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Evaluating the Performance of Production Lines Using Expanded Data Envelopment Analysis, Analytic Hierarchy Process, and Entropy in a Grey Environment (Case Study: Kaleh Company)

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Abstract

In today's competitive world, production at any cost is no longer on the agenda of organizations. In this context, the efficiency of production units in converting inputs to outputs is crucial, as inefficiency in a production unit can lead to wasting resources and inputs. For this reason, the Data Envelopment Analysis (DEA) method has attracted the attention of many researchers worldwide in recent years, and various applications of this method are observed for evaluating the performance of different institutions and activities. In this research, DEA is used to evaluate the performance of Kalleh Company's production line. After determining the efficient units, a combined method of Analytic Hierarchy Process (AHP) and Entropy is used to rank the efficient units. In other words, the Entropy method is used to weight the influential criteria, and the AHP is used to rank the efficient units. In other words, this research uses a combination of DEA, Entropy, and AHP methods to evaluate the performance of Kalleh Company's production line. Additionally, to consider real-world uncertainties and decision-making, the grey theory is used. Grey Theory uses interval numbers and creates more degrees of freedom to consider uncertainty. For this purpose, the combined method presented in this research is developed in a grey environment to deal with uncertainty. Finally, the proposed method is applied to Kalleh Company to evaluate performance. The results of the proposed method showed that production lines 1, 4, 8, and 14 were efficient. These lines were then re-evaluated using the combined Grey AHP and Entropy method, and line 4 was selected as the best production line.
Keywords: Production line performance evaluation, Data envelopment analysis method, Entropy method, Analytic hierarchy process method, Grey theory.

1 | Introduction

Maximizing output while minimizing input has consistently been a primary objective in manufacturing industries. Nevertheless, ongoing assessment of production systems not only ensures that production targets are achieved but also guarantees that each operational unit performs optimally in comparison to established

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production benchmarks. This continuous evaluation process is crucial for maintaining efficiency and effectiveness in manufacturing operations. In this regard, the efficiency of production units in converting inputs to outputs is of great importance, as the inefficiency of a production unit can lead to a waste of resources and inputs. For this reason, in recent years, the Data Envelopment Analysis (DEA) method has attracted the attention of researchers worldwide. This method has various applications for evaluating the performance of institutions and diverse activities in different fields. The reason for the greater popularity of the DEA method compared to other methods is its ability to examine complex and often unknown relationships between multiple inputs and outputs that are usually not measurable [1]. In this research, the efficiency of Kalleh Company's production line is evaluated using the non-parametric efficiency measurement technique in DEA.

Performance evaluation of units allows senior decision-makers as well as middle and operational managers of organizations to evaluate, control, and correct the performance of units under their supervision. The widely used DEA technique allows them to evaluate the efficiency of units under supervision while obtaining accurate information about how to reduce or increase the inputs and outputs of each unit to improve their efficiency. One of the most important issues that decision-makers and senior and middle managers, especially in production units, face is the balance of inputs and outputs of these units [2].

The size of the Kalleh dairy factory is 51 hectares, which is considered one of the largest factories in Iran. On the other hand, Kalleh Company has been able to become the largest main hub for milk absorption in the country by absorbing more than 2,500 tons of milk daily. In addition, Kalleh Company is the first dairy factory to put nationwide distribution of dairy products on its agenda. Currently, using capillary distribution and with more than 44 branches, it distributes its products from Azerbaijan to Hormozgan. Daily, 4,000 people are active in various sections of the company to deliver more than 2,650 tons of various dairy products to the final consumer. The quality of Kalleh products has led to a large part of this company's products being exported outside Iran, mostly to Europe, and this company has been consistently selected as the exemplary exporter of the food industry over the past years. The Kalleh brand was recognized as one of the top 100 brands in Iran at the 10th National Festival of Iranian Industry Champions in 2013.

According to Euromonitor, Kalleh Company is a popular brand in Iran and Europe. Therefore, the managers of this company are looking to increase the efficiency of their production lines, increase efficiency, and consequently reduce production costs. On the other hand, the DEA method is looking for a management method that measures the efficiency of units relatively and identifies inefficient units. It should also be stated which feature should be improved to enhance efficiency [3]. For this reason, applying this method to Kalleh Company's production lines is necessary.

Also, in the evaluation process using the DEA method, only efficient units are determined, so a combined decision-making method for evaluating and ranking efficient units is necessary. In this regard, in this research, a combined method of entropy and Analytic Hierarchy Process (AHP) is used to rank efficient units. It is also worth noting that the production environment and decision-making have many uncertainties. Therefore, presenting an approach to deal with uncertainty can improve decision-making accuracy. So, considering uncertainties is necessary. In this research, grey set theory is used to deal with uncertainty. In total, in this research, the efficiency of Kalleh dairy company's production lines, which include 21 product production lines, is calculated using the grey DEA technique. Then, using the combined method of entropy and AHP, the ranking of efficient units is performed. Also, to better deal with the uncertainties in the decision-making and production environment, grey set theory is used.

This research is structured as follows: In the second section, a literature review is conducted in three areas. Then, the preliminary knowledge required for grey sets is stated in the third section, and the proposed method, which includes a combination of DEA, AHP, and entropy methods developed in a grey environment, is stated in the fourth section. In the fifth section, Kalleh Company's production lines are examined and the proposed method is applied to them. Finally, the conclusion is stated in the sixth section.

2 | Literature Review

The research background is examined in three areas. First, the literature related to grey DEA is reviewed. Then, performance evaluation in production units based on the grey DEA method is examined, and finally, the AHP method and entropy are reviewed.

Regarding grey DEA, grey DEA was first introduced by [4]. This method was developed to deal with uncertainty and incomplete information. In this method, grey systems are used for modeling and efficiency analysis to process incomplete or ambiguous data in evaluating the efficiency of decision-making units in uncertain environments [4]. This method has also received much attention in recent years. Huang et al. [5] presented a combined approach of DEA and grey factor analysis for efficiency evaluation and ranking in uncertain systems. By using grey theory to manage data uncertainty, they increased the accuracy of efficiency assessments in complex and uncertain environments and helped identify and rank decision-making units based on efficiency and system uncertainty.

Wang et al [6] presented a combined approach of DEA and multi-criteria decision-making based on grey theory for selecting solar power plant locations in Vietnam. This method, by combining solar energy efficiency and data uncertainty management, considered various criteria such as cost, solar radiation, and environment in the decision-making process. Asnaashari et al. [7] used a two-stage grey DEA approach to select efficient contractors by applying claim reduction criteria. In the first stage, contractors' efficiency was evaluated based on inputs and outputs. In the second stage, grey data theory was used to manage uncertainty and prioritize contractors. Wang et al. [8] used an integrated approach of DEA and grey theory to optimize efficiency in blockchain service markets. They analyzed inputs and outputs of key variables in the blockchain service market and identified efficient units by managing uncertainty in data.

