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# The Investment Policy for The Sustainability of The Electricity Supply Chain: A Case in The Power Industry

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## Abstract

The waste of available resources and the harmful effects of toxic emissions play a fundamental role in the sustainability assessment of energy, production, transmission, and distribution sectors in the power industry. Investing in appropriate capacity allocation and accurate resource control can significantly reduce the negative effects of pollutant gas emissions and wasted energy in the electricity supply chain. The current paper introduces a DEA-based model for sustainability evaluation of the electricity supply chain through harmful substances management and greenhouse gas (GHG) control in the energy, power plant, transmission, and distribution sectors. The study aims to determine the limited and effective investment regions of supply chain divisions for pollutant gas abatement. Indeed, the proposed approach distinguishes between effective and limited investment opportunities for 10 supply chain divisions, as the investment increases in the divisions with a high level of investment opportunities provide a significant decrease in flare gas and greenhouse gases (GHG) in the energy and power plant sectors and wasted energy harness in transmission and distribution lines. In 60% of supply chains, the results show that there is a distribution line network with a high level of good investment opportunities.

**Keywords**:
Appropriate Allocation
Effective Investment
Environmental Preservation
Pollutant Emissions

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## INTRODUCTION

One of the major problems of environmental pollution is the excessive utilization of fossil fuels such as oil, fuel oil, coal, and gas. Fossil fuel consumption creates steam, carbon dioxide (CO2), and oxide nitration into the air. Moreover, the available toxic gases in the air are combined with atmospheric precipitation to create acid rain and water pollution in rivers, lakes, and underground reservoirs. The destructive effects of harmful substances and pollution gases have emerged at global and area levels. Moreover, it is necessary to determine effective regions of investment for energy and power plant sections and transmission and distribution lines where there are significant capacities for undesirable effects. Each supply chain or decision-making unit (DMU) is built of five stages, and the partners of each stage are connected by intermediate measures to the successor stage. In this conformation oil and gas fields and refineries provide demand fuels of power plants and district power plants transfer the produced power from regional power companies to the area distribution companies to be dispatched to consumers or residents of their area.

This study will answer the question of how a DMU or a supply chain designates effective investment regions to decrease pollution gas emissions and waste energy in the energy, power plant, transmitter, and distributor sectors. In managerial disposability, a firm increases a directional vector of inputs to decrease a directional vector of undesirable outputs by utilizing technology innovation on undesirable outputs. A coal-fired power plant, for example, produces more electricity by burning more coal. Even if the power plant increases the amount of coal combustion, the increase can reduce the amount of CO2 emissions by a managerial effort, such as using high quality coal with fewer CO2 emissions and/or an engineering effort to utilize new generation technology (e.g., clean coal technology) that can reduce the amount of CO2 emissions. Furthermore, under managerial disposability, supply chain management should propose a managerial effort to emissions level control, such as handling flare gas, reducing pollution emissions and greenhouse gases (GHGs) in energy sections, and harnessing wasted energy in transmitter and distributor networks.

This paper determines divisions of a supply chain that have the required capacities for investment to decrease undesirable output. Moreover, divisions with limited or effective investment opportunities are distinguished here. As a result, the highest amount of electricity can be produced in divisions with high and effective opportunities. Engineering efforts in this regard can be effective in increasing economic achievements.

In this study, managerial disposability is achieved through investment in the energy section to reduce flare gas emissions and protect the environment, the construction and commissioning of renewable power plants, and pollution emission prevention in the power plant section. Meanwhile, transmission and distribution lines are equipped with improved engineering facilities for power loss reduction. Also, dual-role factors control the cost recovery of flare gas, the inner electricity consumption of power plants (technical and non-technical), and the specialized workforce for the power loss inhibition in transmission operations.

In the current paper, two concepts of natural and managerial disposability are applied to environmental assessment as the inputs are separated into two categories under natural and managerial disposability.

The remainder of this paper is organized as follows: In the next section, an appropriate literature review on how DEA has been used for research in investment opportunities and technology innovation is presented. Then, the following section is devoted to introduce a procedure to calculate supply chain efficiency in the presence of two categories of inputs, desirable and undesirable products, dual-role factors, and the two sets intermediate measures. In the next section, a case study is presented to demonstrate the applicability of the proposed method to the Iranian power industry. Finally, the last section presents the conclusions.

## LITERATURE REVIEW

The following subsections briefly summarize various studies on environmental and operational assessment, green supply chain management (GSCM), and dual-role factors.

### Environmental and operational assessment

To include the two concepts of natural and managerial disposability in environmental assessment technology and account for the harmful substances' prevention and negative impact on productivity, (Amirteimoori et al., 2018) presented an approach for sustainability assessment in gas companies in the presence of undesirable factors.

(Sueyoshi et al., 2009) discussed the history of data envelopment analysis (DEA) from the contributions of Cooper, who first invented DEA in the 19th century.

(Sueyoshi et al., 2010) proposed a description of the conventional uses of DEA for environmental assessment. Then, the concept of natural and managerial disposability was applied as a conceptual basis for preceding research efforts. (Sueyoshi et al., 2017) calculated returns to scale for a large photovoltaic power station in the United States and Germany.

(Sueyoshi et al., 2014) proposed a staged DEA model for operational and environmental assessment of Japanese industrial sectors. They calculated a unified efficiency score under natural and managerial disposability of the DMU by resource utilization and technology innovation. (Sueyoshi et al., 2014) measured returns to damage under undesirable congestion and damages to return under desirable congestion by DEA environmental assessment. Furthermore, they proposed an intermediate approach for social sustainability measurement. Additionally, (Sueyoshi et al., 2017) proposed a new intermediate approach, analytically located between radial and nonradial measures, as the third alternative. The new approach measures the degree of unified inefficiency for each production factor and determines the level of total unified inefficiency from the average sum of this inefficiency. Sueyoshi et al.'s discussed analytical features by comparing the intermediate approach with radial and nonradial models. They compared radial, nonradial, and intermediate approaches for DEA environmental assessment. This study discussed analytical features by comparing the intermediate approach with radial and nonradial models. Therefore, the proposed approach determined the methodological bias issue from the practice of the three DEA approaches (radial, nonradial, and intermediate) in the operational and environmental assessment of the organization. (Sueyoshi et al., 2012) compared radial, nonradial, and intermediate approaches for DEA environmental assessment.

### Green supply chain management (GSCM)

(Kao, 2009) modified the conventional DEA model by taking into account the series relationship of the two sub-processes within the whole process.

(Ton et al., 2010) proposed a slacks-based network DEA model called network SBM. (Tavana et al., 2013) extended the EBM model proposed by (Ton et al., 2010) and proposed a new network EBM (NEMB).

(Tajbakhsh et al., 2015) proposed a multi-stage DEA model to evaluate the sustainability of a chain of business partners. They assessed supply chain sustainability in the banking sector and the beverage case.

(Pouralizadeh, 2021) proposed two models for sustainability assessment of the electricity supply chain via reduction of wasted resources and pollution emissions management. She indicated that, generally, the supply chains are evaluated under natural and management disposability based on unified operational and environmental efficiency. Also, the supply chain divisions with the necessary facilities and new technology to confront undesirable outputs can utilize more inputs (under managerial disposability) for more output production without increasing undesirable outputs. Those supply chain divisions that lack the adequate ability to reduce undesirable outputs should prevent the increase of undesirable outputs by using available capacities control under natural disposability.

Based on DEA, (Pouralizadeh, 2020 b) presented a radial model to study investment regions of supply chain divisions. She also investigated whether investing in the electricity supply chain division can effectively reduce the number of undesirable outputs or whether increasing the inputs under managerial disposability has a limited effect on reducing the number of undesirable outputs.

(Pouralizadeh et al., 2020 a) proposed a new DEA-based model for sustainability evaluation of an electricity supply chain in the presence of undesirable outputs. They planned a supply chain with five stages and fifteen divisions from different districts in Iran. Also, the weak disposability assumption was adopted for activity level control in production activity. The proposed model can determine the type and size of inputs to control undesirable outputs. They also proposed a radial model for the performance assessment of the electricity supply chain. By scaling down the production levels, Pouralizadeh et al.'s model dramatically decreased harmful emissions in the energy and power plant sectors and harnessed power losses in transmission and distribution networks.

**Dual-role factors**

(Farzipoor, 2010 a) proposed a model for selecting third-party reverse logistics providers in the presence of multiple dual-role factors and proposed (2010 b) a model for selecting 3PL providers in the presence of both dual-role factors and imprecise data.

(Mirhedayrian et al., 2014) presented a DEA-based model in the presence of undesirable outputs, dual-role factors, and fuzzy data in a supply chain. They indicated a method to improve environmental performance through green supply chain management and incorporated dual-role factors and undesirable output into the NSBM model proposed by (Tone et al., 2017).

**Fundamental Concepts**

In this section, fundamental concepts for environmental and operational assessment of an electricity supply chain and the approach to calculating the unified efficiency (operational and environmental) of the electricity supply chain are introduced.

