1): 353–378. DOI: 10.7086/TJAE.201009.0059

Zhai, D., Shang, J., Yang, F., and Ang, S. (2019). Measuring energy supply chains' efficiency with emission trading: A two-stage frontier-shift data envelopment analysis. Journal of cleaner production, 210(1): 1462–1474. DOI: 10.1016/j.jclepro.2018.10.355

Zhu, C., Zhu, N., Emrouznejad, A., and Ye, T. (2024). A new Malmquist productivity index with an application to commercial banks. IMA Journal of Management Mathematics, 35(2): 215–240. DOI: 10.1093/imaman/dpad015