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A study into the sustainability efficiency of supply chain network based on economic, social, and environmental trade-offs

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Abstract. Assessing the sustainability efficiency of a supply chain network (SCN) is a complex issue due to the inherent conflict of interest among components. In these systems, there are two levels of conflict of interest: on the one hand, network players, including suppliers, manufacturers, retailers, etc., have conflicting interests. On the other hand, the three sustainability goals, namely economic, social and environmental, are not in line with each other. Improvement in one of these goals is not possible while keeping the others constant. Using hybrid models of game network data envelopment analysis (GNDEA), this study presented a new framework to measure an Iranian pharmaceutical company's supply chain network sustainability efficiency (SCNSE). This was done considering two levels of conflict of interest simultaneously, which is the main contribution of this study. The proposed model also measures the performance of components and the entire network in all three dimensions of sustainability. It enables managers to gain a better insight into the sustainability efficiency of an SCN and its individual components. Acquiring this knowledge allows managers to identify system weaknesses and design more effective improvement plans. Future studies can develop models for appraising the sustainability efficiency of an SCN under uncertain conditions considering different players.

Keywords. Sustainable supply chain; efficiency evaluation; trade-off; network data envelopment analysis; Nash bargaining game; leader–follower game.

1. Introduction

The sustainable supply chain network (SSCN) paradigm has attracted considerable attention over recent years. An SSCN, besides economic goals, simultaneously considers other goals, such as social responsibility and environmental impacts. The pressures of rapid micro and macro-level environmental changes and the intensity of competition in industrial supply chains, on the one hand [1], and the need to pay attention to the limitations in available resources and energy [2], on the other hand, have led businesses to consider achieving sustainability and guaranteeing the SCN efficiency in all three economic, environmental and social dimensions. This issue is of special importance in industries such as pharmaceuticals that deal with human health [3]. To ensure the sustainability efficiency of an SCN, developing an appropriate performance evaluation framework seems essential. The existence of conflict of interest or the trade-offs between the components [4] and the players of this network [5] turns performance evaluation into a complex issue.

Trade-offs in SSCNs occur at two separate but simultaneous levels: one is the conflict of interest among the SCN players [5], and the other is the trade-offs among the sustainability goals of each player [4].

In the real world, each player, whether manufacturer or supplier, has their own incentives and specific goals. Also, there is no single super decision-maker that has access to all information in the SCN, controlling the whole SCN in an integrated manner and deciding for it. This issue leads to a conflict among the players, pointing to the first level of conflict [6, 7].

On the other hand, to create a sustainable SCN, the three goals, called the triple bottomline, should be integrated and balanced, despite not being in line with each other. This issue refers to the second level of the conflict of interest [8].

However, simultaneously considering these two trade-offs is much more complicated but essential to achieve a proper and reliable performance evaluation system. An effective performance evaluation framework capable of overcoming the complexity of SCNSE evaluation is required to ensure the realization of the SSCN goals [9, 10].

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Reviewing the literature on the problems of SCNs' sustainability efficiency evaluation shows that the trade-off among players has rarely been noticed while the trade-off among sustainability goals has been neglected totally. In addition, no integrated evaluation system capable of appraising the sustainability efficiency of an SCN while considering the mentioned conflict of interest has been developed so far [11]. GNDEA, as a hybrid model of network data envelopment analysis (NDEA) and game theory, is among the most popular methods to formulate the trade-off between players in SCN and SCN performance evaluation problems [12, 13]. Accordingly, in this paper, GNDEA models were adopted. The advantages of this model, compared to other quantitative techniques such as analytic hierarchy process (AHP), analytic network process (ANP), and simulation [3], are the ability to analyze network structure, the unique capability in modeling the conflict of interest among network components, the ability to present the efficiency level relative to the whole system, each subsystem, and network components, and the ability to present improvement plans after evaluating efficiency [14]. The SCN players can interact with each other in cooperative and non-cooperative manners. Hence, in the present study, the following minor questions are posed: Does the selection of different cooperation approaches among the members affect the results of sustainability efficiency goals? Does a player's efficiency guarantee its efficiency in all three aspects of sustainability? And, how can the proposed model help managers provide plans for improving the sustainability efficiency of the players as well as the entire network?

The present study intends to establish a framework for evaluating the sustainability efficiency of SCN by considering two levels of conflict of interest to enable senior managers to measure the sustainability efficiency of the entire network and that of the network players simultaneously. Also, this framework is able to calculate the efficiency separately for each of the sustainability goals and provide improvement plans by analyzing the weaknesses.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature on SCNSE problems based on the GNDEA model. The problem and its mathematical models are presented in Sect. 3. The proposed model is implemented by adopting a real-world case study of an Iranian pharmaceutical SCN, and the results are presented in Sect. 4. The findings and managerial insights are discussed in Sect. 5. Conclusion and suggestions for future research are presented in Sect. 6.

2. Literature review

In an SSCN, the flow of materials, information, and financial resources is managed to achieve all three environmental, social, and economic goals [12, 15]. SCNSE depends on the sustainability of the network players and the cooperation among them, as the origins of two different but simultaneous types of trade-offs [16]. Evaluating the sustainability efficiency of SCN without considering these trade-offs does not provide accurate results and insights about the current situation leading to improvement plans. In recent years, researchers have addressed the issue of the trade-off among sustainability goals, i.e., economic, social, and environmental ones in the SSCN design problem. A multi-objective mathematical model was presented to design an SSCN considering the trade-offs. Sustainability goals compose the objective functions of the model, explicitly showing the conflict of interest among them [8]. Optimization of the SCN under the trade-off among total cost, greenhouse gas emissions, and waiting time (as characteristics of each of the sustainability goals) [17], the conflict of interest among sustainability goals in resource management [18], performance evaluation of SCN under trade-off between the characteristics of lean SCN and green SCN [19], and examination of the impact of conflicts among sustainability goals on decision making systems [20] are among the other research topics in this area.

The second level is the trade-off between the players. Liang *et al* first showed the trade-off among players in the SCN efficiency evaluation problem. They formulated it using combined data envelopment analysis and game theory (GT) models in a two-tier supply chain of the seller and buyer [21]. Since then, researchers have made remarkable efforts to develop this method and make it closer to real-world problems [22, 23]. Therefore, a comprehensive review of studies evaluating SCNSE was conducted using NDEA models. These studies can be classified according to whether they have only measured the sustainability efficiency of the whole network or calculated each player's sustainability efficiency separately and whether they have measured the efficiency of each player based on each dimension of sustainability goals. A summary of the review of previous studies and the position of the present research in comparison with similar studies is presented in table 1. This review shows that studies have mainly focused on evaluating the sustainability efficiency of the whole network so far, and they have neglected to assess the sustainability performance of the components of SCN, such as players and sustainability goals. While the intrinsic conflict of interest or trade-offs among the components of a network is an undeniable fact ignored in previous studies. The trade-offs in a network are demonstrated in two types. The first one deals with the intrinsic conflict of interest among the network players, and the second one is associated with the conflict among sustainability goals for every player.