Regarding the application of the DEA method in examining production line performance, much research has been conducted in recent years. Pourjavad and Shirouyehzad [9] used the DEA approach to measure the efficiency of continuous production lines. Zhang et al. [10] examined the efficiency of global food production and environmental sustainability using an entropy-DEA model. This combined method, by weighting various environmental and production indicators, analyzed the efficiency of different countries in food production and natural resource conservation. Ammirato et al. [11] presented an integrated approach of AHP and DEA to evaluate the efficiency of production processes. The AHP method was used for weighting various criteria and DEA for analyzing the efficiency of decision-making units.

Wang et al. [11] presented an improved model of DEA to evaluate the efficiency of two-stage production processes with feedback. This model, in addition to the two-stage analysis, considered the feedback effect between production stages to provide a more accurate efficiency assessment. He et al. [12] used a three-stage DEA model to examine production productivity in China's advanced industries during the 13th Five-Year Plan, considering environmental factors.

Regarding the development of the AHP method in a grey environment, Thakkar and Thakkar [13] applied an integrated approach of grey AHP and grey TOPSIS, which is particularly suitable for decision-making under uncertainty and ambiguous information. Ortega et al. [14] examined a two-stage decision-making process based on the grey AHP to evaluate the location of park-and-ride facilities. Ni et al. [15] used grey relational analysis and multi-criteria decision-making methods to evaluate the suitability of underground space development.

Regarding the development of the entropy method in a grey environment, Esangbedo et al. [16] evaluated human resource information systems using grey pairwise comparison methods in multi-criteria decision analysis. Zhang et al. [17] introduced a TOPSIS model with generalized grey entropy weighting for financial performance evaluation considering distinctions. Çirkin et al. [19] presented an integrated model based on grey entropy and COPRAS methods to solve the machine selection problem in the decision-making process. Han et al. [18] presented a new grey multi-criteria decision-making framework for selecting the optimal location of electrochemical energy storage stations.

Given the literature review, few studies have been conducted in the field of evaluating a company's production lines using the DEA method. Also, for ranking efficient units in the DEA method, few studies have used the combined method of AHP and entropy. Additionally, the use of this combined method in Kalleh dairy industries is being done for the first time. Finally, to consider the uncertainty in the production and decision-making environment, grey set theory is used.

3 | Proposed Method

In this section, the proposed method of this research is presented. In this study, first, the efficiency of production lines is determined using the extended grey DEA method. Then, a combined extended method of AHP and entropy in a grey environment is used to evaluate efficient units. In other words, the entropy method is used for weighting the criteria, and the AHP method is used for ranking the efficient units. Initially, the basic knowledge required for grey sets is explained, and then the proposed extended method in the grey environment is presented.

3.1 | Basic Knowledge Required for Grey Set Theory

In real-world decision-making, goals and their importance cannot be determined precisely. Grey number theory is one of the first methods used to deal with uncertainty. Grey theory provides an effective approach to solving problems with uncertainty and is therefore applied in various fields such as analysis, modeling, and prediction. Experts may not be able to express a definite number for their evaluations or opinions, which is why they use grey numbers. With this approach, feelings and judgments can be considered more logically and realistically [19].

Here, some basic mathematical definitions of grey numbers and grey sets are presented as follows:

Definition 1. A grey system is defined as a system containing uncertain information presented by grey numbers and grey variables, as shown in *Fig. 1* [20–22]. The grey system is a mathematical method for modeling and analyzing systems that have incomplete, imperfect, or specific information. This theory is very effective in situations where data is limited, insufficient, or uncertain.

Definition 2. If X is a reference set, then a grey set G from X is defined as follows [22]:

$$\bar{\mu}_G(x): x \rightarrow [0,1]. \quad (1)$$

$$\underline{\mu}_G(x): x \rightarrow [0,1]. \quad (2)$$

$$\bar{\mu}_G(x) \geq \underline{\mu}_G(x), x \in X. \quad (3)$$

where $\bar{\mu}_G(x), \underline{\mu}_G(x)$ illustrates the upper and lower bounds of the grey number.

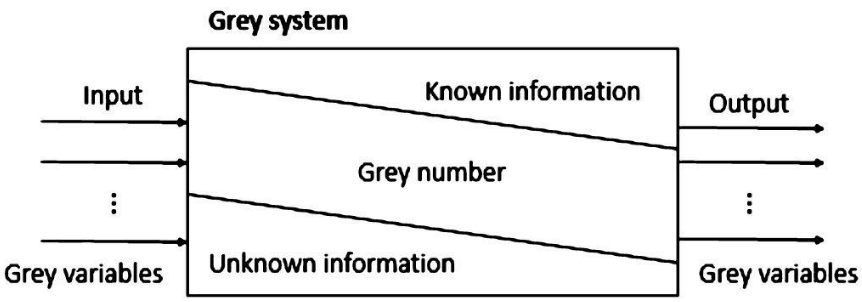

Fig. 1. Concept of grey numbers.

Definition 3. Grey numbers are defined as numbers with uncertain information. For example, measuring the performance of a phenomenon or characteristic can be described with linguistic variables, which can be expressed as a numerical range. It is evident that this numerical range encompasses uncertain information, which is written as follows [22]:

$$\otimes G = G\Big|_{\underline{\mu}}^{\bar{\mu}} \tag{4}$$

Definition 4. Basic operations between two grey numbers $\otimes\theta_1 = \left[\underline{\theta}_1, \bar{\theta}_1\right]$ and $\otimes\theta_2 = \left[\underline{\theta}_2, \bar{\theta}_2\right]$ are defined by using the following [22]:

$$\otimes\theta_1 + \otimes\theta_2 = \left[\underline{\theta}_1 + \underline{\theta}_2, \bar{\theta}_1 + \bar{\theta}_2\right]. \tag{5}$$

$$\otimes\theta_1 + \otimes\theta_2 = \left[\underline{\theta}_1 + \underline{\theta}_2, \bar{\theta}_1 + \bar{\theta}_2\right]. \tag{6}$$

$$\otimes\theta_1 \times \otimes\theta_2 = \left[\underline{\theta}_1\underline{\theta}_2, \bar{\theta}_1\bar{\theta}_2\right]. \tag{7}$$

$$\otimes\theta_1 \div \otimes\theta_2 = \left[\underline{\theta}_1, \bar{\theta}_1\right] \times \left[\frac{1}{\underline{\theta}_2}, \frac{1}{\bar{\theta}_2}\right]. \tag{8}$$

3.2 | Proposed Method

The proposed method consists of grey DEA, grey AHP, and grey entropy. The framework of the proposed method is presented in *Fig. 2*. Now, the proposed method is explained step by step. In other words, first, grey DEA is explained, followed by grey AHP and grey entropy.