**Weak, strong, natural, and managerial disposability of the supply chain divisions**

Let us now suppose a supply chain (or DMU) is concluded with five stages: supplier, manufacturer, transmitter, distributor, and customer. We treat each supply chain as a DMU. Let us consider $h_s, h_m, h_t, h_d, h_c$ the number of divisions in the supplier, manufacturer, transmitter, distributor, and customer. The electricity supply chains are power suppliers in power production activities. They are comprised of fuel suppliers (oil and gas fields), power producers (power plants), electricity transmitters (transmission lines), power distributors (distribution lines), and final customers. These entities collaborate on power production and management in economic business.

Let us suppose $X_j^h = (x_{1j}^h, x_{2j}^h, \dots, x_{3j}^h)^T > 0$ $G_j^h = (g_{1j}^h, g_{2j}^h, \dots, g_{sj}^h)^T > 0$, presents column vectors of inputs and desirable and undesirable outputs of the h^th^ division in the j^th^ supply chain.

The weak disposability concept specifies two output vectors of the h^th^ division $(G^h, B^h)$ as follows:

$$P_w^h(x) = \left\{ (G^h, B^h) : G^h \le \sum_{j=1}^{n} G_j^h \lambda_j^h ,\ B^h = \sum_{j=1}^{n} B_j^h \lambda_j^h ,\ X^h \ge \sum_{j=1}^{n} X_j^h \lambda_j^h ,\ \sum_{j=1}^{n} \lambda_j^h = 1 ,\ (j = 1, \dots, n) \right\} \quad (1)$$

The subscript (j) shows the j^th^ supply chain (or DMU) and $\lambda_j$ indicates the j^th^ intensity variable (j = 1,…,n). The inequality constraints ($X^h \ge \sum_{j=1}^{n} X_j^h \lambda_j^h$), ($G^h \le \sum_{j=1}^{n} G_j^h \lambda_j^h$) indicate strong disposability on inputs and desirable outputs from the h^th^ division, respectively, and $B^h = \sum_{j=1}^{n} B_j^h \lambda_j^h$ measures congestion on undesirable outputs from the h^th^ division. Similarity, strong disposability is specified on the two output vectors of the h^th^ division as follows:

$$P_s^h(x) = \left\{ (G^h, B^h) : G^h \le \sum_{j=1}^{n} G_j^h \lambda_j^h ,\ B^h \le \sum_{j=1}^{n} B_j^h \lambda_j^h ,\ X^h \ge \sum_{j=1}^{n} X_j^h \lambda_j^h ,\ \sum_{j=1}^{n} \lambda_j^h = 1 ,\ (j = 1, \dots, n) \right\} \quad (2)$$

The inequality constraint $B^h \le \sum_{j=1}^{n} B_j \lambda_j$ allows for strong disposability on undesirable outputs. The constraint $\sum_{j=1}^{n} \lambda_j = 1$ is incorporated into the two expressions, which indicates variable return to scale in the production processes. The production technology set to the definition of natural and managerial disposability is specified by the following two types of output vectors and an input vector for the h$^{th}$ division of the supply chain:

$$P_N^h(x) = \left\{ (G^h, B^h) : G^h \le \sum_{j=1}^{n} G_j^h \lambda_j^h, B^h \le \sum_{j=1}^{n} B_j^h \lambda_j^h, X^h \ge \sum_{j=1}^{n} X_j^h \lambda_j^h, \sum_{j=1}^{n} \lambda_j^h = 1, (j = 1, \ldots, n) \right\} \quad (3)$$

$$P_M^h(x) = \left\{ (G^h, B^h) : G^h \le \sum_{j=1}^{n} G_j^h \lambda_j^h, B^h \le \sum_{j=1}^{n} B_j^h \lambda_j^h, X^h \le \sum_{j=1}^{n} X_j^h \lambda_j^h, \sum_{j=1}^{n} \lambda_j^h = 1, (j = 1, \ldots, n) \right\} \quad (4)$$

Here, $P_N^h(x)$ is defined as a production possibility set under natural (N) disposability and $P_M^h(x)$ managerial (M) disposability from the h$^{th}$ division. Both production technology sets have common constraints, $G^h \le \sum_{j=1}^{n} G_j^h \lambda_j^h$, $B^h \le \sum_{j=1}^{n} B_j^h \lambda_j^h$, under natural and managerial disposability.

**The operational and environmental performance assessment**

Let us suppose $X_j = (x_{1j}, x_{2j}, \ldots, x_{mj})^T > 0$, $G_j = (g_{1j}, g_{2j}, \ldots, g_{sj})^T > 0$, $B_j = (b_1, b_2, \ldots, b_{hj})^T > 0$ presents column vectors of inputs, desirable and undesirable outputs in j$^{th}$ DMU, respectively. (Sueyoshi et al., 2014) proposed a radial model to measure the unified efficiency (operational and environmental) of the k$^{th}$ DMU under natural and managerial disposability of inputs as follows:

$$\theta = \min \xi + \varepsilon \left( \sum_{i=1}^{m^-} R_i d_i + \sum_{q=1}^{m^+} R_q d_q + \sum_{f=1}^{h} R_f d_f \right)$$

$$\sum_{j=1}^{n} x_{ij}^{-} \lambda_j + d_i = x_{ik}^{-} \qquad i = 1, \ldots, m^-$$

$$\sum_{j=1}^{n} x_{qj}^{+} \lambda_j - d_q^x = x_{qk}^{+} \qquad q = 1, \ldots, m^+$$

$$\sum_{j=1}^{n} g_{rj} \lambda_j + \xi g_{rk} = g_{rk} \qquad r = 1, \ldots, s$$

$$\sum_{j=1}^{n} b_{fj} \lambda_j - d_f^b = b_{fk} \qquad f = 1, \ldots, h$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j \ge 0,\ j = 1, \ldots, n,\ \ \xi URS,\ i = 1, \ldots, m^-,\ q = 1, \ldots, m^+,\ f = 1, \ldots, h$$

(5)

In this model, the number of original m inputs is separated into two categories $m^-$ (under natural disposability) and $m^+$ (under managerial disposability). In addition, $\varepsilon$ is a small amount, and it is considered as 0.0001 for our computation convenience. It is possible for the model to use $\varepsilon = 0$ in the model (5). In proposed model $R_i^x, R_q^x, R_f^b$ are specified by the decision maker as follows:

$$R_i^x = (m + s + h)^{-1} \left( \max \{ x_{ij} \mid j = 1, \ldots, n \} - \min \{ x_{ij} \mid j = 1, \ldots, n \} \right)^{-1}$$

$$R_q^x = (m + s + h)^{-1} (\max \{ x_{qj} \mid j = 1, \ldots, n \} - \min \{ x_{qj} \mid j = 1, \ldots, n \})^{-1}$$

$$R_f^b = (m + s + h)^{-1} \left( \max \{ b_{fj} \mid j = 1, \ldots, n \} - \min \{ b_{fj} \mid j = 1, \ldots, n \} \right)^{-1}$$

(6)

A unified efficiency score under natural and managerial disposability is measured as follows:

$$UEMN = 1 - \left[ \xi^* + \varepsilon \left( \sum_{i=1}^{m^-} R_i^x d_i^{x*} + \sum_{q=1}^{m^+} R_q^x d_q^{x*} + \sum_{f=1}^{h} R_f^b d_f^{b*} \right) \right]$$

(7)

where the inefficiency score and all slack variables are determined on the optimality of model(5).

## METHODOLOGY

Suppose a supply chain (or DMU) is concluded from a five-stage supplier, manufacturer, transmitter, distributor, and customer. Let us consider $h_s, h_m, h_t, h_d, h_c$ are the number of divisions in the supplier, manufacturer, transmitter, distributor, and customer. The electricity supply chains are comprised of fuel suppliers (oil and gas fields), power producers (power plants), electricity transmitters (transmission lines), power distributors (distribution lines), and final customers. These entities collaborate in power production and management to achieve economic growth. In this study, the supply chains have been selected in the northern, southern, eastern, western, and central districts of Iran, where oil and gas fields and refineries provide demand fuel for power plants, and district power plants transfer the produced power by regional power companies to the area distribution companies to be dispatched to consumers or residents of their area. Moreover, the intermediated measures are sent from oil and gas fields to power plants, from power plants to transmission companies, from transmission companies to distribution companies, and, finally, to customers. Furthermore, the inverse intermediate measures exit transmitter divisions and enter manufacture divisions, exit manufacture divisions, and enter supplier divisions. These measures indicate the entities' relationships in the supply chain. However, each division of entities operates independently from other divisions of entities per stage in production activities and supply chains compete for high efficiency in economic business (see Pouralizadeh et al., 2020 a). Fig. 1 shows an electricity supply chain structure in the power industry. The electricity supply chains are power suppliers in power production activities. They are comprised of fuel suppliers (oil and gas fields), power producers (power plants), electricity transmitters (transmission lines), power distributors (distribution lines) and final customers. These entities collaborate to power production and management in economic business.