To the best of our knowledge, sufficient attention to both levels of the intrinsic conflict of interest in this problem is considered a strong achievement of the present study. In summary, the most prominent innovations of this research are as follows:

Table 1. A review of the supply chain sustainability efficiency evaluation studies

Row	References	Contribution of the Research	Sustainability efficiency of the whole network	Sustainability efficiency of each player	The efficiency of each player with respect to each goal of sustainability	Quantitative technique	Trade-off		Case study
							Between players	Between goals	
1	Tajbakhsh and Hassini [12]	Evaluating the SSCN performance in cooperative and non-cooperative approaches between players	✔	✔	–	NDEA	✔	–	1. Manufacturing 2. Banking
2	Khodakarami *et al* [24]	Sustainability efficiency of SCN evaluated by developing a slack based multi-stage DEA	✔	✔	–	Two-stage DEA	–	–	Chemical industry
3	Jauhar *et al* [25]	assessing the sustainability efficiency of SCN with overlooking the conflict of interest between components	✔	✔	–	NDEA and Differential Evolution	✔	–	Indian educational supply chain
4	Haghighi *et al* [26]	Evaluating the SSCN efficiency with categorizing sustainability indicators in each perspective of the balanced scorecard	✔	✔	–	Hybrid of NDEA and (BSC)	✔	–	Recycling industry
5	Badiezadeh *et al* [27]	optimistic and pessimistic efficiency scores calculation based on undesirable environmental variables	✔	✔	–	multi-stage DEA and big data	–	–	Iranian food industry
6	Ramezankhani *et al* [28]	Evaluate the overall efficiency of an automotive SCN under sustainability and resilience paradigms.	✔	✔	–	Dynamic NDEA	–	–	Automotive industry
7	Tajbakhsh and Hassini [29]	Applying multi-stage DEA model to appraise SSCN efficiency, economic aspect in the first stage and the other aspect in the second stage	✔	–	✔	Two-stage DEA	–	–	US fossil power plant stations
8	Gong *et al* [30]	assessing the SSCN efficiency and investigating the impact of integrating environmental, social, and operational management goals	✔	–	–	NDEA	–	–	Retailing industry
5	DE *et al* [31]	Designing a mixed framework of lean and sustainability innovation to analyze sustainability performance	✔	–	–	DEA in state CRS, VRS, and scale efficiency	–	–	Indian manufacturing SMEs
9	Wang *et al* [32]	Assessing sustainability performance of global supply chains	✔	–	–	hybrid of multi-regional input-output and NDEA	–	–	Manufacturing sectors in top 16 economies
10	Jomthanachai *et al* [33]	Evaluate the Efficiency of SSCs to contribute toward determining a sustainable strategy	✔	✔	–	Alternative coherent DEA model	–	–	Simple and complex SC
	This research	Proposed a performance appraisal framework considering bi-level trade-offs between goals and players	✔	✔	✔	Game NDEA	✔	✔	Pharmaceutical industry

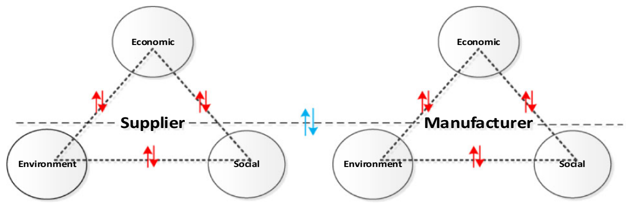

Figure 1. Two levels of trade-off in the SCNSE problem [4, 5].

- Besides evaluating the sustainability efficiency of the whole SCN, providing the possibility for appraising the sustainability efficiency of players of SCN and the efficiency of each sustainability goal related to each player;
- Considering two different trade-offs simultaneously and mathematical formulation using cooperative and non-cooperative game approaches and comparing the impact of the type of cooperation among network components on the efficiency results.
- Implementing the proposed model to assess the sustainability efficiency of an Iranian pharmaceutical SCN.

3. SCNSE measurement

To properly describe the proposed framework, the trade-off model and the mathematical modeling of the problem are presented in this section. The presented trade-off model considers three key elements as given below:

First, as a business enterprise, each player of the SCN seeks to increase its output while minimizing the input resources. Creating the highest rate of return for a player means that the input resources are provided to the next players at the highest cost, which, in turn, can reduce their efficiency. This is the reason behind the inherent conflict of interest among network players, referred to as the first type of trade-off. Second, although implementing plans to control the pollution arising from production operations improves the environmental goal, it leads to a rise in costs. Furthermore, while paying more attention to employees' occupational safety, creating more jobs, or increasing the level of support for employee insurance improve the social goals, they would increase the costs and weaken the economic goal. In other words, the behavior of sustainability goals toward each other has a negative covariance, which proves the conflict of interest among them and creates economic-social-environmental trade-offs, considered as the second type of trade-off in our model. Third, an SCN should also have sustainable players. That is, to ensure the sustainability efficiency of the whole network, one should also be assured of the sustainability efficiency of each player in the network. Given these three key elements, the trade-off model of SCNSE is shown in figure 1. The studied SCN has two players, a supplier, and a manufacturer. The proposed model allows to formulate and evaluate the sustainability efficiency of the whole network, the sustainability efficiency of each player, and the efficiency of each player with respect to each goal of sustainability, considering two levels of the trade-offs.

In this study, two different scenarios are used to model the two types of trade-offs simultaneously. In the first scenario, the trade-off related to players of the SCN is modeled with the centralized game, and economic-social-environmental trade-offs are modeled with the Nash bargaining game.

The trade-off associated with network players is considered with a non-cooperative game in the second scenario, which is the main difference between the two scenarios. Figure 2 illustrates the general network of the problem considering two types of trade-offs. The notations of the proposed model are defined in table 2.

3.1 *Mathematical modeling of scenario (I)*

This section presents the mathematical modeling of the first scenario in two steps. As mentioned earlier, the players interact under a centralized cooperative game in this scenario. In the first step, an input-oriented approach with a constant return to scale condition is utilized to model the overall efficiency assessment problem. It is linearized using the Charnes–Cooper transformation and calculated θ_o^{OC}, θ_o^{Sup*} and θ_o^{Man*} in a similar manner [14, 34].

In the second step, the efficiency of the supplier and the manufacturer is calculated with the optimal values of the overall efficiency at hand [21, 35]. Then, the efficiency of the sustainability goals of each player is appraised based on the Nash bargaining game and the status of maintaining the optimal efficiency of that player. For this purpose, the bargaining breakdown points for each of the sustainability goals are computed basically the same as the classic

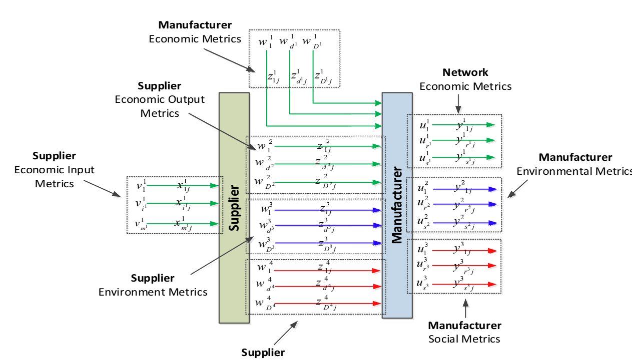

Figure 2. The general network of the proposed SSCNEE model [23].

Table 2. Notations of the model.

Notation		Description
Indices	j	DMU jth, $j \in \{1, 2, \ldots, n\}$
	i, $d1$, $d2$, $d3$, $d4$, $r1$, $r2$, $r3$	Input variable of economic goal that $i \in \{1, 2, \ldots, m\}$, The additional variable of economic goal that $d1 \in \{1, 2, \ldots, D1\}$, The intermediate variable of economic goal that $d2 \in \{1, 2, \ldots, D2\}$, The intermediate variable of environmental goal that $d3 \in \{1, 2, \ldots, D3\}$, The intermediate variable of social goal that $d4 \in \{1, 2, \ldots, D4\}$. Output variable of economic goal that $r1 \in \{1, 2, \ldots, S1\}$. Output variable of environmental goal that $r2 \in \{1, 2, \ldots, S2\}$ and Output variable of social goal that $r3 \in \{1, 2, \ldots, S3\}$
Parameters	x^1_{ij}, z^1_{d1j}, z^2_{d2j}, z^3_{d3j}, z^4_{d4j}, y^1_{r1j}, y^2_{r2j}, y^3_{r3j}	The value of the input parameter ith , The value of the additional parameter $d1$th, value of the intermediate variable $d2$th, The value of the intermediate variable $d3$th, The value of the intermediate variable $d4$th, The value of the output parameter $r1$th, The value of the output parameter $r2$, thThe value of the output parameter $r3$th for DMU jth, respectively
Decision Variables	v^1_{i1}, w^1_{d1}, w^2_{d1}, w^3_{d1}, w^4_{d4}, u^1_{r1}, u^2_{r2}, u^3_{r3}	Weight of economic input variable ith, Weight of additional economic variable $d1$th, Weight of intermediate economic variable $d2$th, Weight of environmental intermediate variable $d3$th, Weight of intermediate social variable $d4$th, Weight of economic output variable $r1$th, Weight of environmental output variable $r2$th, and Weight of social output variable $r3$th for DMU jth, respectively
Efficiency values	θ^{OC}_o, θ^{ON}_o	The optimal overall efficiency under cooperative and non-cooperative for DMU_o respectively
	θ^{Sup*}_o, θ^{Man*}_o	The optimal efficiency value of the supplier and manufacturer for DMU_o, respectively
	θ^{Ec1}_o, θ^{En1}_o, θ^{So1}_o	The optimal value of the economic goal efficiency, environmental goal efficiency, and social goal efficiency at the supplier stage for DMU_o
	θ^{Ec2}_o, θ^{En2}_o, θ^{So2}_o	The optimal value of the economic goal efficiency, environmental goal efficiency, and social goal efficiency at the manufacturer stage for DMU_o
	$\theta^{Ec1}_{\min,o}$, $\theta^{En1}_{\min,o}$, $\theta^{So1}_{\min,o}$	The breakdown points of each goal at the supplier for DMU_o
	$\theta^{Ec2}_{\min,o}$, $\theta^{En2}_{\min,o}$, $\theta^{So2}_{\min,o}$	The breakdown points of each goal at the manufacturer for DMU_o