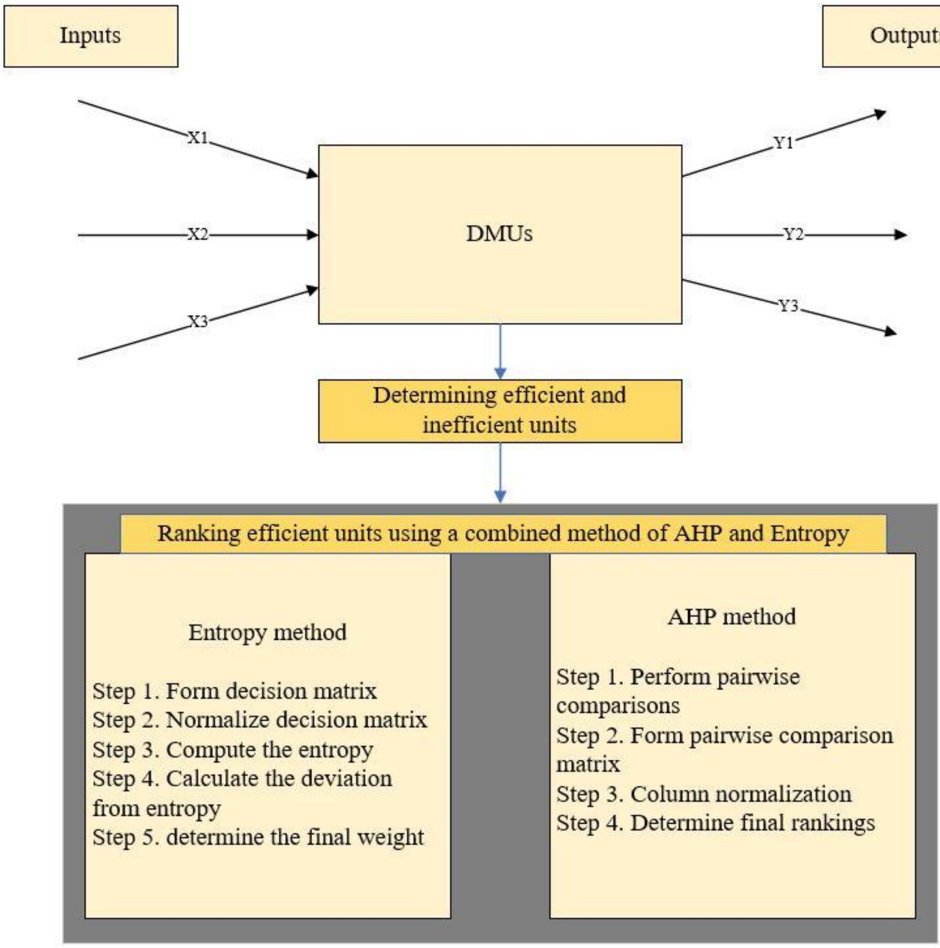

Fig. 2. Framework of proposed method.

3.2.1 | Grey DEA

The DEA values for each efficient decision-making unit are equal to 1, and for each inefficient decision-making unit, they are less than 1. Suppose there are *n* decision-making units, each $DMU_j (j = 1, 2, ..., n)$ using m inputs $x_{ij}(i=1,2,...,m)$ to produce s outputs $y_{rj}(r=1,2,...,s)$. Now, the CCR model is presented as follows for evaluating the efficiency of decision-making units:

$$\max \frac{\sum_{r=1}^{s} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik}},$$
$$\text{s.t.}$$
$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \le 1, \quad j=1,2,...,n, \tag{9}$$
$$u_r, v_i \ge \zeta, \quad i=1,...,m; r=1,2,...,s.$$

Banker et al. [25] developed the CCR model assuming variable returns to scale. Their proposed model was called BCC and is described as follows:

$$\max \frac{\sum_{r=1}^{s} u_r y_{rk} - u_k}{\sum_{i=1}^{m} v_i x_{ik}},$$
$$\text{s.t.}$$
$$\frac{\sum_{r=1}^{s} u_r y_{rj} - u_j}{\sum_{i=1}^{m} v_i x_{ij}} \le 1, \quad j=1,2,...,n, \tag{10}$$
$$u_o \text{ is free}, \quad u_r, v_i \ge \zeta, \quad i=1,...,m; r=1,2,...,s.$$

Conventional DEA methodologies are not suitable for assessing decision-making units that have numerous inputs or outputs. Moreover, when there is an insufficient quantity of decision-making units, the efficiency scores produced may lack significance. It's important to recognize that the correlation between the number of decision-making units and the quantity of inputs and outputs is typically expressed as $3(m+s)<n$ [23].

This study employs and expands upon the BCC model of DEA, transforming it into a grey DEA model. This modified approach is then implemented alongside the entropy method and grey AHP. The initial step involves converting the BCC model into a grey format, necessitated by the often uncertain nature of factor values [23]. While DEA is a highly effective tool for measuring performance, its sensitivity to data can lead to inaccurate results when dealing with uncertain information. A significant limitation of the traditional DEA model is its requirement for definitive input and output values [24]. Consequently, the values of determining factors can be represented in grey form to address this issue. In the BCC model, efficiency $DMU_j(\theta_j)$ is defined as follows:

$$\theta_j = \frac{\sum_{r=1}^{s} u_r y_{rj} - u_j}{\sum_{i=1}^{m} v_i x_{ij}}, \quad j=1,2,...,n. \tag{11}$$

Given that inputs and outputs are considered as grey, $\theta_j(j=1,2,...,n)$ are obtained as follows:

$$\theta_j = \frac{\sum_{r=1}^{s} u_r\left[\underline{y}_{rj}, \overline{y}_{rj}\right] - u_j}{\sum_{i=1}^{m} v_i\left[\underline{x}_{ij}, \overline{x}_{ij}\right]} = \frac{\left[\sum_{r=1}^{s} u_r \underline{y}_{rj} - u_j, \sum_{r=1}^{s} u_r \overline{y}_{rj} - u_j\right]}{\left[\sum_{i=1}^{m} v_i \underline{x}_{ij}, \sum_{i=1}^{m} v_i \overline{x}_{ij},\right]} = \left[\frac{\sum_{r=1}^{s} u_r \underline{y}_{rj} - u_j}{\sum_{i=1}^{m} v_i \overline{x}_{ij}}, \frac{\sum_{r=1}^{s} u_r \overline{y}_{rj} - u_j}{\sum_{i=1}^{m} v_i \underline{x}_{ij}}\right] = \left[\underline{\theta}_j, \overline{\theta}_j\right]. \tag{12}$$