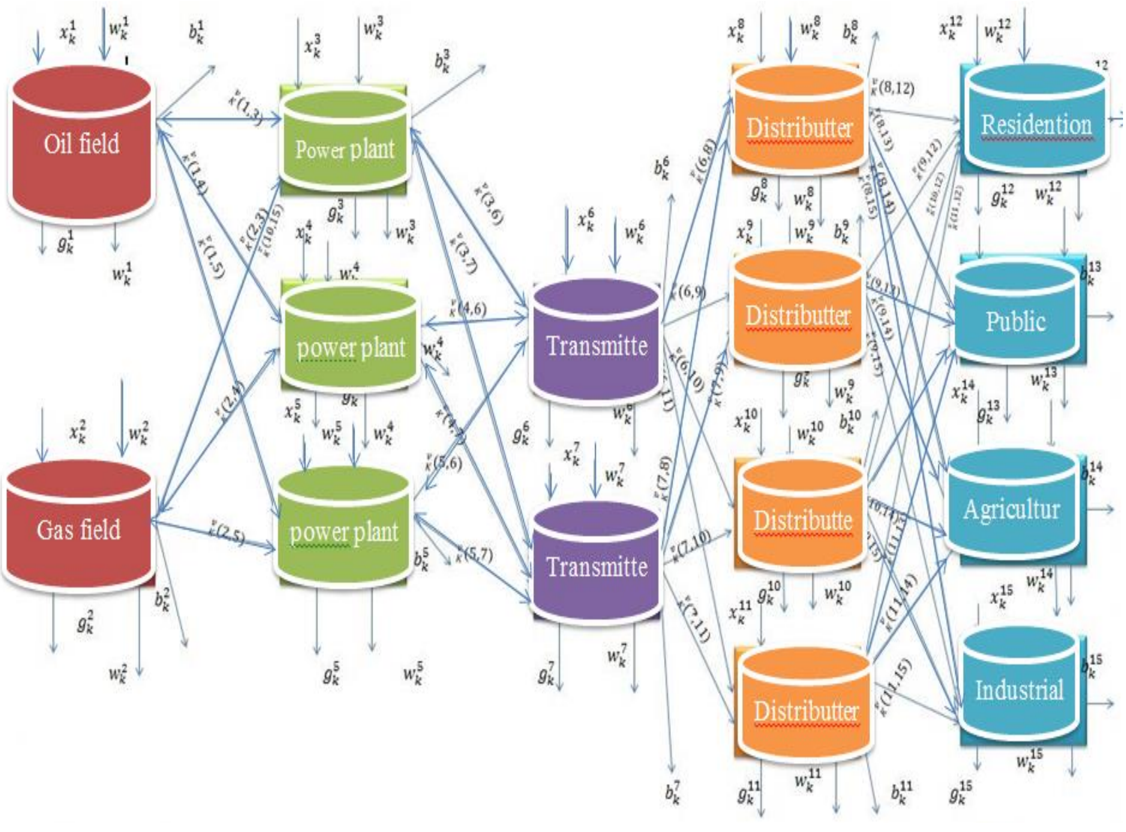


Fig. 1. The supply chain structure

In this study, the supply chains have been built in northern, southern, eastern, western and central districts in Iran. In this conformation Oil and gas fields and refineries provide demand fuels of power plants and district power plants Transfer produced power by regional power companies to the area distribution companies to dispatching to consumers or residents of their area. Other words, each supply chain or DMU is built of five stages and partners of each stage connected by intermediate measures to the successor stage. Supply chains are comparable and compete in the power industry. In Fig. 1 is depicted intermediated measures sent from oil and gas fields to power plants, from power plants to transmissions companies, from transmissions companies to distributions companies and finally from them to customers. Furthermore, the inverse intermediate measures exit from transmitter divisions and enter to manufacture divisions and exit from manufacture divisions and enter to supplier divisions. These measures indicate entities' relationship in the supply chain. However, each division of entities operates independent from other divisions of per stage in production activities and supply chains compete to high efficiency earn in economic business (see Pouralizadeh et al.,2020 b).

## Modeling of effective investment

Let us consider $x_{mj}^{h}$, $g_{rj}^{h}$, $b_{fj}^{h}$ , $w_{ej}^{h}$ indicate the m<sup></sup>th input $(m=1,...,M)$, the r<sup></sup>th desirable outputs $(r=1,...,S)$, the f<sup></sup>th undesirable outputs $(f=1,...,F)$, and the e<sup></sup>th dual-role factors $(e=1,...,E)$ of the h<sup></sup>th division $(h=1,...,H)$ in the j<sup></sup>th $(j=1,...,n)$ supply chain, respectively. Also, $\bar{x}_{mj}^{h}$ , $\tilde{x}_{mj}^{h}$ indicate the original m inputs are separated into two categories $m^{-}$ and $m^{+}$, as $M=m^{-}+m^{+}$. Furthermore, $v_{pj}^{(h,h')}$ represents the intermediate measures between the $h$ th division to the $h'$ division of the j<sup></sup>th supply chain. The subscript (p, j) indicates the p<sup></sup>th intermediate measure $(p=1,...,P_h)$ in the j<sup></sup>th supply chain $(j=1,...,n)$, and $z_{aj}^{(h',h)}$ represents inverse intermediate measures exiting the $h'$ th division and entering the $h$ th division. The subscript (a, j) indicates the a<sup></sup>th intermediate measure $(a=1,...,A_h)$ in the j<sup></sup>th supply chain $(j=1,...,n)$. Model (5) can be further developed as a network model by incorporating the two categories of intermediate measures and dual-role factors for each supply chain division to assess the overall supply chain.

The first and second category constraints correspond to inputs set under natural and managerial disposability. Also, the third and fourth category constraints are related to desirable and undesirable outputs, and the fifth, sixth, and seventh category constraints correspond to dual-role factors of the supplier, manufacture, and transmitter divisions. The eighth, ninth, tenth, and eleventh category constraints correspond to intermediate measures sent from supplier divisions to manufacturer divisions, manufacturer divisions to transmitter divisions, transmitter divisions to distributor divisions, and from them to customer divisions, respectively. The twelfth and thirteenth category constraints are related to inverse intermediated measures that exit manufacturer divisions and enter supplier divisions. Also, the fourteenth and fifteenth category constraints correspond to inverse intermediate measures that exit transmitter divisions and enter manufacture divisions. The last category constraints relates to variable returns to scale in the production process.

$$\theta = Max \sum_{h=1}^{H} W_h [\xi_h + \varepsilon(\sum_{i=1}^{m^-} R_i^h d_i^h + \sum_{q=1}^{m^+} R_q^h d_q^h + \sum_{f=1}^{F} R_f^h d_f^h + \sum_{h'=1}^{H} \sum_{p=1}^{P} R_p s_p^{(h,h')} + \sum_{h'=1}^{H} \sum_{a=1}^{A} R_a s_a^{+(h',h)}]$$

$$\sum_{j=1}^{n} \bar{x}_{ij}^h \lambda_j^h + d_i^h = \bar{x}_{ik}^h \qquad i = 1,...,m_h^-, \ h = 1,...,H$$

$$\sum_{j=1}^{n} \tilde{x}_{qj}^h \lambda_j^h - d_q^h = \tilde{x}_{qk}^h \qquad q = 1,...,m_h^+, \ h = 1,...,H$$

$$\sum_{j=1}^{n} g_{rj}^h \lambda_j^h + \xi^h g_{rk}^h = g_{rk}^h \qquad r = 1,...,S_h \ , h = 1,...,H$$

$$\sum_{j=1}^{n} b_{fj} \lambda_j^h - d_f^h = b_{fk}^h \qquad f = 1,...,F_h \ , h = 1,...,H$$

$$\sum_{j=1}^{n} w_{ej}^h \lambda_j^h = w_{ek}^h \qquad e = 1,...,E_s \ , h = 1,...,h_s$$

$$\sum_{j=1}^{n} w_{ej}^h \lambda_j^h = w_{ek}^h \qquad e = 1,...,E_m \ , h = 1,...,h_m$$

$$\sum_{j=1}^{n} w_{ej}^h \lambda_j^h = w_{ek}^h \qquad e = 1,...,E_t \ , h = 1,...,h_t$$

$$\sum_{j=1}^{n} \lambda_j^h v_{pj}^{(h,h')} + s_p^{(h,h')} = \sum_{j=1}^{n} \lambda_j^{h'} v_{pj}^{(h,h')} \qquad h = 1,...,h_s \ , p = 1,...,P_s \ , h' = 1,...,h_m$$

$$\sum_{j=1}^{n} \lambda_j^h v_{pj}^{(h,h')} + s_p^{(h,h')} = \sum_{j=1}^{J} \lambda_j^{h'} v_{pj}^{(h,h')} \qquad h = 1,...,h_m \ , p = 1,...,P_m \ , h' = 1,...,h_t$$

$$\sum_{j=1}^{n} \lambda_j^h v_{pj}^{(h,h')} + s_p^{(h,h')} = \sum_{j=1}^{n} \lambda_j^{h'} v_{pj}^{(h,h')} \qquad h = 1,...,h_t \ , p = 1,...,P_t \ , h' = 1,...,h_d$$

$$\sum_{j=1}^{n} \lambda_j^h v_{pj}^{(h,h')} + s_p^{(h,h')} = \sum_{j=1}^{n} \lambda_j^{h'} v_{pj}^{(h,h')} \qquad h = 1,...,h_d \ , p = 1,...,P_d \ , h' = 1,...,h_c$$