Charnes, Cooper, and Rhodes (CCR) model, except that its objective function is changed from maximization to minimization, including $\theta^{Ec1}_{\min,o}$, $\theta^{En1}_{\min,o}$, $\theta^{So1}_{\min,o}$, $\theta^{Ec2}_{\min,o}$, $\theta^{En2}_{\min,o}$, $\theta^{So2}_{\min,o}$ [36]. The efficiency of the sustainability goals is formulated using models (1) to (4) below [34]. The mathematical model of the first step of the first scenario is as follows:

A Nash Bargaining game problem can be defined as a vector $\{N, S, b\}$ where N is the number of players, S shows the feasible set, and b is the breakdown points of bargaining. If u_i is the efficiency of the ith player and b_i is the bargaining breakdown point of the ith player, the problem has a unique solution called the Nash solution, which is equal to maximizing $\prod_{i=1}^{N} (u_i - b_i)$ under the condition of $u_i \geq b_i$ for all players.

The feasible set S is compact and convex, and the solutions must have four basic properties, i.e., (1) Pareto optimality, (2) invariance to affine transformation, (3) independence of irrelevant alternatives, and (4) symmetry [36]. Thus, in the second step of the first scenario, the NDEA Nash bargaining game model to assess the efficiency of the sustainability goals of the supplier can be defined as $\left(\{1,2,3\}, S, \left\{\theta^{Ec1}_{\min,o}, \theta^{En1}_{\min,o}, \theta^{So1}_{\min,o}\right\}\right)$, and the Nash bargaining model for appraising the efficiency of the sustainability goals of the manufacturer is definable as $\left(\{1,2,3\}, S, \left\{\theta^{Ec2}_{\min,o}, \theta^{En2}_{\min,o}, \theta^{So2}_{\min,o}\right\}\right)$.

The formulation $\left(\{1,2,3\}, S, \left\{\theta^{Ec1}_{\min,o}, \theta^{En1}_{\min,o}, \theta^{So1}_{\min,o}\right\}\right)$ is presented in model (1), and then the solution properties of the model are proved.

$$\max \left(\frac{\sum_{d2=1}^{D2} w^2_{d2} z^2_{d2o}}{\sum_{i=1}^{m} v_i x_{io}} - \theta^{Ec1}_{\min,o}\right) * \left(\frac{\sum_{d3=1}^{D3} w^3_{d3} z^3_{d3o}}{\sum_{i=1}^{m} v_i x_{io}} - \theta^{En1}_{\min,o}\right) * \left(\frac{\sum_{d4=1}^{D4} w^4_{d4} z^4_{d4o}}{\sum_{i=1}^{m} v_i x_{io}} - \theta^{So1}_{\min,o}\right) \tag{1}$$

$$st.$$

$$\frac{\sum_{d2=1}^{D2} w^2_{d2} z^2_{d2j}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1; \quad \forall \mathrm{j} = 1, \ldots, \mathrm{n} \tag{1a}$$

$$\frac{\sum_{d3=1}^{D3} w_{d3}^3 z_{d3j}^3}{\sum_{i=1}^{m} v_i x_{ij}} \le 1; \quad \forall \mathrm{j} = 1,\ldots,\mathrm{n} \tag{1b}$$

$$\frac{\sum_{d4=1}^{D4} w_{d4}^4 z_{d4j}^4}{\sum_{i=1}^{m} v_i x_{ij}} \le 1; \quad \forall \mathrm{j} = 1,\ldots,\mathrm{n} \tag{1c}$$

$$\frac{\sum_{d2=1}^{D2} w_{d2}^2 z_{d2o}^2}{\sum_{i=1}^{m} v_i x_{io}} \ge \theta_{\min,o}^{Ec1} \tag{1d}$$

$$\frac{\sum_{d3=1}^{D3} w_{d3}^3 z_{d3o}^3}{\sum_{i=1}^{m} v_i x_{io}} \ge \theta_{\min,o}^{En1} \tag{1e}$$

$$\frac{\sum_{d4=1}^{D4} w_{d4}^4 z_{d4o}^4}{\sum_{i=1}^{m} v_i x_{io}} \ge \theta_{\min,o}^{So1} \tag{1f}$$

$$\frac{\sum_{d2=1}^{D2} w_{d2}^2 z_{d2o}^2 + \sum_{d3=1}^{D3} w_{d3}^3 z_{d3o}^3 + \sum_{d4=1}^{D4} w_{d4}^4 z_{d4o}^4}{\sum_{i=1}^{m} v_i x_{io}} = \theta_o^{Sup^*} \tag{1g}$$

$$\mathrm{w}_{d2}^2, \mathrm{w}_{d3}^3, \mathrm{w}_{d4}^4, v_i \ge \varepsilon \tag{1h}$$

In this model, the constraints (1a) to (1c) ensure that the efficiency of each sustainability goal in all DMUs is less than 1. The constraints (1d) to (1f) guarantee that the efficiency score of the DMU under evaluation is at least equal to its bargaining breakdown point, and the constraint (1g) ensures that the efficiency of the supplier is maintained at the optimal value obtained for it in the first step. "Appendix A" proves that the feasible set S is compact and convex. To simplify model (1), the transformation of $t = \left(\sum_{i=1}^{m} v_i x_{io}\right)^{-1}$, $\upsilon_i = t v_i$, $\omega_{d2}^2 = t w_{d2}^2$, $\omega_{d3}^3 = t w_{d3}^3$, and $\omega_{d4}^4 = t w_{d4}^4$ is done. As a result, model (2), a nonlinear and transformed form of model (1), is presented below.

$$\max\left(\sum_{d2=1}^{D2} \omega_{d2}^2 z_{d2o}^2 - \theta_{\min,o}^{Ec1}\right) * \left(\sum_{d3=1}^{D3} \omega_{d3}^3 z_{d3o}^3 - \theta_{\min,o}^{En1}\right) * \left(\sum_{d4=1}^{D4} \omega_{d4}^4 z_{d4o}^4 - \theta_{\min,o}^{So1}\right) \tag{2}$$

st.