Efficiency DMU_j which is a grey number, represents as $\left[\underline{\theta}_j, \overline{\theta}_j\right] \subseteq [0,1]$. Therefore, its upper and lower bounds are expressed as follows:

$$\underline{\theta}_j = \left[\frac{\sum_{r=1}^{s} u_r \underline{y}_{rj} - u_j}{\sum_{i=1}^{m} v_i \overline{x}_{ij}}\right] \geq \zeta, \ \ j = 1, 2, \ldots, n. \tag{13}$$

$$\overline{\theta}_j = \left[\frac{\sum_{r=1}^{s} u_r \overline{y}_{rj} - u_j}{\sum_{i=1}^{m} v_i \underline{x}_{ij}}\right] \leq 1, \ \ j = 1, 2, \ldots, n. \tag{14}$$

Consequently, the lower and upper bound of efficiency DMU_k is determined by using two models:

$$\begin{aligned} &\max \underline{\theta}_j = \frac{\sum_{r=1}^{s} u_r \underline{y}_{rk} - u_k}{\sum_{i=1}^{m} v_i \overline{x}_{ik}}, \\ &\text{s.t.} \\ &\frac{\sum_{r=1}^{s} u_r \overline{y}_{rj} - u_j}{\sum_{i=1}^{m} v_i \underline{x}_{ij}} \leq 1, \ \ j = 1, 2, \ldots, n, \\ &u_r, v_i \geq \xi, \quad i = 1, 2, \ldots, m, \ r = 1, 2, \ldots, s, \ j \prec k, j \neq k. \end{aligned} \tag{15}$$

$$\begin{aligned} &\max \overline{\theta}_j = \frac{\sum_{r=1}^{s} u_r \overline{y}_{rk} - u_k}{\sum_{i=1}^{m} v_i \underline{x}_{ik}}, \\ &\text{s.t.} \\ &\frac{\sum_{r=1}^{s} u_r \overline{y}_{rj} - u_j}{\sum_{i=1}^{m} v_i \underline{x}_{ij}} \leq 1, \ \ j = 1, 2, \ldots, n, \\ &u_r, v_i \geq \xi, \quad i = 1, 2, \ldots, m, \ r = 1, 2, \ldots, s, j \prec k, j \neq k. \end{aligned} \tag{16}$$

Through the application of the Charnes and Cooper transformation to these two models (assuming the denominator of the objective function in both models equals one), the aforementioned models are converted into the following linear programming models:

$$\begin{aligned}
&\max \underline{\theta}_j = \sum_{r=1}^{s} u_r \underline{y}_{rk} - u_k,\\
&\text{s.t.}\\
&\sum_{i=1}^{m} v_i \overline{x}_{ik} = 1,\\
&\sum_{r=1}^{s} u_r \overline{y}_{rj} - u_j - \sum_{i=1}^{m} v_i \underline{x}_{ij} \le 0, \quad j = 1,2,\dots,n,\\
&u_r, v_i \ge \xi, \quad i = 1,2,\dots,m, \; r = 1,2,\dots,s.
\end{aligned} \tag{17}$$

$$\begin{aligned}
&\max \overline{\theta}_j = \sum_{r=1}^{s} u_r \overline{y}_{rk} - u_k,\\
&\text{s.t.}\\
&\sum_{i=1}^{m} v_i \underline{x}_{ik} = 1,\\
&\sum_{r=1}^{s} u_r \overline{y}_{rj} - u_j - \sum_{i=1}^{m} v_i \underline{x}_{ij} \le 0, \quad j = 1,2,\dots,n,\\
&u_r, v_i \ge \xi, \quad i = 1,2,\dots,m, \; r = 1,2,\dots,s.
\end{aligned} \tag{18}$$

The two above models respectively represent the upper and lower bounds of efficiency DMU_k. The DEA method can identify efficient units but cannot rank them. In this regard, to obtain the ranking of efficient units, a combination of entropy and grey AHP methods is used. For this purpose, these two methods are also developed in the grey environment in the following sections.

3.2.2 | Grey AHP

This method was introduced by Thomas Saaty in 1983. The purpose of this method is to prioritize several criteria or options. After determining the goal, criteria for decision-making should be identified. These criteria are compared in pairs based on the objective, and their weights are determined. In this research, this method is developed in a grey environment and used for ranking efficient units. The steps of this method are as follows:

Step 1. In this step, pairwise comparisons are made between influential criteria (inputs and outputs). These comparisons are made using expert opinions and linguistic variables defined in *Table 1*.

Table 1. Linguistic variables for the AHP method.

Linguistic Variables	Equivalent Grey Numbers
Equal importance	[1,1]
Slightly preferred	[2,4]
Preferred	[4,6]
Very preferred	[6,8]
Completely preferred	[8,9]

Step 2. The pairwise comparison matrix is also formed as follows:

$$A_{ij} = \begin{bmatrix} \otimes a_{11} & \otimes a_{12} & \cdots & \otimes a_{1n} \\ \otimes a_{21} & \otimes a_{22} & \cdots & \otimes a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes a_{n1} & \otimes a_{n2} & \cdots & \otimes a_{nn} \end{bmatrix}, \quad (19)$$

where $1 \le i \le n$ and $1 \le j \le n$ represents the number of criteria. Also, $\otimes a_{nn} = (1,1)$ and $\otimes a_{n1} = \left(\frac{1}{\bar{a}_{n1}}, \frac{1}{\underline{a}_{n1}} \right)$.

Step 3. Column normalization is performed as follows:

$$\underline{a}_{ij} = \frac{\left(\underline{a}_{ij} - \min_i \underline{a}_{ij} \right)}{\max_i \bar{a}_{ij} - \min_i \underline{a}_{ij}}. \quad (20)$$

$$\bar{a}_{ij} = \frac{\left(\bar{a}_{ij} - \min_i \underline{a}_{ij} \right)}{\max_i \bar{a}_{ij} - \min_i \underline{a}_{ij}}. \quad (21)$$

Step 4. In this step, the final weight is calculated as follows:

$$\otimes w_i^{ahp} = \frac{\sum_{j=1}^{n} \otimes a_{ij}}{n} = \left(\frac{\sum_{j=1}^{n} \otimes \underline{a}_{ij}}{n}, \frac{\sum_{j=1}^{n} \otimes \bar{a}_{ij}}{n} \right). \quad (22)$$

The weight of each criterion is indicated by $\otimes w_i^{ahp}$, and higher values indicate greater importance.