$$\sum_{j=1}^{n} \lambda_j^h z_{aj}^{(h',h)} - s_a^{+(h',h)} = z_{ak}^{(h',h)} \qquad h = 1,...,h_s \ , h' = 1,...,h_m \ , a = 1,...,A_s$$

$$\sum_{j=1}^{n} \lambda_j^h z_{aj}^{(h',h)} + s_a^{+(h',h)} = z_{ak}^{(h',h)} \qquad h = 1,...,h_s \ , h' = 1,...,h_m \ , a = 1,...,A_m \qquad *$$

$$\sum_{j=1}^{n} \lambda_j^{h'} z_{aj}^{(h',h)} - s_a^{-(h',h)} = z_{ak}^{(h',h)} \qquad h = 1,...,h_m \ , h' = 1,...,h_t \ , a = 1,...,A_m$$

$$\sum_{j=1}^{n} \lambda_j^{h'} z_{aj}^{(h',h)} + s_a^{-(h',h)} = z_{ak}^{(h',h)} \qquad h = 1,...,h_m \ , h' = 1,...,h_t \ , a = 1,...,A_t \qquad *$$

$$\sum_{j=1}^{n} \lambda_j^h = 1 \qquad h = 1,...,H \ , j = 1,...,n$$

$$\lambda_j \geq 0 \ , s_a^{+(h,h')} \geq 0, \ s_a^{-(h,h')} \geq 0, \ s_p^{(h,h')}, \ \xi \ UR \ , \quad j = 1,...,n \ , \ h = 1,...,H$$

A unified efficiency score under natural and managerial disposability is measured from the supply chain as follows:

$$UENM = 1 - \sum_{h=1}^{H} W_h \left[ \xi_h^* + \varepsilon(R_i^h d_i^{*h} + R_q^h d_q^{*h} + R_f^h d_f^{*h} + \sum_{p=1}^{P} R_p s_p^{*(h,h')} + \sum_{a=1}^{A} R_a S_a^{+*(h',h)}) \right] \tag{9}$$

The objective function of the DMU (or supply chain) is calculated by a weighted average of the optimal inefficiency scores of each division of the supply chain, so the objective function weights could be obtained through an expert opinion process. $\xi^h$ is the inefficiency score of the h[th]

division that is calculated by model 8. Furthermore, the overall efficiency score is calculated by a combination of weighted scores of inefficiency of divisions of supply chains. Also, appropriate combinations of slack variables related to inputs, undesirable outputs, and intermediate measures are considered in the calculation of the objective function.
Therefore, the efficiency score on DMU is measured by where the inefficiency score and all slack variables correspond to inputs under natural and managerial disposability and undesirable outputs, and the two sets of intermediate measures are determined by the optimality of the model (8). Let us consider $t_i^h(i=1,...,m^-)$, $l_q^h(i=1,...,m^+)$, $u_r^h(r=1,...,s)$, $c_f^h(f=1,...,F)$, $y_e^h(e=1,...,E)$ indicate the dual variables corresponding to the $i^{th}$ the category constraints of the input under natural disposability, the $q^{th}$ the category constraints of the input under managerial disposability, the $r^{th}$ the category constraints of the desirable output, the $f^{th}$ category constraints of the undesirable output, and the $e^{th}$ the category constraints of the dual-role factor from the $h^{th}$ division $(h=1,...,H)$ in the model (8).

According to model (8) the supporting hyper plane is expressed for an arbitrary division as follows:

$$t^h\bar{x}^h - l^h\tilde{x}^h + u^h g^h - c^h b^h + w^h y^h + \sigma^h = 0 \quad h=1,...,H \tag{10}$$

In this case, all production factors have a single component. The concept of damage to return (DTR) is defined as $(db/dg)_h/(b/g)_h$ for the $h^{th}$ division in the case of a single component of the two production factors. Based on the sign of $(db/dg)_h/(b/g)_h$ , the type of a supporting hyperplane is specified for an arbitrary division from electricity supply chain on desirable output (g) and undesirable output (b) as follows:
(a) If $(db/dg)_h/(b/g)_h > 0$ ; then the DTR is as positive.
(b) If $(db/dg)_h/(b/g)_h = 0$ ; then the DTR is as zero.
(c) If $(db/dg)_h/(b/g)_h < 0$ ; then the DTR is as negative.

After solving model (8), the desirable outputs congestion or technology innovation for the $h^{th}$ division is identified under the assumption of a unique optimal solution by the dual variables corresponding to desirable output constraints as follows:

$$(db/dg)_h/(b/g)_h = \frac{{-F_g}/{F_b}}{b/g} = \frac{-u/c}{b/g} = \frac{-ug}{bc} \tag{11}$$

Therefore, the sign of damage to return depend on the dual variables sign of desirable output.

(a) If $(u_r^h)^* = 0$ for some (at least one) r, then the ‘zero DTR’ occurs on the $h^{th}$ division from the supply chain under consideration.
(b) If $(u_r^h)^* < 0$ for some (at least one) r, then the ‘negative DTR’ occurs on the $h^{th}$ division from the supply chain under consideration.
(c) If $(u_r^h)^* > 0$ for all r, then the ‘positive DTR’ occurs on the $h^{th}$ division from the supply chain under consideration.
Note, If $(u_r^h)^* < 0$ for some r and $(u_r^h)^* = 0$ for other r, then we consider that the negative DTR occurs on the $h^{th}$ division from the supply chain under consideration. In other words, this case indicates a status of desirable congestion or technology innovation on undesirable outputs. Furthermore, if $(u_r^h)^* < 0$ for all r, then this case indicates the best status because technology innovation increase all of the desirable outputs, and the increase of desirable output always creates abatement of undesirable outputs. Furthermore, If $(u_r^h)^* < 0$ is defined for some r, then it indicates a case to abatement of the number of undesirable outputs. Therefore, the effect of investment is specified by the dual variable $(l_q^h)^*$

as if $(l_q^h)^* > W_h \, \varepsilon R_q^h$ ,then the q$^{th}$ the input for investment under managerial disposability is able to decrease the amount of undesirable output in the $h$ $^{th}$ division, and if $(l_q^h)^* = W_h \, \varepsilon R_q^h$ , then the q$^{th}$ the input has a limited effect on reducing of undesirable output.

**A Real Case**

In our application, we consider 10 supply chains (or DMUs), including oil and gas fields (suppliers) that provide different fuels to power stations, power plants (manufacturers), regional power companies (transmitters), distribution companies (distributors), and customers. Two suppliers are assumed per supply chain: oil and gas companies that satisfy the fuel demand of power plants (intermediate product) and sell fuel as final output.

In the proposed model, suppliers use one input (capital) under natural disposability and one input under managerial disposability (labor) to produce two desirable outputs: oil or gas sold and the share of oil and gas consumption of suplier, and one undesirable output (flaring gas). The dual-role factor is considered the cost of cleanup of burned gas. Each manufacturer includes at least three power plants with different technologies (thermal, combined cycle, gas, hydro, wind, and solar). They use fuels, capital, and labor (under natural disposability) and the labor of hydropower plants under managerial disposability to produce electricity, and they sell it to regional power companies.

To update and increase their capacity, manufacturers can replace the existing plants with more efficient ones or construct new ones. Also, the percentage of gross production is considered the second desirable output. Three undesirable outputs are considered for manufacturers' SOx, NOx, and CO2 emissions. Also, the dual-role factor is the inner consumption of power plants (technical and non-technical consumption). The transmitters transfer electricity from manufacturers to distributing companies, and the capacity and length of the lines are considered inputs under natural disposability, while the number of employees in the department of programming and research is used as an input under managerial disposability. The dual-role factor is considered a specialist workforce in programming and research. The loss in the transmission lines is considered an undesirable output, while the construction of new lines and the percentage share of gross product are desirable outputs.

Distribution companies receive electricity from transmitters and dispatch it to the final consumers. They use two additional capital inputs estimated as capacity and length of the distribution lines under natural disposability and the number of employees of the engineering assistance department and programming as inputs under managerial disposability, two final desirable outputs as the meter of electricity and the percentage of sale share of power, and one undesirable output as losses in the distribution lines. Finally, customers are classified as residential, agricultural, public, or industrial. They use one input under natural disposability and one input under managerial disposability and produce two desirable outputs and one undesirable output (see Pouralizadeh, 2020 b).

In more detail, the parameters used to characterize this supply chain are defined as follows:

$h_s$ : Numerator of divisions in the supplier level ( $h_s$ : 1, 2).

$\bar{x}_{1j}^{h(s)}$ : Capacity of oil ($10^3$ Barrels) and gas ($10^6$ m$^3$) fields of the $h_s$ $^{th}$ supplier in j$^{th}$ supply chain.

$\tilde{x}_{1j}^{h(s)}$ : Number of employees from the $h_s$ $^{th}$ supplier in j$^{th}$ supply chain.

$g_{1j}^{h(s)}$ : Oil ($10^3$ Barrels) and gas ($10^6$ m$^3$) sold to other companies from the $h_s$ $^{th}$ supplier in the j$^{th}$ supply chain.

$g_{2j}^{h(s)}$ : The share of oil and gas consumption of the $h_s$ $^{th}$ supplier from the whole country in the j$^{th}$ supply chain (%).