$$\sum_{d2=1}^{D2} \omega_{d2}^2 z_{d2j}^2 - \sum_{i=1}^{m} \upsilon_i x_{ij} \le 0; \quad \forall \mathrm{j} = 1,\ldots,\mathrm{n} \tag{2a}$$

$$\sum_{d3=1}^{D3} \omega_{d3}^3 z_{d3j}^3 - \sum_{i=1}^{m} \upsilon_i x_{ij} \le 0; \quad \forall \mathrm{j} = 1,\ldots,\mathrm{n} \tag{2b}$$

$$\sum_{d4=1}^{D4} \omega_{d4}^4 z_{d4j}^4 - \sum_{i=1}^{m} \upsilon_i x_{ij} \le 0; \quad \forall \mathrm{j} = 1,\ldots,\mathrm{n} \tag{2c}$$

$$\sum_{d2=1}^{D2} \omega_{d2}^2 z_{d2o}^2 \ge \theta_{\min,o}^{Ec1} \tag{2d}$$

$$\sum_{d3=1}^{D3} \omega_{d3}^3 z_{d3o}^3 \ge \theta_{\min,o}^{En1} \tag{2e}$$

$$\sum_{d4=1}^{D4} \omega_{d4}^4 z_{d4o}^4 \ge \theta_{\min,o}^{So1} \tag{2f}$$

$$\sum_{d2=1}^{D2} \omega_{d2}^2 z_{d2o}^2 + \sum_{d3=1}^{D3} \omega_{d3}^3 z_{d3o}^3 + \sum_{d4=1}^{D4} \omega_{d4}^4 z_{d4o}^4 = \theta_o^{Sup*} \tag{2g}$$

$$\sum_{i=1}^{m} \upsilon_i x_{io} = 1 \tag{2h}$$

$$\omega_{d2}^2, \omega_{d3}^3, \omega_{d4}^4, \upsilon_i \ge \varepsilon \tag{2i}$$

The formulation $\left(\{1,2,3\}, S, \left\{\theta_{\min,o}^{Ec2}, \theta_{\min,o}^{En2}, \theta_{\min,o}^{So2}\right\}\right)$ is presented in model (3), which is significantly different from model (1) due to the presence of additional variables.

$$\max\left(\frac{\sum_{r1=1}^{S1} u_{r1}^1 y_{r1o}^1}{\sum_{d1=1}^{D^1} w_{d1}^1 z_{d1o}^1 + \sum_{d2=1}^{D2} w_{d2}^2 z_{d2o}^2} - \theta_{\min,o}^{Ec2}\right) * \left(\frac{\sum_{r2=1}^{S2} u_{r2}^2 y_{r2o}^2}{\sum_{d3=1}^{D3} w_{d3}^3 z_{d3o}^3} - \theta_{\min,o}^{En2}\right) * \left(\frac{\sum_{r3=1}^{S3} u_{r3}^3 y_{r3o}^3}{\sum_{d4=1}^{D^4} w_{d4}^4 z_{d4o}^4} - \theta_{\min,o}^{So2}\right) \tag{3}$$

st.

$$\frac{\sum_{r1=1}^{S1} u_{r1}^1 y_{r1j}^1}{\sum_{d1=1}^{D^1} w_{d1}^1 z_{d1j}^1 + \sum_{d2=1}^{D2} w_{d2}^2 z_{d2j}^2} \le 1; \quad \forall \mathrm{j} = 1,\ldots,\mathrm{n} \tag{3a}$$

$$\frac{\sum_{r2=1}^{S2} u_{r2}^2 y_{r2j}^2}{\sum_{d3=1}^{D3} w_{d3}^3 z_{d3j}^3} \le 1; \quad \forall \mathrm{j} = 1,\ldots,\mathrm{n} \tag{3b}$$

$$\frac{\sum_{r3=1}^{S3} u_{r3}^3 y_{r3j}^3}{\sum_{d4=1}^{D^4} w_{d4}^4 z_{d4j}^4} \le 1; \quad \forall \mathrm{j} = 1,\ldots,\mathrm{n} \tag{3c}$$

$$\frac{\sum_{r1=1}^{S1} u_{r1}^1 y_{r1o}^1}{\sum_{d1=1}^{D^1} w_{d1}^1 z_{d1o}^1 + \sum_{d2=1}^{D2} w_{d2}^2 z_{d2o}^2} \ge \theta_{\min,o}^{Ec2} \tag{3d}$$

$$\frac{\sum_{r2=1}^{S2} u_{r2}^2 y_{r2o}^2}{\sum_{d3=1}^{D3} w_{d3}^3 z_{d3o}^3} \ge \theta_{\min,o}^{En2} \tag{3e}$$

$$\frac{\sum_{r3=1}^{S3} u_{r3}^3 y_{r3o}^3}{\sum_{d4=1}^{D^4} w_{d4}^4 z_{d4o}^4} \ge \theta_{\min,o}^{So2} \tag{3f}$$

$$\mathrm{w}_{d1}^1, \mathrm{w}_{d2}^2, \mathrm{w}_{d3}^3, \mathrm{w}_{d4}^4, \mathrm{u}_{r1}^1, \mathrm{u}_{r2}^2, \mathrm{u}_{r3}^3 \ge \varepsilon \tag{3h}$$

$$\frac{\sum_{r1=1}^{S1} u_{r1}^1 y_{r1o}^1 + \sum_{r2=1}^{S2} u_{r2}^2 y_{r2o}^2 + \sum_{r3=1}^{S3} u_{r3}^3 y_{r3o}^3}{\sum_{d1=1}^{D1} w_{d1}^1 z_{d1o}^1 + \sum_{d2=1}^{D2} w_{d2}^2 z_{d2o}^2 + \sum_{d3=1}^{D3} w_{d3}^3 z_{d3o}^3 + \sum_{d4=1}^{D4} w_{d4}^4 z_{d4o}^4} = \theta_o^{Man*} \tag{3g}$$

To simplify model (3), the transformation of $t_1 = (\sum_{d1=1}^{D1} w_{d1}^1 z_{d1o}^1 + \sum_{d2=1}^{D2} w_{d2}^2 z_{d2o}^2)^{-1}$, $t_2 = (\sum_{d3=1}^{D3} w_{d3}^3 z_{d3o}^3)^{-1}$, $t_3 = (\sum_{d4=1}^{D4} w_{d4}^4 z_{d4o}^4)^{-1}$, $\mu_{r1}^1 = t_1 u_{r1}^1$, $\mu_{r2}^2 = t_2 u_{r2}^2$, $\mu_{r3}^3 = t_3 u_{r3}^3$, $\omega_{d1}^1 = t_1 w_{d1}^1$, $\omega_{d2}^2 = t_2 w_{d2}^2$, $\omega_{d3}^3 = t_2 w_{d3}^3$, $\omega_{d4}^4 = t_3 w_{d4}^4$ and also $\mu_{r1}^4 = t_4 u_{r1}^1$, $\mu_{r2}^5 = t_5 u_{r2}^2$, and $\mu_{r3}^6 = t_6 u_{r3}^3$ is applied. So, the equation $\mu_{r1}^4 = \frac{t_4}{t_1}\mu_{r1}^1$ represents the linear relationship between μ_{r1}^1 and μ_{r1}^4, and in this equation, $\frac{t_4}{t_1}$ is equal to α, which is a positive variable. Therefore, $\mu_{r1}^4 = \alpha\mu_{r1}^1$ can be defined for all members of $r1$. For μ_{r2}^2 and μ_{r2}^5, the equation $\mu_{r2}^5 = \beta\mu_{r2}^2$ is established for all members of $r2$. β is equal to $\frac{t_5}{t_2}$, which is a positive variable. For μ_{r3}^3 and μ_{r3}^6, the equation $\mu_{r3}^6 = \gamma\mu_{r3}^3$ is established for all members of $r3$. γ equals $\frac{t_6}{t_3}$, which is a positive variable.