3.2.3 | Grey entropy

The entropy method is one of the multi-criteria decision-making methods for calculating the weight of criteria. This method requires a decision matrix and was introduced by Shannon and Weaver in 1974. The main idea of this method is that the greater the dispersion in the values of an indicator, the more important that indicator is. To deal with uncertainty, in this research, this method is developed in a grey environment and is used to weight the criteria in the process of evaluating efficient units. The steps of this method are as follows:

Step 1. First, a decision matrix must be formed. In this research, the options are the same as the decision units, and the inputs and outputs are the same as the criteria. So, the decision matrix is formed as follows:

$$R_{ij} = \begin{bmatrix} \otimes r_{11} & \otimes r_{12} & \cdots & \otimes r_{1m} \\ \otimes r_{21} & \otimes r_{22} & \cdots & \otimes r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes r_{n1} & \otimes r_{n2} & \cdots & \otimes r_{nm} \end{bmatrix}, \quad (23)$$

where, $1 \le i \le n$ depicts the numbers of criteria and $1 \le j \le m$ represents the decision units.

Step 2. The decision matrix is normalized by using the following:

$$R_{ij} = \begin{bmatrix} \otimes x_{11} & \otimes x_{12} & \cdots & \otimes x_{1m} \\ \otimes x_{21} & \otimes x_{22} & \cdots & \otimes x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes x_{n1} & \otimes x_{n2} & \cdots & \otimes x_{nm} \end{bmatrix}, \quad (24)$$

where

$$\underline{x}_{ij} = \frac{\underline{r}_{ij}}{\sum_{i=1}^{n} \overline{r}_{ij}}, \overline{x}_{ij} = \frac{\overline{r}_{ij}}{\sum_{i=1}^{n} \overline{r}_{ij}}. \tag{25}$$

Step 3. Now the entropy of each index is calculated as follows:

$$\underline{h}_i = \min\left\{-h_0 \sum_{j=1}^{m} \underline{x}_{ij}.\ln(\underline{x}_{ij}), -h_0 \sum_{j=1}^{m} \overline{x}_{ij}.\ln(\overline{x}_{ij})\right\},$$
$$\overline{h}_i = \max\left\{-h_0 \sum_{j=1}^{m} \underline{x}_{ij}.\ln(\underline{x}_{ij}), -h_0 \sum_{j=1}^{m} \overline{x}_{ij}.\ln(\overline{x}_{ij})\right\}, \tag{26}$$

where,

$$h_0 = \frac{1}{\ln(m)}. \tag{27}$$

Step 4. In this step, the degree of deviation of each option from its entropy is determined as follows:

$$\underline{d}_i = 1 - \overline{h}_i,$$
$$\overline{d}_i = 1 - \underline{h}_i. \tag{28}$$

Step 5. The weight of the criteria is specified as below:

$$\otimes w_i = (\underline{w}_i, \overline{w}_i) = \underline{w}_i = \frac{\underline{d}_i}{\sum_{i=1}^{n} \overline{d}_i}, \overline{w}_j = \frac{\overline{d}_i}{\sum_{i=1}^{n} \overline{d}_i}. \tag{29}$$

Each criterion with a larger number has a higher importance. The obtained weights in this method are used in the AHP to rank efficient units.

4 | Case Study

The proposed model in this research is applied to a case study to demonstrate its efficiency and computational process. The case study for this research is Kalleh Dairy Company. Kalleh Company was founded in 1987 to improve the quality of Iranian families' food baskets. The continuous efforts of this company over the past years, all aimed at improving the nutrition of Iranian people, have led Kalleh to rank 48th in the global food industry (according to Euromonitor report).

This brand has also been recognized as a popular and superior brand and for seven consecutive years the only exemplary exporter of dairy products in Iran. Kalleh's activity began with a daily intake of 3 liters of milk, but now this number has reached more than 2,500 tons per day. This increase in production capacity has enabled the daily production of more than 2,650 tons of various dairy products.

In this production process, about 4,000 people work daily in different departments to provide quality products to consumers. The company also can produce 4,000 tons of cheese and, by utilizing experienced specialists, has been able to offer a variety of products, similar to those produced abroad, in the Iranian domestic market and make them available to consumers.

The Kalleh brand was established in 1987 to improve and enhance the level of the Iranian people's food basket. As a result of the activities carried out by this company over the past years, all of which are aimed at improving the Iranian food basket, this brand has been ranked 48th in the global food industry (according to Euromonitor report), as a popular and superior brand, and for 7 years as the only exemplary exporter of dairy products in Iran.

Kalleh started its activity by absorbing 3 liters of milk daily, and today it has a daily milk absorption of more than 2,500 tons; which results in the daily production of more than 2,650 tons of various dairy products. In this production process, 4,000 people work daily in different departments to deliver the final products to consumers.

Kalleh can produce 4,000 tons of cheese and has been able to produce and provide Iranians with various products that are produced abroad by having professional specialists. In this research, Kalleh company's production lines are examined. This company has 21 production lines. Kalleh company's production lines are presented in *Table 2*.

Table 2. Production lines of Kalleh company.

Production Lines	Description
Line 1	Low-fat milk
Line 2	High-fat milk
Line 3	Fortified milk
Line 4	Spindle ice cream
Line 5	Tiramisu ice cream
Line 6	Cup ice cream
Line 7	Chocolate milk
Line 8	Kefir drink
Line 9	Natural plant-based drink
Line 10	Irish butter
Line 11	French butter
Line 12	US butter
Line 13	Seven low-fat yogurt
Line 14	Seven high-fat yogurt
Line 15	Minarin khalifeh confectionery
Line 16	Minarin premium confectionery
Line 17	Camembert cream cheese
Line 18	Kalait cheese
Line 19	Prato cheese
Line 20	Camembert cheese
Line 21	Orange cutlet

The inputs and outputs of the DEA method which are used to evaluate the Kalleh Company are presented in *Fig. 3*.