$b_{1j}^{h(s)}$ : Flaring gas of oil field ($10^3$ barrels) and gas field ($10^6$m$^3$) of the $h_s$ $^{th}$ supplier in the j$^{th}$ supply chain.

$w_{1j}^{h(s)}$: The cost of cleanup of burned gas (flaring gas) of the $h_s$ th supplier in jth supply chain.

$h_m$: Numerator of division in the manufacturer level ($h_m$: 3, 4, and 5).

$\bar{x}_{1j}^{h(m)}$: Power nominal of the $h_m$ th manufacturer in the jth supply chain ($10^6$ Kwh).

$\bar{x}_{2j}^{h(m)}$: Number of employees of the $h_m$ th manufacturer in the jth supply chain.

$\tilde{x}_{1j}^{h(m)}$: Number of hydropower employees of the $h_m$ th manufacturer in the jth supply chain.

$g_{1j}^{h(m)}$: Percentage of new construction of power plant of the $h_m$ th manufacturer in the jth supply chain.

$g_{2j}^{h(m)}$: Percentage of share of gross production of the $h_m$ th manufacturer from the whole country in the jth supply chain (%).

$b_{1j}^{h(m)}$: Emissions of $No_X$ harmful substances of the $h_m$ th manufacturer in the jth supply chain ($10^3$Kg/$10^6$Kwh).

$b_{2j}^{h(m)}$: Emissions of $SO_X$ harmful substance of the $h_m$ th manufacturer in the jth supply chain ($10^3$Kg/$10^6$Kwh).

$b_{3j}^{h(m)}$: Emission of $CO_2$ harmful substance of the $h_m$ th manufacturer in the jth supply chain ($10^3$ Kg/$10^6$ Kwh).

$w_{1j}^{h(m)}$: Inner consumption of power plants (technical and nontechnical consumptions) of the $h_m$ th manufacturer in the jth supply chain ($10^6$ kWh).

$h_t$: Numerator of the divisions the level of the transmitters ($h_t$: 6, 7).

$\bar{x}_{1j}^{h(t)}$: Capacity of transmission lines of the $h_t$ th transmitter in the jth supply chain (MWa).

$\bar{x}_{2j}^{h(t)}$: Length of transmission line of the $h_t$ th transmitter in the jth supply chain (km circuit).

$\tilde{x}_{1j}^{h(t)}$: Number of employees of the department of programing and research of the $h_t$ th transmitter in the jth supply chain.

$g_{1j}^{h(t)}$: New construction of transmission lines of the $h_t$ th transmitter in the jth supply chain (km circuit).

$g_{2j}^{h(t)}$: Percentage of share of gross product of the $h_t$ th transmitter from the whole country in the jth supply chain (%).

$b_{1j}^{h(t)}$: Loos of transmission line of the $h_t$ th transmitter in the jth supply chain (%).

$w_{1j}^{h(t)}$: Number of employees of deputy transfer and exploitation of the $h_t$ th transmitter in the jth supply chain.

$h_d$: Numerator of division in the distributer level ($h_d$: 8, 9, 10, and 11).

$\bar{x}_{1j}^{h(d)}$: Capacity of distribution lines of the $h_d$ th distributer in the jth supply chain (MWa).

$\bar{x}_{2j}^{h(d)}$: Length of the distribution line of the $h_d$ th distributer in the jth supply chain (km).

$\tilde{x}_{1j}^{h(d)}$: Number of employees of the engineering assistance department and programming of the $h_d$ th distributer in the jth supply chain.

$g_{1j}^{h(d)}$: Meter of electricity of the $h_d$ th distributer in jth supply chain.

$g_{2j}^{h(d)}$: Percentage of sale share of the $h_d$ th distributer from the whole country in the jth supply chain (%).

$b_{1j}^{h(d)}$: Percentage of losses of the distribution line of the $h_d$ th distributer in the jth supply chain.

$h_c$: Numerator of division in the customer level ($h_c$: 12, 13, 14, 15).

$x_{1j}^{h(c)}$: Average cost with fuel subsidy of the $h_c$ th customer in the jth supply chain (USD).

$\tilde{x}_{1j}^{h(c)}$: Direct selling of electricity from transmitter company to the $h_c$ th customer in the jth supply chain ($10^6$ kWh).

$g_{1j}^{h(c)}$ : Number of customers of the $h_c$ th customer in the j th supply chain.
$g_{2j}^{h(c)}$ : Sales of electricity of the $h_c$ th customer in the j th supply chain ($10^6$ kWh).
$b_{2j}^{h(c)}$ : Cutting off the power of the $h_c$ th customer in the jth supply chain (minute/year).
$v_{pj}^{(h,h')}$: Material flow from division $h$ to division $h'$ ($10^6$ kVA).
$z_{aj}^{(h_m,h_s)}$: Power flow sent from power plants to oil and gas fields ($10^6$ kVA)
$\xi^h$ : Inefficiency score of ht h division.
$\varepsilon$: A small amount considered as 0.0001 for computation convenience.
Ten supply chains (or DMUs), including oil and gas fields (suppliers) that provide different fuels to power stations, power plants (manufacturers), regional power companies (transmitters), distribution companies (distributors), and customers, are considered here. All data from the two oil and gas fields (suppliers), power plants (manufacturers), regional power companies (transmitters), distribution companies (distributors), and customers (residential, public, agriculture, industrial) are available on the TAVANIR website (2015). The dataset has been collected from the power industry company in Iran and the reference year is 2015 (see Pouralizadeh et al., 2020a) for the detailed data).

The data sets corresponding to the second desirable output of 15 divisions in the 10 supply chains (or DMUs) under analysis are presented in Tables 1 and 2.

Table1: The second desirable output of supplier and manufacturer divisions

| DMU | $g_{2k}^{1}$ | $g_{2k}^{2}$ | $g_{2k}^{3}$ | $g_{2k}^{4}$ | $g_{2k}^{5}$ |
|---|---|---|---|---|---|
| 1 | 0.5 | 5.7 | 11.9 | 7 | 6.2 |
| 2 | 12 | 6.3 | 0.8 | 8.7 | 1.5 |
| 3 | 18.1 | 7.2 | 4.9 | 3 | 1.5 |
| 4 | 22.8 | 10.1 | 1.8 | 8.7 | 1.5 |
| 5 | 7.3 | 2 | 1.6 | 4.9 | 2.5 |
| 6 | 406 | 3 | 1 | 0.8 | 3.9 |
| 7 | 22.6 | 3.7 | 4.9 | 8.7 | 4.2 |
| 8 | 24.4 | 9.3 | 5.3 | 5.3 | 7.9 |
| 9 | 1.6 | 2.2 | 3.9 | 7 | 6.2 |
| 10 | 17.3 | 4.9 | 7 | 5.3 | 1.9 |

Source: http//amar.tavanir.org.ir//tolid and calculations $10^6$ kWh

Table2: The second desirable output of the transmitter and distributer lines

| DMU | $g_{2k}^{6}$ | $g_{2k}^{7}$ | $g_{2k}^{8}$ | $g_{2k}^{9}$ | $g_{2k}^{10}$ | $g_{2k}^{11}$ |
|---|---|---|---|---|---|---|
| 1 | 2.7 | 8.1 | 6.3 | 2.9 | 2.3 | 3.6 |
| 2 | 0.4 | 5.3 | 4.9 | 1.9 | 1.3 | 1 |
| 3 | 5.3 | 1.5 | 4.9 | 2 | 1.3 | 0.7 |
| 4 | 5.3 | 4.1 | 4.9 | 1.3 | 1.7 | 0.8 |
| 5 | 1.5 | 0.6 | 0.7 | 1.9 | 1.3 | 2 |
| 6 | 0.4 | 2 | 4.9 | 0.6 | 1 | 1.9 |
| 7 | 0.6 | 4 | 3.3 | 1.3 | 0.7 | 4.9 |
| 8 | 5 | 3.9 | 2.2 | 3.3 | 2.9 | 3.8 |
| 9 | 1.6 | 2.7 | 6.3 | 1.9 | 2.3 | 2.9 |
| 10 | 1.4 | 3.9 | 2.1 | 2.2 | 2.9 | 3.8 |

Source: http//amar.tavanir.org.ir//entaghl

## RESULTS

We now describe the results obtained using the proposed approach. The model (8) is applied to estimate the efficiency score of supply chains 10 (DMUS) and 15 divisions. The model (8) is solved by a linear programming solver using the GAMS software on an 8GB RAM, 2.0 GHz desktop computer. The runtime of the computation in this study is negligible in the model. The results are listed in Table 3.

The first column of Table 4 represents the global inefficiency score of the 10 supply chains. It can be easily seen that supply chains numbers 1 and 6 reached an inefficiency equal to null. This implies that the other supply chains could improve their performance in some of the divisions. Supply chains numbers 1 and 6 are those that reach the highest efficiency score (1), while supply chain number 3 is the worst performing one.