As a result, model (4), which is a parametric nonlinear model and transformed form of model (3), is presented below.

$$\max\left(\sum_{r1=1}^{S1} \mu_{r1}^1 y_{r1o}^1 - \theta_{\min,o}^{Ec2}\right) * \left(\sum_{r2=1}^{S2} \mu_{r2}^2 y_{r2o}^2 - \theta_{\min,o}^{En2}\right) * \left(\sum_{r3=1}^{S3} \mu_{r3}^3 y_{r3o}^3 - \theta_{\min,o}^{So2}\right) \tag{4}$$

st.

$$\sum_{r1=1}^{S1} \mu_{r1}^1 y_{r1j}^1 - \sum_{d1=1}^{D1} \omega_{d1}^1 z_{d1j}^1 - \sum_{d2=1}^{D2} \omega_{d2}^2 z_{d2j}^2 \le 0; \quad \forall j = 1, \ldots, n \tag{4a}$$

$$\sum_{r2=1}^{S2} \mu_{r2}^2 y_{r2j}^2 - \sum_{d3=1}^{D3} \omega_{d3}^3 z_{d3j}^3 \le 0; \quad \forall j = 1, \ldots, n \tag{4b}$$

$$\sum_{r3=1}^{S3} \mu_{r3}^3 y_{r3j}^3 - \sum_{d4=1}^{D4} \omega_{d4}^4 z_{d4j}^4 \le 0; \quad \forall j = 1, \ldots, n \tag{4c}$$

$$\sum_{r1=1}^{S1} \mu_{r1}^1 y_{r1o}^1 \ge \theta_{\min,o}^{Ec2} \tag{4d}$$

$$\sum_{r2=1}^{S2} \mu_{r2}^2 y_{r2o}^2 \ge \theta_{\min,o}^{En2} \tag{4e}$$

$$\sum_{r3=1}^{S3} \mu_{r3}^3 y_{r3o}^3 \ge \theta_{\min,o}^{So2} \tag{4f}$$

$$\alpha\sum_{r1=1}^{S1} \mu_{r1}^1 y_{r1o}^1 + \beta\sum_{r2=1}^{S2} \mu_{r2}^2 y_{r2o}^2 + \gamma\sum_{r3=1}^{S3} \mu_{r3}^3 y_{r3o}^3 = \theta_o^{Man*} \tag{4g}$$

$$\sum_{d1=1}^{D1} \omega_{d1}^1 z_{d1o}^1 + \sum_{d2=1}^{D2} \omega_{d2}^2 z_{d2o}^2 = 1 \tag{4h}$$

$$\sum_{d3=1}^{D3} \omega_{d3}^3 z_{d3o}^3 = 1 \tag{4i}$$

$$\sum_{d4=1}^{D4} \omega_{d4}^4 z_{d4o}^4 = 1 \tag{4j}$$

$$\begin{aligned}&\omega_{d1}^1, \omega_{d2}^2, \omega_{d3}^3, \omega_{d4}^4, \mu_{r1}^1, \mu_{r2}^2, \mu_{r3}^3 \ge \varepsilon\\&\alpha, \beta, \gamma \ge 0\end{aligned} \tag{4k}$$

3.2 *Mathematical modeling of scenario (II)*

In this section, the mathematical model of the second scenario is presented in two steps. In the first step, the efficiency of the players is assessed based on the non-cooperative leader-follower game under an input-oriented model with a constant return to scale condition. The model has been formulated considering the manufacturer as the leader and the supplier as the follower. In other words, first, the manufacturer's efficiency as a leader is calculated. Then, by maintaining (preserving) the efficiency of the leader (θ_o^{Man*}), the efficiency of the supplier (θ_o^{Sup*}) is calculated similarly. Afterward, the overall efficiency of the whole network (θ_o^{ON}) is evaluated based on the efficiency scores obtained for the leader and follower [21].

The second step in this scenario is the same as the second step of the first scenario. Therefore, the network's overall efficiency is calculated using the geometric mean of the efficiency scores of its players. As mentioned earlier, the mathematical modeling for evaluating the efficiency of sustainability goals is similar to models (2) and (4).

4. Results and discussion

The pharmaceutical industry is among the industries in which attention to sustainability goals is of particular importance. Stakeholders expect this industry to deliver high-quality medical procedures and drugs, provide valuable solutions to social needs, create job opportunities, and help to achieve national interests [37, 38]. Improper use of resources, creating environmental waste, and dissatisfaction among employees and other stakeholders are some of the main challenges of this industry. From the perspective of the company's shareholders, creating an SSCN is a strategic goal that brings a competitive advantage and is very useful in overcoming these challenges. Establishing a proper evaluation system that could calculate the sustainability efficiency of the whole SCN, the sustainability efficiency of each player, and the efficiency of the sustainability goals of each player in this industry is valuable. The accurate knowledge of the current performance state helps executives identify weaknesses, set target points, and compute the variances from ideal points.

4.1 *Case study*

The SCN under study, shown in figure 3, produces many products, among which 35 products are selected as decision-making units (DMUs) of the SCNSE problem. Pharmaceutical companies use the Global Reporting Initiative (GRI) as an approach to implement and measure the sustainability of their SCNs. The GRI was also adopted in this study to identify input and output indicators of the SSCN. Today, GRI is a very popular tool in various industries because it provides guidelines containing more than 100 possible measures for evaluating the performance of companies in sustainability approach dimensions: environmental, social, and economic [39, 40]. Sustainability indicators were selected using the GRI measures and interviews with the experts of the planning department of the company. The interview questionnaire form is provided in "Appendix B".

The data for measuring each indicator were collected for each DMU, as summarized in table 3. This table presents each indicator's status in terms of being desirable or undesirable, its classification in terms of sustainability goals, and statistical values related to all DMUs.

It should be noted that environmental indicators, including air and water pollution, hazardous pollution, and waste of resources, are undesirable variables, and the inverse values of these variables are used for the models. Moreover, manufacturing cost and total energy consumed annually are two additional input variables included. The proposed model using the collected data was implemented in Lingo 17 in a laptop with a Core i5 2.67 GHz CPU and 4.00 GB Ram. Lingo could easily find a global solution for linear models of players' efficiency. Because of the non-linearity of the bargaining models (models 2 and 4), the global solver option of Lingo software was implemented to achieve a global solution. As shown earlier, the Nash bargaining models were parametric and nonlinear in the production stage. To solve them in each scenario, an innovative interpolation algorithm was considered for computing the constant equal values of the parameters α, β, γ. In this regard, the acceptable values for these parameters in the first and second scenarios were 0.57 and 0.62, respectively.

4.2 *Numerical results*

The results obtained by implementing the proposed models for the case study are presented in "Appendix C".

According to the results, under the first scenario, 17% of the DMUs are overall efficient, and the average overall efficiency is 0.94, with a variance of 0.005. Furthermore, based on the results obtained from implementing the cooperative model, DMU14, DMU16, DMU29, DMU32,

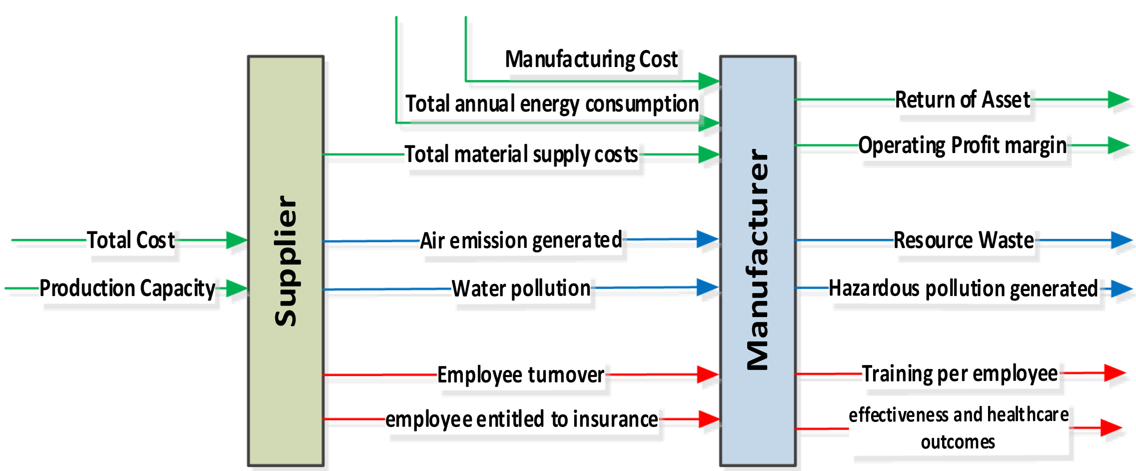

Figure 3. SSCN of the pharmaceutical company.