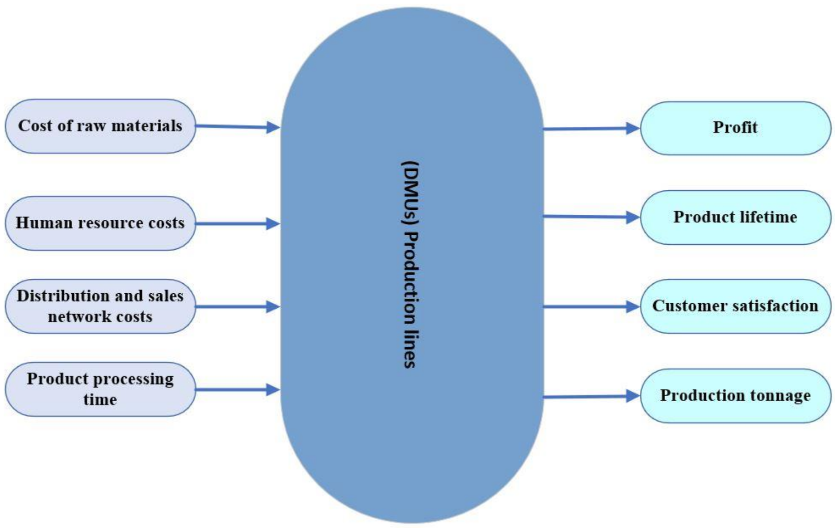

Fig. 3. Proposed DEA model for Kalleh company's production lines.

To implement the grey DEA method and evaluate the performance of Kalleh Company's production lines, we need information on raw material costs, human resource costs, distribution and sales network costs, and product processing time as inputs. We also require data on profit, product lifetime, customer satisfaction, and production tonnage as outputs for each of the company's 21 production lines. To account for uncertainty in the production line, these numbers are defined as grey numbers. The initial information required for these production lines is presented in *Tables 3* and *4* for the year 2021.

Since all inputs are undesirable and all outputs are desirable, the inputs need to be adjusted. Therefore, this research uses the inverse transformation method [25]. In other words, all 4 inputs in this study are converted to desirable inputs using the inverse transformation method before solving the problem.

Table 3. Inputs information.

Production Lines	Raw Material Costs (Million Tomans)	Human Resource Costs (Million Tomans)	Distribution And Sales Network Costs (Million Tomans)	Product Processing Time (Hours)
Line 1	[11632, 13958]	[1396, 1675]	[977, 1172]	[7,8]
Line 2	[16215, 19458]	[2108, 2529]	[1180, 1416]	[8,9]
Line 3	[18100, 21720]	[2534, 3040]	[709, 851]	[4,5]
Line 4	[22458, 26949]	[2538, 3045]	[532, 639]	[2.5,3.5]
Line 5	[24765, 29718]	[2848, 3417]	[1993, 2392]	[3.5,4.5]
Line 6	[19231, 23077]	[2327, 2792]	[325, 390]	[2,3]
Line 7	[19151, 22981]	[2509, 3010]	[526, 632]	[1,2]
Line 8	[38102, 45722]	[5372, 6446]	[3384, 4061]	[5,6]
Line 9	[38050, 45660]	[3805, 4566]	[2397, 2876]	[6,7]
Line 10	[34220, 41064]	[4243, 5091]	[1188, 1425]	[1,2]
Line 11	[26145, 31374]	[3817, 4580]	[534, 641]	[1.5,2.5]
Line 12	[21750, 26100]	[2915, 3497]	[1428, 1713]	[2,3]
Line 13	[36750, 44100]	[5255, 6306]	[367, 441]	[3,4]
Line 14	[40302, 48362]	[4030, 4836]	[1692, 2031]	[24,26]
Line 15	[44865, 53838]	[5070, 6083]	[2839, 3406]	[4,5]
Line 16	[46568, 55881]	[4657, 5588]	[977, 1173]	[5,6]
Line 17	[28867, 34640]	[5773, 6928]	[2424, 2909]	[4.5,5.5]
Line 18	[32864, 39436]	[3911, 4692]	[273, 328]	[5,6]
Line 19	[45867, 55040]	[6330, 7595]	[4430, 5316]	[5,6]
Line 20	[26869, 32242]	[3197, 3836]	[2238, 2685]	[4,5]
Line 21	[48572, 58286]	[5440, 6528]	[1904, 2284]	[3,4]

Table 4. Output information.

Production Lines	Production Tonnage (Kg)	Customers Satisfaction (Percentage)	Product Lifetime (Day)	Profit (Percentage)
Line 1	[16800000, 1848000]	[%95,%96]	[5,6]	[%15,%16]
Line 2	[144000, 15840]	[%90,%92]	[5,6]	[%14,%15]
Line 3	[360000, 396000]	[%75,%78]	[5,6]	[%14,%15]
Line 4	[410000, 451000]	[%93,%95]	[240,270]	[%15,%16]
Line 5	[360000, 396000]	[%77,%79]	[240,270]	[%14,%15]
Line 6	[270000, 297000]	[%89,%91]	[240,270]	[%14,%15]
Line 7	[240000, 264000]	[%90,%93]	[5,6]	[%13,%14]
Line 8	[221000, 243100]	[%93,%95]	[60,70]	[%15,%16]
Line 9	[54000, 59400]	[%79,%81]	[30,40]	[%13,%14]
Line 10	[75000, 82500]	[%81,%83]	[240,270]	[%13,%14]
Line 11	[60000, 66000]	[%85,%87]	[240,270]	[%14,%15]
Line 12	[80000, 88000]	[%74,%75]	[240,270]	[%14,%15]
Line 13	[412000, 453200]	[%91,%92]	[20,30]	[%13,%14]
Line 14	[448000, 492800]	[%95,%96]	[20,30]	[%15,%16]
Line 15	[600000, 660000]	[%88,%89]	[240,270]	[%14,%15]
Line 16	[650000, 715000]	[%83,%85]	[240,270]	[%13,%14]
Line 17	[48000, 52800]	[%74,%76]	[90,100]	[%13,%14]
Line 18	[40000, 44000]	[%65,%69]	[120,130]	[%12,%13]
Line 19	[40000, 44000]	[%68,%71]	[120,130]	[%13,%14]
Line 20	[40000, 44000]	[%70,%73]	[90,100]	[%14,%15]
Line 21	[12000, 13200]	[%64,%68]	[240,270]	[%12,%13]

Now, equations (17) and (18) are used to evaluate the performance of the production line. That is, the problem is solved once for the upper limit and once for the lower limit, and the performance of the production lines is produced as an interval. The results are presented in *Table 5*. As can be observed, production lines 1, 4, 8, and 14 are efficient production lines, and the rest of the production lines are also ranked. However, efficient production lines cannot be ranked. Now, to determine the best production line and also to evaluate efficient production lines, a combined method of AHP and entropy is used.

Table 5. results of DEA for evaluation of Kalleh company's production lines.