Table3: The inefficiency scores of supply chains (DMUs)

| DMU | $\theta_o$ | $\xi_k^{S1}$ | $\xi_k^{S2}$ | $\xi_k^{M1}$ | $\xi_k^{M2}$ | $\xi_k^{M3}$ | $\xi_k^{T1}$ | $\xi_k^{T2}$ | $\xi_k^{D1}$ | $\xi_k^{D2}$ | $\xi_k^{D3}$ | $\xi_k^{D4}$ | $\xi_k^{C1}$ | $\xi_k^{C2}$ | $\xi_k^{C3}$ | $\xi_k^{C4}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0.068 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.19 | 0 | 0.33 | 0 | 0.15 | 0.30 |
| 3 | 0.088 | 0 | 0.15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.36 | 0 | 0.28 | 0.33 |
| 4 | 0.106 | 0 | 0 | 0 | 0 | 0 | 0.55 | 0 | 0 | 0 | 0.35 | 0 | 0.23 | 0 | 0.08 | 0 |
| 5 | 0.022 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.58 | 0 | 0 | 0 | 0 |
| 6 | 0.000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0.076 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.32 | 0.32 | 0 | 0.32 |
| 8 | 0.020 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.25 | 0 | 0 | 0 |
| 9 | 0.012 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.26 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0.004 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Looking vertically across the tables, the more efficient divisions are divisions 1, 3, 4, 5, and 7, with efficient values in ten supply chains. This implies that supplier 1, manufacturers 1, 2, 3, and transmitter 2 are the more efficient divisions. Just five efficient units (90%) are obtained in the cases of supplier 2, transmitter 1, distributers 1 and 2, and customer 2.

The values of dual variables related to the divisions of the supplier, power plant, transmission, and distribution on 10 electricity companies in different regions of Iran are presented in Tables 4-18.

Tables 4 and 5 show the quantities of dual variables related to two categories of inputs and the desirable output constraints for oil and gas field.

Table4: The dual variables of inputs and desirable outputs of oil fields

| DMU | Dual variable of inputs under Natural disposability t | Dual variable of inputs under Managerial disposability l | Dual variable of desirable output $u_1$ | Dual variable of desirable output $u_2$ | DTR | Effective of investment |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 0.00000000001549 | 0.0000000005075 | 0.000038800 | 0.00000000 | P | -- |
| 2 | 0.00000000001549 | 0.0000000005075 | 0.00000090645 | 0.003 | P | -- |
| 3 | 0.00000000001549 | 0.0000000005075 | 0.0000081141 | -0.0003035 | N | L |
| 4 | 0.0000011459 | 0.0000000005075 | 0.0000022568 | 0.00033478 | P | -- |
| 5 | 0.00000000001549 | 0.0000000005075 | 0.000014826 | 0.00000000 | P | -- |
| 6 | 0.00000000001549 | 0.0000000005075 | 0.0000022240 | 0.003 | P | -- |
| 7 | 0.00000000001549 | 0.0000000005075 | 0.0000080955 | -0.003 | N | L |
| 8 | 0.00000000001549 | 0.0000000005075 | 0.000013843 | -0.006 | N | L |
| 9 | 0.00000000001549 | 0.0000000005075 | 0.000010189 | 0.004 | P | -- |
| 10 | 0.00000000001549 | 0.0000000005075 | 0.0000027047 | -0.0001011 | N | L |

According to Table 4, $u_2^* < 0$ for supply chains numbers 3, 7, 8, and 10 of the oil field and belonged to negative DRT, indicating technology innovation was essentially necessary for enhancing their efficiency and sustainability.
On the other hand, supply chains numbers 3, 7, 8, and 10 belonged to negative DTR and $l^* = W \varepsilon R_q^x$, so the input for investment under managerial disposability had a limited effect on the decrease of undesirable outputs because $l^*$ is a very small positive number. Therefore, the investment has only a limited effect and is rated as L (limited investment). Also, the supply chains numbers 1, 2, 4, 5, 6, and 9 belonged to positive DTR, so technological innovation was not essentially necessary for increasing their unified efficiency and sustainability improvements in performance assessment.

Table5: The dual variables of inputs and desirable outputs of the gas field

| DMU | Dual variable of inputs under Natural disposability<br>t | Dual variable of inputs under Managerial disposability<br>l | Dual variable of desirable output<br>$u_1$ | Dual variable of desirable output<br>$u_2$ | DT | Effective of investment |
|---|---|---|---|---|---|---|
| 1 | 0.0000000000780 | 0.000052985 | 0.000069549 | 0.000 | P | -- |
| 2 | 0.0000000000780 | 0.000000000728 | 0.000011453 | 0.000 | P | -- |
| 3 | 0.0000000000780 | 0.0000096535 | 0.000024932 | -0.001 | N | E |
| 4 | 0.0000000000780 | 0.000000000728 | 0.000043348 | -0.0001151 | N | L |
| 5 | 0.0000000000780 | 0.000000000728 | 0.0000050569 | 0.015 | P | -- |
| 6 | 0.0000000000780 | 0.000010298 | 0.000018597 | 0.007 | P | -- |
| 7 | 0.0000000000780 | 0.000000000728 | 0.000032330 | 0.002 | P | -- |
| 8 | 0.0000000000780 | 0.000000000728 | 0.000033241 | -0.025 | N | L |
| 9 | 0.0000000000780 | 0.0000022292 | 0.0000075506 | 0.004 | P | -- |
| 10 | 0.0000000000780 | 0.0000069510 | 0.000037357 | 0.000 | P | -- |

According to, Table 5, the gas field of supply chains number 3, 4, and 8 have $u_2^* < 0$ and the number $l_1^* > W \varepsilon R_1^x$ for supply chains number 3; hence, input for investment under managerial disposability can effectively decrease the number of undesirable outputs and is rated as E (effective investment). In other words, for supply chains number 4 and 8 $l_1^* = W \varepsilon R_1^x$, so the input under managerial disposability had a limited effect on the decrease of their undesirable outputs.
Similarly, the quantities of dual variables related to two categories of inputs and the desirable output constraints for power plant sectors are presented in Tables 6-8.

Table6: The dual variables of inputs and desirable output of the first power plant

| DMU | Dual variable of inputs under Natural disposability | Dual variable of inputs under | Dual variable of inputs under | Dual variable of desirable output | Dual variable of | Effective of |
|---|---|---|---|---|---|---|

| | $t_1$ | Natural disposability $t_2$ | Managerial disposability $l$ | $u_1$ | desirable output $u_2$ | | inves tment |
|---|---|---|---|---|---|---|---|
| 1 | 0.00000000001022 | 0.0000000002597 | 0.0000000010432 | 0.006 | 0.000 | P | -- |
| 2 | 0.00000000001022 | 0.0000000002597 | 0.0000000010432 | 0.006 | 0.00000197 | P | -- |
| 3 | 0.00000000001022 | 0.0000000002597 | 0.0000000010432 | 0.005 | 0.000 | P | -- |
| 4 | 0.0000000012644 | 0.0000000002597 | 0.0000000010432 | 0.006 | 0.000 | P | -- |
| 5 | 0.00000000001022 | 0.0000000002597 | 0.0000000010432 | 0.00032891 | 0.076 | P | -- |
| 6 | 0.00000000001022 | 0.0000000002597 | 0.0000000010432 | 0.00055141 | 0.015 | P | -- |
| 7 | 0.000010311 | 0.0000000002597 | 0.0000000010432 | 0.00028440 | 0.009 | P | -- |
| 8 | 0.00000000001022 | 0.0000000002597 | 0.0000000010432 | 0.00081871 | 0.000 | P | -- |
| 9 | 0.00000000001022 | 0.0000000002597 | 0.0000000010432 | 0.005 | 0.000 | P | -- |
| 10 | 0.00000000001022 | 0.0000000002597 | 0.0000000010432 | 0.00029279 | 0.006 | P | -- |

It can be easily seen that the first power plant sector has positive DTR in 10 supply chains. In this case, the increase in input under managerial disposability was not necessary for the undesirable output abatement. According to Tables 7 and 8, the supply chain numbers 2, 6, 7, and 8 for the second power plant and the supply chain numbers 3, 4, 6, 9, and 10 for the third power plant belonged to negative DTR, indicating that the increase in resources allocated under investment had no significant effect on the increase in desirable outputs.