Table 3. Statistical summary of the collected data in the SSCN of the pharmaceutical company.

Measures		Type	Sustainable goals	Mean	Median	SD	MIN	MAX	Coef. Var.
Total cost	x_{11}	Desirable	Economic	1135.229	1139	143.535	798	1551	0.126
Production capacity	x_{12}	Desirable	Economic	9.267	9.49	0.757	7.920	10.220	0.082
Manufacturing cost	w_{11}	Desirable	Economic	113.143	116	14.937	84	158	0.132
Total annual energy consumption	w_{12}	Desirable	Economic	45.943	47	7.487	29	58	0.163
Total material supply costs	w_{21}	Desirable	Economic	1878	1872	401.731	1166	3037	0.214
Co^2 emission generated	$1/w_{31}$	Undesirable	Environmental	3.088	2.97	0.823	1.850	4.900	0.266
Water pollution	$1/w_{32}$	Undesirable	Environmental	0.045	0.05	0.020	0.010	0.080	0.444
Employee turnover	w_{41}	Desirable	Social	251.343	249	76.923	93	432	0.306
employee entitled to insurance	w_{42}	Desirable	Social	6.943	7	2.413	3	12	0.347
Return of Asset	u_{11}	Desirable	Economic	0.685	0.681	0.157	0.380	0.991	0.229
Operating Profit margin	u_{12}	Desirable	Economic	0.181	0.18	0.027	0.130	0.260	0.151
Resource Waste	$1/u_{21}$	Undesirable	Environmental	0.137	0.11	0.104	0.010	0.400	0.759
Hazardous pollution generated	$1/u_{22}$	Undesirable	Environmental	0.003	0.002	0.001	0.001	0.004	0.305
Training per employee	u_{32}	Desirable	Social	13.686	14	2.447	9	22	0.179
Healthcare outcomes	u_{31}	Desirable	Social	0.914	0.942	0.080	0.730	0.999	0.088

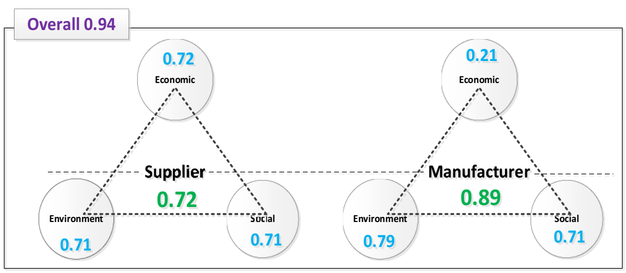

Figure 4. The average efficiency of the network and its components under scenario (I).

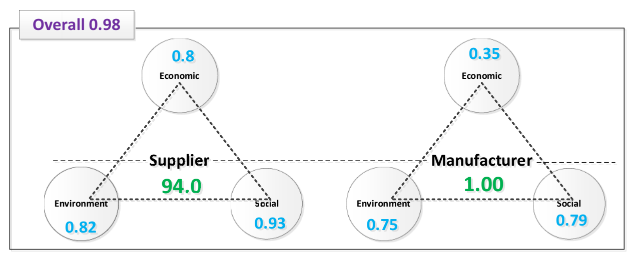

Figure 5. The average efficiency values of the network and its components under scenario (II).

DMU33, and DMU35 are on the overall efficiency frontier. DMU18 and DMU35 are efficient suppliers. DMU4, DMU10, DMU13, DMU16, DMU22, DMU27, and DMU28 are also efficient in the production stage. Therefore, no DMU is efficient in all three modes.

Moreover, according to the second scenario results, 37% of the DMUs are overall efficient, and the average global efficiency value is 0.97, with a variance of 0.002. The results indicate that DMU14, DMU16, DMU29, DMU32, DMU33, and DMU35 are efficient in all three modes. It is also worth mentioning that DMU16 is the only efficient unit in both cooperative and non-cooperative models.

5. Findings and managerial implication

Examination of the results shows that in comparison to previous models of SCNSE, the model proposed in this study provides deeper knowledge of the realities of the SSCN elements' performance because it can evaluate the overall efficiency of the whole SCN, the efficiency of its players, and the efficiency of the sustainability goals related to each player, simultaneously. In addition, it clearly shows the impact of cooperation type among network components on the efficiency results. As presented in figures 4 and 5, the framework proposed in this study can calculate the efficiency values of all components while modeling the trade-off among network components in different states.

The results reveal that only 6% of the supplier's DMUs are efficient under the first scenario, while 43% are efficient under the second scenario. Furthermore, the average efficiency of suppliers is 0.72 and 0.95, respectively, in the first and second scenarios, with variances of 0.023 and 0.006. Comparing the manufacturer's efficiency under the first and second scenarios shows that 6% and 51% of the DMUs are efficient in this player. Their average efficiency values are 0.89 with 0.99, with variances of 0.009 2E−7, respectively. As the first point, it is important to note that based on initial assumptions, we expected sustainability goals for efficient DMUs to be on the efficient frontier or at least as close to it as possible. At the same time, the results indicate a gap between the efficiency of the players and the efficiency of their sustainability goals. The research findings specifically show:

- In the cooperative model, DMU16 and DMU35 are efficient in the supplier stage, while DMU16 is inefficient in economic goals, and DMU35 is inefficient in environmental goals.

- Based on the results of the cooperative model, in the manufacturer stage, DMU1, DMU2, DMU12, DMU21, DMU23, DMU26, and DMU27 are on the efficient frontier, but among them, the efficiency is observed only for DMU1 and only in social goal, which is a serious gap. In other words, although these DMUs are efficient manufacturers, their sustainability goals' efficiency is considerably low. The two findings mentioned above show that a player's efficiency does not necessarily guarantee its efficiency in all three aspects of sustainability.
- Since it was shown that the cooperative model has a higher quality than the non-cooperative one because it showed better contrast between the efficiency of DMUs (higher variance), a wider functional gap is expected between the efficiency of the players and that of their sustainability goals in the non-cooperative model. The average efficiency value of the supplier for all DMUs is 0.95 with 0.06 variance, while the average efficiency values of the sustainability goal are 0.8, 0.82, and 0.83, with variances of 0.05, 0.05, and 0.08 for the economic, environmental, and social goals, respectively. Besides, the results in the manufacturer stage for each DMU show that the average efficiency is 0.99 and the variance is 2E−7, while the average efficiency values of the economic, environmental, and social goals are 0.35, 0.75, and 0.79, with variances of 0.11, 0.019, and 0.014, respectively. Therefore, the cooperative approach provides a more accurate evaluation of the problem under study. In other words, it separates efficient and inefficient units more properly. In order to have a better understanding, figures 6 and 7 illustrate the functional gap between the efficiency of the supplier and the efficiency of sustainability goals in this stage under the first and second scenarios, respectively. Figures 8 and 9 demonstrate the functional gap between the manufacturer's overall efficiency and the efficiency of its sustainability goals in this stage under the first and second scenarios, respectively.

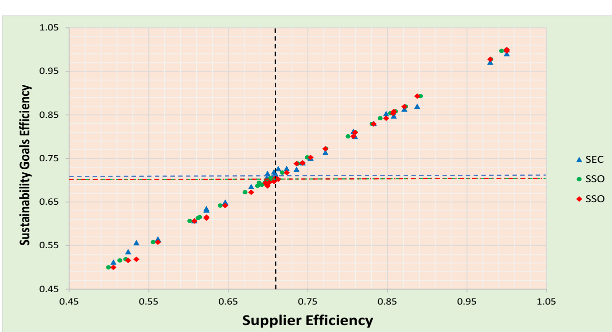

Figure 6. Comparison of the efficiency of the supplier and its sustainability goals in the cooperative model.