Production Lines	Description	Lower Bound of Efficiency	Upper Bound of Efficiency
Line 1	Low-fat milk	1	1
Line 2	High-fat milk	0.93	0.96
Line 3	Fortified milk	0.89	0.91
Line 4	Spindle ice cream	1	1
Line 5	Tiramisu ice cream	0.78	0.79
Line 6	Cup ice cream	0.79	0.81
Line 7	Chocolate milk	0.89	0.93
Line 8	Kefir drink	1	1
Line 9	Natural plant-based drink	0.75	0.79
Line 10	Irish butter	0.83	0.88
Line 11	French butter	0.79	0.80
Line 12	US butter	0.77	0.81
Line 13	Seven low-fat yogurt	0.96	1
Line 14	Seven high-fat yogurt	1	1
Line 15	Minarin khalifeh confectionery	0.67	0.72
Line 16	Minarin premium confectionery	0.69	0.73
Line 17	Camembert cream cheese	0.79	0.82
Line 18	Kalait cheese	0.73	0.76
Line 19	Prato cheese	0.69	0.75
Line 20	Camembert cheese	0.61	0.67
Line 21	Orange cutlet	0.59	0.63

Now, efficient production lines 1, 4, 8, and 14 are considered as options. The inputs include raw material costs, human resource costs, distribution and sales network costs, and product processing time as negative criteria. Profit, production tonnage, customer satisfaction, and product lifetime are considered positive criteria. Then, the weight of these criteria is determined using the entropy method, and the options are ranked using the AHP. The problem-solving process is presented below.

As observed in the previous section, the performance of production lines was evaluated. However, efficient production lines have the same number, and no specific distinction can be made between them. For this purpose and to rank these lines, a combined method of AHP and entropy is used. Initially, to determine the weight of criteria using the entropy method, a decision matrix is formed. This decision matrix includes 4 production lines 1, 4, 8, and 14, and the criteria are raw material costs, human resource costs, distribution and sales network costs, product processing time, profit, product lifespan, customer satisfaction, and production tonnage. Thus, the decision matrix is formed with these criteria and options. Since each criterion has a different unit of measurement, the data are normalized using equations 24 and 25. Now, using equations 26 and 27, the upper and lower limits of entropy for each criterion are calculated. The results are presented in *Table 6*.

Table 6. Entropy of each criterion.

Criteria	Final Weight
Raw material cost	[0590,0.621]
Human resource cost	[0.586,0.615]
Distribution and sales network costs	[0.545,0.566]
Product processing time	[0.498,0.527]
Profit	[0.654,0.667]
Product Lifetime	[0.381,0.394]
Customers' satisfaction	[0.664,0.667]
Production tonnage	[0.515,0.521]

At this stage, using equation 28, the lower and upper limits of the deviation degree for each criterion are calculated. In this section, the final weight of each criterion is determined using equation 29. The results are shown in *Table 7*.

Table 7. Final weight of criteria.

Criteria	Final Weight
Raw material cost	[0.111,0.115]
Human resource cost	[0.112,0.116]
Distribution and sales network costs	[0.127,0.128]
Product processing time	[0.138,0.141]
Profit	[0.097,0.097]
Product Lifetime	[0.173,0.177]
Customers' satisfaction	[0.094,0.097]
Production tonnage	[0.136,0.140]

As observed, the highest weight belongs to the product lifetime and production tonnage. Now, it is necessary to solve the problem using the AHP method and rank the efficient production lines. For this purpose, initially, using *Table 1*, all lines are evaluated and compared based on the considered criteria. *Tables 8-15* represent the experts' opinions regarding the comparison of production lines according to the criteria.

Table 8. Pairwise comparison of production lines according to the raw material cost criterion.

Raw Material Cost								
Production Lines	**Line 14**		**Line 8**		**Line 4**		**Line 1**	
Line 1	2	4	4	6	2	4	1	1
Line 2	4	6	6	8	1	1	0.25	0.5
Line 3	2	4	1	1	0.125	0.166667	0.166667	0.25
Line 4	1	1	0.25	0.5	0.166667	0.25	0.25	0.5

Table 9. Pairwise comparison of production lines according to the human resource cost criterion.

Human Resource Cost								
Production Lines	**Line 14**		**Line 8**		**Line 4**		**Line 1**	
Line 1	4	6	6	8	2	4	1	1
Line 2	2	4	6	8	1	1	0.25	0.5
Line 3	0.25	0.5	1	1	0.125	0.1667	0.125	0.1667
Line 4	1	1	2	4	0.25	0.5	0.1667	0.25

Table 10. Pairwise comparison of production lines according to the distribution and sales network costs criterion.

Distribution and Sales Network Costs								
Production Lines	**Line 14**		**Line 8**		**Line 4**		**Line 1**	
Line 1	2	4	6	8	0.25	0.5	1	1
Line 2	2	4	8	9	1	1	2	4
Line 3	0.25	0.5	1	1	0.1111	0.125	0.125	0.1667
Line 4	1	1	2	4	0.25	0.5	0.25	0.5

Table 11. Pairwise comparison of production lines according to the product processing time criterion.

Product Processing Time								
Production Lines	**Line 14**		**Line 8**		**Line 4**		**Line 1**	
Line 1	6	8	0.25	0.5	0.125	0.1667	1	1
Line 2	8	9	2	4	1	1	6	8
Line 3	6	8	1	1	0.25	0.5	2	4
Line 4	1	1	0.125	0.1667	0.11111	0.125	0.125	0.1667

Table 12. Pairwise comparison of production lines according to the profit criterion.

Profit								
Production Lines	**Line 14**		**Line 8**		**Line 4**		**Line 1**	
Line 1	2	4	2	4	1	1	1	1
Line 2	2	4	2	4	1	1	1	1
Line 3	1	1	1	1	0.25	0.5	0.25	0.5
Line 4	1	1	1	1	0.25	0.5	0.25	0.5

Table 13. Pairwise comparison of production lines according to the product lifetime criterion.

Product Lifetime								
Production Lines	**Line 14**		**Line 8**		**Line 4**		**Line 1**	
Line 1	0.25	0.5	0.1667	0.25	0.125	0.1667	1	1
Line 2	6	8	4	6	1	1	6	8
Line 3	2	4	1	1	0.1667	0.25	4	6
Line 4	1	1	0.25	0.5	0.125	0.1667	2	4

Table 14. Pairwise comparison of production lines according to the customer's satisfaction criterion.

Customers' Satisfaction								
Production Lines	**Line 14**		**Line 8**		**Line 4**		**Line 1**	
Line 1	1	1	2	4	2	4	1	1
Line 2	0.25	0.5	1	1	1	1	0.25	0.5
Line 3	0.25	0.5	1	1	1	1	0.25	0.5
Line 4	1	1	2	4	2	4	1	1

Table 15. Pairwise comparison of production lines according to the production tonnage criterion.