Table7: The dual variables of inputs and desirable output of the second power plant

| DMU | Dual variable of inputs under Natural disposability $t_1$ | Dual variable of inputs under Natural disposability $t_2$ | Dual variable of inputs under Managerial disposability $l$ | Dual variable of desirable output $u_1$ | Dual variable of desirable output $u_2$ | DTR | Effectiv e of investm ent |
|---|---|---|---|---|---|---|---|
| 1 | 0.00000000004044 | 0.00000000019 | 0.00000001560 | 0.00070175 | 0.000 | P | -- |
| 2 | 0.00000000004044 | 0.00000000019 | 0.00000001560 | 0.006 | -0.002 | N | L |
| 3 | 0.00000000004044 | 0.00000000019 | 0.00000001560 | 0.005 | 0.000 | P | -- |
| 4 | 0.00000000004044 | 0.00000000019 | 0.000032565 | 0.002 | 0.000 | P | -- |
| 5 | 0.0000000003246 | 0.00000001526 | 0.00000001560 | 0.005 | 0.000 | P | -- |
| 6 | 0.00000000004044 | 0.00000000019 | 0.00000001560 | -0.0005124 | 0.130 | N | L |
| 7 | 0.00000000004044 | 0.00000000019 | 0.00000001560 | 0.007 | -0.002 | N | L |
| 8 | 0.00000000004044 | 0.00000000019 | 0.00000001560 | -0.00003139 | 0.011 | N | L |
| 9 | 0.00000000004044 | 0.00000000019 | 0.000039792 | 0.00033887 | 0.004 | P | -- |
| 10 | 0.00000000004044 | 0.000017740 | 0.00000001560 | 0.00018937 | 0.008 | P | -- |

Table8: The dual variables of inputs and desirable output of the third power plant

| DMU | Dual variable of inputs under Natural disposability $t_1$ | Dual variable of inputs under Natural disposability $t_2$ | Dual variable of inputs under Managerial disposability $l$ | Dual variable of desirable output $u_1$ | Dual variable of desirable output $u_2$ | DTR | Effectiv e of investm ent |
|---|---|---|---|---|---|---|---|
| 1 | 0.000000000040 | 0.000000000199 | 0.000000006003 | 0.00095109 | 0.000 | P | -- |
| 2 | 0.000000000040 | 0.000000000199 | 0.000000006003 | 0.00095109 | 0.000 | P | -- |
| 3 | 0.000000000040 | 0.000000000199 | 0.000000006003 | -0.356 | 23.478 | N | L |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4 | 0.000000000040 | 0.000000000000 | 0.000000006003 | -0.001 | 0.056 | N | L |
| 5 | 0.000000000040 | 0.000000000000 | 0.000060703 | 0.00013112 | 0.023 | P | -- |
| 6 | 0.000000000040 | 0.000000000199 | 0.000000006003 | 0.006 | -0.003 | N | L |
| 7 | 0.000000000040 | 0.000000000000 | 0.000000006003 | 0.005 | 0.000 | P | -- |
| 8 | 0.000000000040 | 0.000000000000 | 0.000000006003 | 0.005 | 0.000 | P | -- |
| 9 | 0.000000000040 | 0.000000000199 | 0.000000006003 | 0.286 | -0.590 | N | L |
| 10 | 0.000000000040 | 0.000000000199 | 0.000000006003 | 0.440 | -0.241 | N | L |

The values of dual variable correspond to input and desirable output of constraints of transmitter lines (6, 7 divisions) are presented in Tables 9 and 10. Supply chains numbers 3, 5, 8, and 10 have $u_2^* < 0$ and the number $l_1^* > W\ \varepsilon R_1^x$ for supply chains number 3. Therefore, the increase of inputs under managerial disposability of supply chain number 3 provides considerable reduction from power losses in the first transmitter, while $l_1^* = W\ \varepsilon R_1^x$ for supply chains number 5, 8, and 10. Moreover, the investment in the increase of capacities utilization has a limited effect on power losses reduction.

Table9: The dual variables of inputs and desirable output of the first transmission line

| DMU | Dual variable of inputs under Natural disposability | Dual variable of inputs under Natural disposability | Dual variable of inputs under Managerial disposability | Dual variable of desirable output | Dual variable of desirable output | | Effective of investment |
|---|---|---|---|---|---|---|---|
| | $t_1$ | $t_2$ | $l$ | $u_1$ | $u_2$ | DTR | |
| 1 | 0.000000000032 | 0.0000026772 | 0.000000020400 | 0.00013131 | 0.000 | P | -- |
| 2 | 0.000000000032 | 0.00000000000091 | 0.000000020400 | 0.000078241 | 0.070 | P | -- |
| 3 | 0.000000000032 | 0.00000000000091 | 0.000017941 | 0.00018599 | -0.044 | N | E |
| 4 | 0.000000000032 | 0.00000000000091 | 0.000017698 | 0.000035652 | 0.014 | P | -- |
| 5 | 0.000000000032 | 0.00000000000091 | 0.000000020400 | 0.00040656 | -0.001 | N | L |
| 6 | 0.000000000032 | 0.00000000000091 | 0.0000045041 | 0.00030141 | 0.000 | P | -- |
| 7 | 0.000000000032 | 0.00000000000091 | 0.000000020400 | 0.000082477 | 0.000 | P | -- |
| 8 | 0.000000000032 | 0.00000000000091 | 0.000000020400 | 0.003 | -0.381 | N | L |
| 9 | 0.000000000032 | 0.00000000000091 | 0.00000066208 | 0.000006250 | 0.075 | P | -- |
| 10 | 0.000000000032 | 0.00000000000091 | 0.000000020400 | 0.00021799 | -0.000 | N | L |

According to Table 10, supply chains number 2 and 10 of the second transmitter have $u_2^* < 0$ a negative DTR and $l_1^* = W\ \varepsilon R_1^x$ , so the increase of investment creates a slight reduction of power losses and wasted energy.

Table10**:** The dual variables of inputs and desirable output of the second transmission line

| DMU | Dual variable of inputs under Natural disposability | Dual variable of inputs under Natural disposability | Dual variable of inputs under Managerial disposability | Dual variable of desirable output | Dual variable of desirable output | | Effective of investment |
|---|---|---|---|---|---|---|---|
| | $t_1$ | $t_2$ | $l$ | $u_1$ | $u_2$ | DTR | |
| 1 | 0.000000000016 | 0.00000000004405 | 0.0000060573 | 0.000045413 | 0.000 | P | -- |
| 2 | 0.000000000016 | 0.00000000004405 | 0.000000009563 | 0.00094505 | -0.006 | N | L |
| 3 | 0.000000000016 | 0.00000000004405 | 0.000000009563 | 0.000051498 | 0.002 | P | -- |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4 | 0.000000000016 | 0.00000000004405 | 0.000000009563 | 0.000094933 | 0.001 | P | -- |
| 5 | 0.000000000016 | 0.00000000004405 | 0.000000009563 | 0.000016835 | 0.062 | P | -- |
| 6 | 0.000000000016 | 0.00000000004405 | 0.000000009563 | 0.00063084 | 0.0003040 | P | -- |
| 7 | 0.000000000016 | 0.00000000004405 | 0.000000009563 | 0.000093807 | 0.000 | P | -- |
| 8 | 0.000000000016 | 0.00000000004405 | 0.000000009563 | 0.00018135 | 0.000 | P | -- |
| 9 | 0.000000000016 | 0.00000000004405 | 0.000000009563 | 0.00063636 | 0.000 | P | -- |
| 10 | 0.000000000016 | 0.000016186 | 0.000000009563 | -0.00003256 | 0.030 | N | L |

In Tables 11–14, the values of dual variables correspond to constraints on two categories of inputs, and desirable outputs for four distribution lines are presented. The first distribution lines for supply chains 1, 5, and 9 have the necessary capacities for power loss reduction as the increase in inputs under investment causes power loss abatement. Also, investment capacity utilization for supply chain numbers 2, 3, 8, and 9 creates a limited effect on undesirable output reduction, while investment on increased inputs has no significant effect on power loss reduction for supply chain numbers 4, 7, and 10.

The second distribution line can apply appropriate resources for wasted energy control in supply chains 3 and 5, while the investment was not essential for other supply chains in the performance assessment. Moreover, the increase of inputs under investment for the third distribution line has a limited effect on power losses in supply chain number 1.

Table11:The dual variables of inputs and desirable output of the first distribution line

| DMU | Dual variable of inputs under Natural disposability $t_1$ | Dual variable of inputs under Natural disposability $t_2$ | Dual variable of inputs under Managerial disposability $l$ | Dual variable of desirable output $u_1$ | Dual variable of desirable output $u_2$ | DT | Effective of investment |
|---|---|---|---|---|---|---|---|
| 1 | 0.000000000040 | 0.00000000000797 | 0.00000092737 | 0.00000037321 | -0.028 | N | E |
| 2 | 0.000000000040 | 0.00000000000797 | 0.000000001566 | -0.000001234 | 0.510 | N | L |
| 3 | 0.000000000040 | 0.00000000000797 | 0.000000001566 | -0.000001204 | 0.510 | N | L |
| 4 | 0.000000000040 | 0.00000000000797 | 0.000000001566 | 0.00000002582 | 0.0008644 | P | -- |
| 5 | 0.000000000040 | 0.00000000000797 | 0.0000039162 | -0.0000001289 | 0.102 | N | E |
| 6 | 0.000000000040 | 0.00000000000797 | 0.000000001566 | -0.000001204 | 0.510 | N | L |
| 7 | 0.000000000040 | 0.00000000000797 | 0.00000063241 | 0.00000006828 | 0.001 | P | -- |
| 8 | 0.000000000040 | 0.00000000000797 | 0.000000001566 | 0.00000014835 | -0.003 | N | L |
| 9 | 0.000000000040 | 0.00000000000797 | 0.00000092737 | 0.00000037321 | -0.028 | N | E |
| 10 | 0.000000000040 | 0.00000000000797 | 0.0000012686 | 0.00000003100 | 0.011 | P | -- |