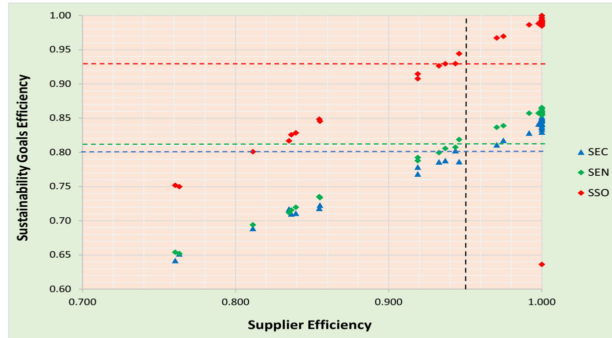

Figure 7. Comparison of the efficiency of the supplier and its sustainability goals in the non-cooperative model.

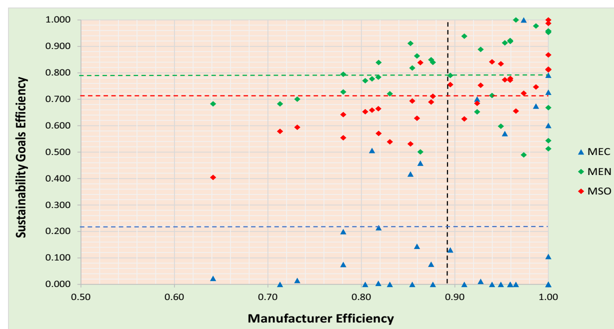

Figure 8. Comparison of the efficiency of the manufacturer and its sustainability goals in the cooperative model.

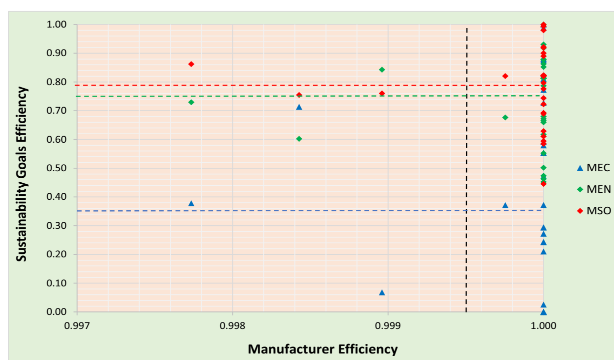

Figure 9. Comparison of the efficiency of the manufacturer and its sustainability goals in the non-cooperative model.

- In continuation, the necessity of considering the trade-off among sustainability goals and investigating it in improvement plans through a sensitivity analysis is discussed. In classical DEA models, improvement plans for inefficient DMUs are presented regardless of the possibility of conflict of interest among the components, which is a fundamental weakness described using the example below:
In the first scenario, in DMU (1), the manufacturer is on the efficient frontier, and the efficiency of the

economic, environmental, and social goals is equal to 0.6, 0.5, and 1, respectively. Suppose the manager decides to promote the efficiency of the environmental goal by reducing the generated hazardous pollution using clean fuels. And at the same time, they try to reduce production costs and the annual costs of energy consumption. While these plans are inherently contradictory, implementing one without considering the other reduces the efficiency of the other goal. Therefore, the manager is recommended to consider the sensitivity of the other goal's efficiency and related measures for each unit of change created before implementing any operational improvement plan.

To this aim, the effect of changes in the values of the index "hazardous pollution generated" on the optimal solutions was investigated. We reduced the value of this index in DMU (1) 10 times, one unit in each step, and then the bargaining model related to the first scenario (Model 2) was implemented, and economic, environmental, and social efficiency was calculated. As shown in figures 10, 11 and 12, as a result of these changes, environmental efficiency and economic inefficiency in the third step were significantly improved, and social efficiency deteriorated because sustainability goals were bargained with the condition of maintaining the player's efficiency.

Accordingly, the proposed model helps the executives to examine the impact of any operational improvement plan that will be executed to promote the efficiency of each of the sustainability goals. This is the second implication and another managerial insight of this research.

Through simultaneous modeling of two levels of conflicts, this study contributes to the literature on the evaluation of SCN sustainability efficiency. Also, inspired by the concept of triple bottomline, the three economic, environmental, and social aspects were considered simultaneously for defining the concept of sustainability.

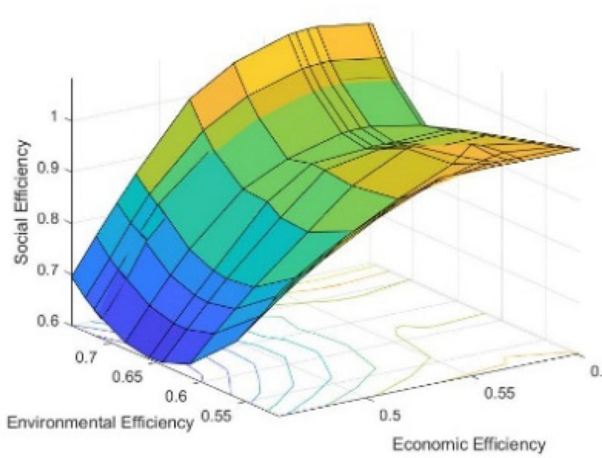

Figure 10. Impact of changes in environmental parameter on economic-environmental-social efficiency.

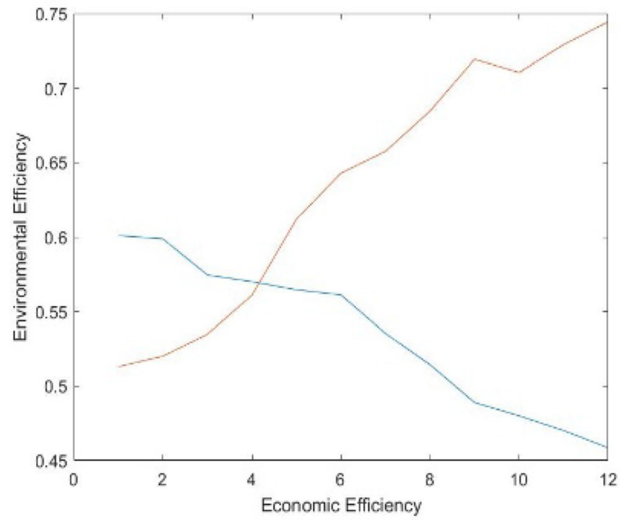

Figure 11. Impact of changes in environmental parameter on economic-environmental efficiency.

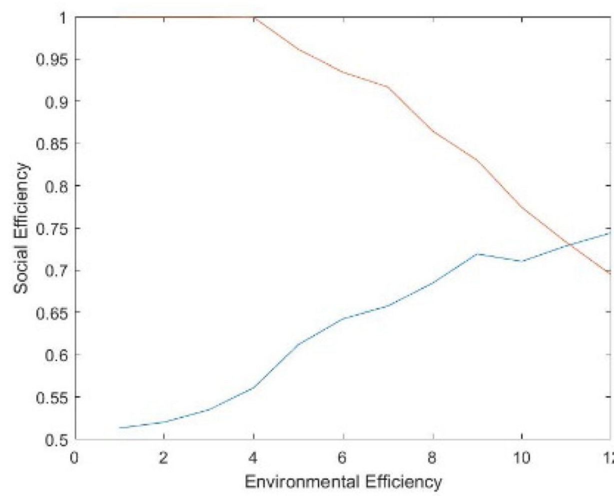

Figure 12. Impact of changes in environmental parameter on social-environmental efficiency.

In summary, the proposed models help managers gain more accurate knowledge of the performance of the SCN components, including players and related sustainability goals, while modeling the inherent conflict of interest among the network components. This insight provides more reliable conditions so that the decision-makers can adopt more cost-effective strategies and plans for promoting their social responsibility and reducing environmental impacts.

- The proposed models allow organizations to update the relevant key performance indicators, reexamine the efficiency results of network components, identify the weaknesses, and offer improvement plans through strategic changes in each sustainability goal.

6. Conclusion and future research

Nowadays, supply chains should consider sustainability goals to maintain and improve their competitive advantages. Performance evaluation is one of the necessities of establishing the sustainability approach in SCNs. However, evaluating the sustainability efficiency of an SCN is a complicated issue due to the multiplicity of the interactions among different components and, in particular, the inherent conflict of interest between them. This study proposed a hybrid model of NDEA and GT to overcome this complexity. The interactions among players were modeled under cooperative and non-cooperative games, and the bargaining game was used to formulate the interactions among sustainability goals related to each player, as well. The most important innovation of this study is the simultaneous attention to different levels of the trade-off among the components of SSCNs and the mathematical modeling of these conflicts of interest. This approach allows for simultaneous measurement of the efficiency score of players and, at the same time, the efficiency score of the sustainability goals for each player.