Production Tonnage								
Production Lines	**Line 14**		**Line 8**		**Line 4**		**Line 1**	
Line 1	4	6	6	8	4	6	1	1
Line 2	0.25	0.5	4	6	1	1	0.1667	0.25
Line 3	0.1667	0.25	1	1	0.1667	0.25	0.125	0.1667
Line 4	1	1	4	6	2	4	0.1667	0.25

The relative weight of each option is calculated at this stage using equations 20, 21, and 22. The final results are presented in *Table 16*. Now, to calculate the final weight of each option, the obtained weights using the entropy method are multiplied by the matrix in Table 16, and the final weight of each option is calculated. The final weight is presented in *Table 17*.

Table 16. Relative weight of production lines.

Production Lines	Production Tonnage		Customers Satisfaction		Products' Lifetime		Profit		Product Processing Time		Distribution And Sales Network		Human Resource Costs		Raw Material Costs	
Line 1	0.757	1.000	0.667	1.000	0.000	0.024	0.667	1.000	0.196	0.286	0.368	0.635	0.713	1.000	0.542	0.835
Line 2	0.158	0.264	0.000	0.167	0.778	1.000	0.667	1.000	0.776	1.000	0.706	1.000	0.347	0.577	0.417	0.656
Line 3	0.000	0.019	0.000	0.167	0.211	0.371	0.000	0.167	0.311	0.508	0.000	0.023	0.000	0.025	0.074	0.202
Line 4	0.233	0.414	0.667	1.000	0.063	0.158	0.000	0.167	0.000	0.008	0.128	0.277	0.088	0.200	0.028	0.116

Table 17. Weight and rankings of production lines.

Efficient Production Line	Final Grey Weight	Final Crisp Weight	Final Rankings
Line 1	[0.44,0.67]	0.558	2
Line 2	[0.5,0.74]	0.62	1
Line 3	[0.088,0.2]	0.145	4
Line 4	[0.13,0.27]	0.204	3

As can be seen, line 4 is determined as the best production line among the efficient production lines.

4.1 | Sensitivity Analysis

As observed, the highest weight was related to the product lifetime criterion. For this reason, in this section, the weight of this criterion is exchanged with other criteria in pairs and the results are examined. The results are presented in *Table 18*. Also, *Fig. 4* shows the sensitivity analysis more clearly.

Table 18. Results of sensitivity analysis.

Production Lines	Lifetime and Raw Material Costs	Lifetime and Human Resource Costs	Lifetime and Distribution and Sales Network Costs	Lifetime and Product Processing Time	Lifetime and Profit	Lifetime and Customer Satisfaction	Lifetime and Production Tonnage
Line 1	0.6	0.61	0.58	0.566	0.623	0.624	0.591
Line 2	0.598	0.59	0.62	0.62	0.616	0.557	0.595
Line 3	0.13	0.127	0.13	0.149	0.128	0.128	0.134
Line 4	0.2	0.205	0.208	0.199	0.202	0.261	0.212

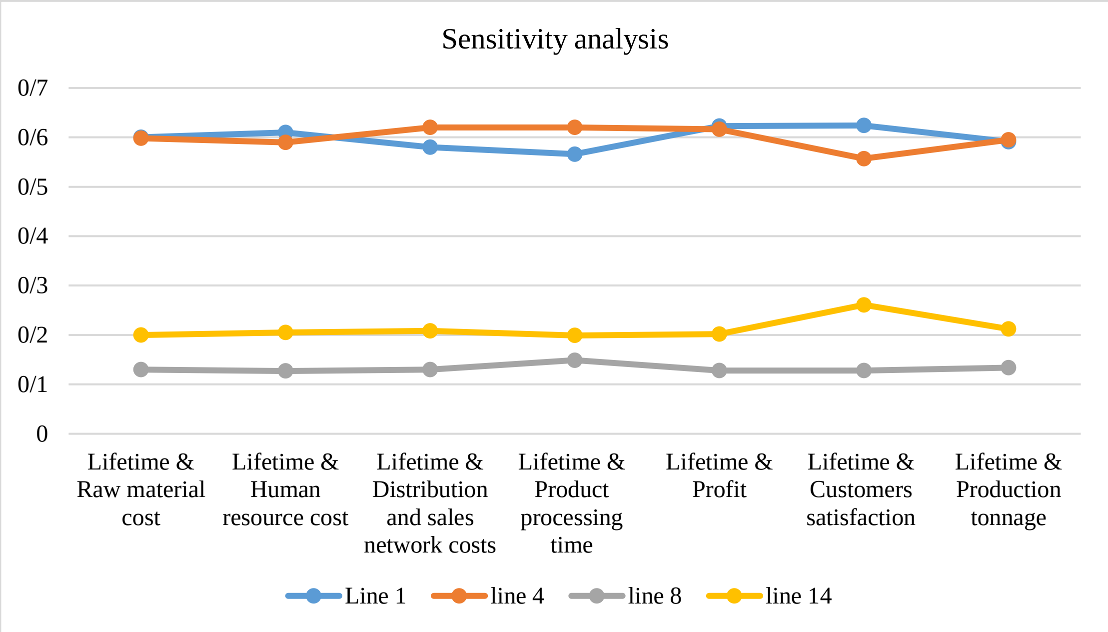

Fig. 4. Results of sensitivity analysis.

As can be seen, the positions of lines 1 and 4 are constantly changing and the best production line is moving. This indicates the sensitivity of the proposed model to the weight of the criteria, which is determined using the entropy method in the proposed method of this study.

5 | Conclusions

In this research, initially, the DEA method was developed in a grey environment to address real-world uncertainty. This method was applied to Kalleh Company's production lines for the first time in the literature, and the performance evaluation of these lines was determined. As observed, four production lines 1, 4, 8, and 14 were selected as efficient production lines.

Then, to evaluate the efficient units produced using the grey DEA method, a combined approach of grey AHP and grey entropy was used. In other words, for the first time in the literature, a combined AHP and entropy method was used to evaluate efficient production lines in Kalleh Company. Finally, all three proposed methods in this research were developed to deal with uncertainty in a grey environment.

As observed, based on this combined method, production line 4 was selected as the best production line. Additionally, in the sensitivity analysis, the weights of the criteria were swapped in pairs, and the final ranking of production lines was determined. Given the continuous changes in production lines, the importance of criteria weights received more attention. To develop the proposed method in the future, it can be extended to fuzzy environments or fuzzy developments for better handling of uncertainty.

Also, due to the more reliable results of group decision-making, the proposed method can be expanded in a group decision-making environment. Furthermore, the proposed method applies to other manufacturing companies and performance evaluation of production lines and other industrial engineering areas such as supplier and distributor evaluation in the supply chain, employee and personnel performance evaluation, performance evaluation of service units like universities, hospitals, banks, and so on.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability

All data are included in the text.

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