Table12: The dual variables of inputs and desirable output of the second distribution line

| DMU | Dual variable of inputs under Natural disposability $t_1$ | Dual variable of inputs under Natural disposability $t_2$ | Dual variable of inputs under Managerial disposability $l$ | Dual variable of desirable output $u_1$ | Dual variable of desirable output $u_2$ | DTR | Effective of investment |
|---|---|---|---|---|---|---|---|
| 1 | 0.00 | 0.00000000001153 | 0.000000005376 | 0.00000033563 | 0.00 | P | -- |
| 2 | 0.000003608 | 0.00000000001153 | 0.00000017902 | 0.000000008331 | 0.009 | P | -- |
| 3 | -0.0001135 | 0.00000000001153 | 0.0000066440 | -0.0000001177 | 0.060 | N | E |
| 4 | 0.00 | 0.00000000001153 | 0.000000005376 | 0.000000088002 | 0.011 | P | -- |
| 5 | 0.000016795 | 0.00000000001153 | 0.00000095894 | -0.00000001612 | 0.029 | N | E |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6 | 0.00 | 0.00000000001153 | 0.000000005376 | 0.000000068456 | 0.016 | P | -- |
| 7 | 0.0000079756 | 0.00000000001153 | 0.000000005376 | 0.000000033059 | 0.024 | P | -- |
| 8 | -0.000009268 | 0.00000000001153 | 0.000000005376 | 0.00000012206 | 0.00 | P | -- |
| 9 | 0.0000042240 | 0.00000000001153 | 0.00000032424 | 0.000000036140 | 0.014 | P | -- |
| 10 | -0.000007311 | 0.00000000001153 | 0.00000047859 | 0.00000012940 | 0.00 | P | -- |

Table13: The dual variables of inputs and desirable output of the third distribution line

| DMU | Dual variable of inputs under Natural disposability $t_1$ | Dual variable of inputs under Natural disposability $t_2$ | Dual variable of inputs under Managerial disposability l | Dual variable of desirable output $u_1$ | Dual variable of desirable output $u_2$ | DTR | Effective of investment |
|---|---|---|---|---|---|---|---|
| 1 | 0.000000000105 | 0.0000000000068 | 0.000000003472 | -0.0000000000061 | 0.013 | N | L |
| 2 | 0.000000000105 | 0.0000000000068 | 0.00000068553 | 0.000000061930 | 0.007 | P | -- |
| 3 | 0.000000000105 | 0.0000000000068 | 0.00000063767 | 0.000000047184 | 0.008 | P | -- |
| 4 | 0.000000000105 | 0.0000000000068 | 0.00000063667 | 0.000000084434 | 0.001 | P | -- |
| 5 | 0.000000000105 | 0.0000000000068 | 0.00000063766 | 0.000000047184 | 0.008 | P | -- |
| 6 | 0.000000000105 | 0.0000000000068 | 0.000000003472 | 0.00000014396 | 0.000007513 | P | -- |
| 7 | 0.000000000105 | 0.0000000000068 | 0.000000003472 | 0.000000075153 | 0.014 | P | -- |
| 8 | 0.00 | 0.0000000000068 | 0.00000038019 | 0.000000050420 | 0.00077825 | P | -- |
| 9 | 0.000000000105 | 0.0000000000068 | 0.000000003472 | 0.00000014399 | 0.00 | P | -- |
| 10 | 0.00 | 0.0000000000068 | 0.00000038019 | 0.000000050420 | 0.00077825 | P | -- |

Finally, according to Table 14, the fourth distribution line of supply chains numbers 1, 5, 6, 7, 8, and 10 has appropriate situations for undesirable output abatement as an increase in input under managerial disposability provides power losses decrease in 60% of supply chains.

Table14:The dual variables of inputs and desirable output of the fourth distribution line

| DMU | Dual variable of inputs under Natural disposability $t_1$ | Dual variable of inputs under Natural disposability $t_2$ | Dual variable of inputs under Managerial disposability l | Dual variable of desirable output $u_1$ | Dual variable of desirable output $u_2$ | DTR | Effective of investment |
|---|---|---|---|---|---|---|---|
| 1 | 0.000000000132 | 0.0000000000085 | 0.000000001526 | 0.00000023050 | -0.11 | N | E |
| 2 | 0.000000000132 | 0.0000000000085 | 0.000000001526 | 0.00000017999 | 0.00 | P | -- |
| 3 | 0.000000000132 | 0.0000000000085 | 0.000000001526 | 0.00000014115 | 0.00 | P | -- |
| 4 | 0.000000000132 | 0.0000000000085 | 0.00000027221 | 0.00000012108 | 0.00 | P | -- |
| 5 | 0.000000000132 | 0.0000000000085 | 0.000000082679 | 0.000000063124 | -0.001 | N | E |
| 6 | 0.000041899 | 0.0000000000085 | 0.0000033140 | 0.00000055546 | -0.078 | N | E |
| 7 | 0.000000000132 | 0.0000000000085 | 0.000000001526 | -0.000001288 | 0.545 | N | E |
| 8 | 0.000000000132 | 0.0000000000085 | 0.0000017671 | 0.00000022177 | -0.30 | N | E |
| 9 | 0.000000000132 | 0.0000000000085 | 0.0000012938 | 0.00000016095 | 0.022 | P | -- |
| 10 | 0.000000000132 | 0.0000000000085 | 0.0000017671 | 0.00000022177 | -0.30 | N | E |

Generally, the supply chains are evaluated under natural and management disposability based on unified operational and environmental efficiency. The supply chain divisions with the necessary facilities and new technology to deal with undesirable outputs can utilize more inputs (under managerial disposability) for more output production without increasing undesirable outputs. According to the obtained results of model performance under natural and management disposability, there are supply chains with necessary capacities for undesirable outputs decrease in energy and power plant sectors and in transmitter and distributor lines. In particular, the investment under managerial disposability created a reduction of power losses of more than 50% in supply chains in the fourth distribution line.

Tables 15–18 summarize effective and limited investment opportunities in oil and gas fields, power plant sectors, and, transmission and distribution lines in ten supply chains.

Table15: Effective and limited investment opportunity on supply chains 10 in the energy sectors

| | Effective investment | Percent % | Limited investment | Percent % |
|---|---|---|---|---|
| Oil field | 0 | 0.0 | 4 | 0.40 |
| Gas field | 1 | 0.10 | 2 | 0.20 |

Table16: Effective and limited investment opportunity on supply chains 10 in the power plants

| | Effective investment | Percent % | Limited investment | Percent % |
|---|---|---|---|---|
| Power plant (division3) | 0 | 0.0 | 0 | 0.0 |
| Power plant (division4) | 0 | 0.0 | 4 | 0.40 |
| Power plant (division5) | 0 | 0.0 | 5 | 0.50 |

Table17: Effective and limited investment opportunity on supply chains 10 in the transmitters

| | Effective investment | Percent % | Limited investment | Percent % |
|---|---|---|---|---|
| Transmitter (division 6) | 1 | 0.10 | 3 | 0.30 |
| Transmitter (division 7) | 0 | 0.0 | 2 | 0.20 |

Table18: Effective and limited investment opportunity on supply chain 10 in the distributors

| | Effective investment | Percent % | Limited investment | Percent % |
|---|---|---|---|---|
| Distributer (division8) | 3 | 0.30 | 4 | 0.40 |
| Distributer (division9) | 2 | 0.20 | 0 | 0.00 |
| Distributer (division10) | 0 | 0.00 | 1 | 0.10 |
| Distributer (division11) | 6 | 0.60 | 0 | 0.00 |

As summarized in Tables 15–18, the gas field, the first transmission, the first and second, and the fourth distribution, all obtained a high level of effective investment capacities (0.10, 0.30, 0.20, and 0.60) in supply chains 10, respectively. According to Table 18, the fourth distribution (division 11) could, with appropriate utilization of a specialist workforce, decrease power losses in 60% of supply chains.

## CONCLUSIONS

The energy sector is one of the most important types of advanced infrastructure in any country. Power plants are the largest consumers of fossil fuels, such as coal, fuel oil, gasoline, and natural gas. In this regard, $CO_2$ has the biggest contribution to pollution emissions in power plants. Fossil fuels cause climate change and global warming problems (a significant threat to human health and other organisms) and decrease economic prosperity in industrial activities. Therefore, it is necessary for us to reduce the number of GHGs by enhancing system efficiency. This study proposes a model radial to a supply chain sustainability assessment that measures an investment opportunity for technology innovation and decreases the number of undesirable outputs in the different sectors of the supply chain. This study analyzes the behavior of the Iranian power industry by subdividing the industry into different regions (each region represents a supply chain or DMU) and measuring the performance of these regions in terms of electricity utilization and environmental protection. This study has two empirical results in the energy and power plant sectors and transmission and distribution lines. First, the results show there is only a limited supply chain in the gas field where an increase in the specialist workforce for flare gas reduction creates an slight increase in desirable output and wasted energy abatement, so this supply chain needs investment and new technology for environmental protection. It is worth mentioning that the fourth distribution company has a high level of investment effectiveness opportunity in 60% of supply chains.

Second, the inputs under managerial disposability play a fundamental role in pollutant emissions reduction and wasted energy inhibition. The inputs' accurate selection and the resources' appropriate allocation create desirable output increment and performance productivity. The proposed approach has methodological limitations in leading to an environmental performance assessment. The sources of energy are different among districts. Each region has its own essential structure and different conditions for business activity. For instance, the southern regions of Iran have noticeable energy resources and a high capacity of power plants in comparison to other regions. These regional differences have an impact on the number of efficiency measures available in each region.

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