Future studies can address the following issues:

In this problem, only 2 players were considered for the network, while other players are involved in the SCN, including distributors, retailers, etc. Therefore, developing a sustainability efficiency evaluation model by considering other players in the SCN can be one of the topics for future research.

In this study, the parameters are considered deterministic, while these parameters may have uncertainty that can be incorporated into the model using probabilistic or possibilistic methods.

Another very important assumption in this study was the type of cooperation among components. The components of the SCN adopted a leader-follower and centralized cooperative game, and the type of cooperation among sustainability goals was modeled through the Nash bargaining game. Changing each of these issues can be a subject for future studies. The proposed model could be applied to other paradigms in the SCN.

Regarding the development of the mathematical model, a key topic that can be studied by future research is how to linearize the proposed Nash bargaining models. In addition, modeling the relationship between the sustainability efficiency of each player as well the sustainability of the entire network is another issue that can be dealt with in future studies.

The models proposed in the present study were applied in the pharmaceutical industry. However, from the perspective of practical implications, they can be utilized in all manufacturing industries, such as oil, gas, automobile, etc., and some service industries, including health services, banking, and financial service chains, etc., provided that the indicators are extracted, screened, and selected in accordance to the industry in question.

Appendix A

Lemma 1 *The feasible set S is compact and convex.*

Proof 1 Since feasible set S is defined in a Euclidean space, the compactness condition has been met. To prove that the solution space is convex, assume:

$$\left(w_1^{1\prime},\ldots,w_{D1}^{1\prime},w_1^{2\prime},\ldots,w_{D2}^{2\prime},w_1^{3\prime},\ldots,w_{D3}^{3\prime},w_1^{4\prime},\ldots,w_{D4}^{4\prime},\; v_1^{1\prime},\ldots,v_m^{1\prime}\right)\in S$$

$$\left(w_1^{1\prime\prime},\ldots,w_{D1}^{1\prime\prime},w_1^{2\prime\prime},\ldots,w_{D2}^{2\prime\prime},w_1^{3\prime\prime},\ldots,w_{D3}^{3\prime\prime},w_1^{4\prime\prime},\ldots,w_{D4}^{4\prime\prime},\; {}''_1,\ldots,v''_m\right)\in S$$

According to this assumption and for each $\lambda\in[0,1]$ there is:

$$\lambda w_{d1}^{1\prime}+(1-\lambda)w_{d1}^{1\prime\prime}>0,\quad \forall d1=1,\ldots,D1$$
$$\lambda w_{d2}^{2\prime}+(1-\lambda)w_{d2}^{2\prime\prime}>0,\quad \forall d2=1,\ldots,D2$$
$$\lambda w_{d3}^{3\prime}+(1-\lambda)w_{d3}^{3\prime\prime}>0,\quad \forall d3=1,\ldots,D3$$
$$\lambda w_{d4}^{4\prime}+(1-\lambda)w_{d4}^{4\prime\prime}>0,\quad \forall d4=1,\ldots,D4$$
$$\lambda v'_i+(1-\lambda)v''_i>0,\quad \forall i=1,\ldots,m$$

Therefore, based on the above assumptions, the feasible set is compact. Thus, in model (2) for the first constraint, there is:

$$\frac{\sum_{d2=1}^{D2} w_{d2}^2 z_{d2j}^2}{\sum_{i=1}^{m} v_i x_{ij}}\le 1;\ \forall \mathrm{j}=1,\ldots,\mathrm{n}\Rightarrow \sum_{d2=1}^{D2} w_{d2}^2 z_{d2j}^2\le\sum_{i=1}^{m} v_i x_{ij}\Rightarrow$$

$$\begin{aligned}\sum_{d2=1}^{D2} w_{d2}^2 z_{d2j}^2 &= \sum_{d2=1}^{D2}\left(\lambda w_{d2}^{2\prime}+(1-\lambda)w_{d2}^{2\prime\prime}\right)z_{d2j}^2\\ &=\lambda\sum_{d2=1}^{D2} w_{d2}^{2\prime}z_{d2j}^2+(1-\lambda)\sum_{d2=1}^{D2} w_{d2}^{2\prime\prime}z_{d2j}^2\\ &\le\lambda\sum_{i=1}^{m} v'_i x_{ij}+(1-\lambda)\sum_{i=1}^{m} v''_i x_{ij}\\ &=\sum_{i=1}^{m}\left(\lambda v'_i+(1-\lambda)v''_i\right)x_{ij}\end{aligned}$$

Similarly, for the second and third constraints, there is:

$$\begin{aligned}\sum_{d3=1}^{D3} w_{d3}^3 z_{d3j}^3 &= \sum_{d3=1}^{D3}\left(\lambda w_{d3}^{3\prime}+(1-\lambda)w_{d3}^{3\prime\prime}\right)z_{d3j}^3\\ &=\lambda\sum_{d3=1}^{D3} w_{d3}^{3\prime}z_{d3j}^3+(1-\lambda)\sum_{d3=1}^{D3} w_{d3}^{3\prime\prime}z_{d3j}^3 cr\\ &=\sum_{i=1}^{m}\left(\lambda v'_i+(1-\lambda)v''_i\right)x_{ij}\end{aligned}$$

$$\sum_{d4=1}^{D4} w_{d4}^4 z_{d4j}^4 = \sum_{d4=1}^{D4} \left(\lambda w_{d4}^{4\prime} + (1-\lambda) w_{d4}^{4\prime\prime}\right) z_{d4j}^4$$
$$= \lambda \sum_{d4=1}^{D4} w_{d4}^{4\prime} z_{d4j}^4 + (1-\lambda) \sum_{d4=1}^{D4} w_{d4}^{4\prime\prime} z_{d4j}^4$$
$$\leq \lambda \sum_{i=1}^{m} v_i^{\prime} x_{ij} + (1-\lambda) \sum_{i=1}^{m} v_i^{\prime\prime} x_{ij}$$
$$= \sum_{i=1}^{m} \left(\lambda v_i^{\prime} + (1-\lambda) v_i^{\prime\prime}\right) x_{ij}$$

For the fourth, fifth, and sixth constraints, there are:

$$\sum_{d2=1}^{D2} w_{d2}^2 z_{d2o}^2 \geq \theta_{\min,o}^{Ec1} \sum_{i=1}^{m} v_i x_{io} \Rightarrow$$
$$\sum_{d2=1}^{D2} \left[\lambda w_{d2}^{2\prime} + (1-\lambda) w_{d2}^{2\prime\prime}\right] z_{d2o}^2 \geq \theta_{\min,o}^{Ec1}$$
$$\sum_{i=1}^{m} \left[\lambda v_i^{\prime} + (1-\lambda) v_i^{\prime\prime}\right] x_{io}$$

$$\sum_{d3=1}^{D3} w_{d3}^3 z_{d3o}^3 \geq \theta_{\min,o}^{En1} \sum_{i=1}^{m} v_i x_{io} \Rightarrow$$
$$\sum_{d3=1}^{D3} \left[\lambda w_{d3}^{3\prime} + (1-\lambda) w_{d3}^{3\prime\prime}\right] z_{d3o}^3$$
$$\geq \theta_{\min,o}^{En1} \sum_{i=1}^{m} \left[\lambda v_i^{\prime} + (1-\lambda) v_i^{\prime\prime}\right] x_{io}$$

$$\sum_{d4=1}^{D4} w_{d4}^4 z_{d4o}^4 \geq \theta_{\min,o}^{So1} \sum_{i=1}^{m} v_i x_{io} \Rightarrow$$
$$\sum_{d4=1}^{D4} \left[\lambda w_{d4}^{4\prime} + (1-\lambda) w_{d4}^{4\prime\prime}\right] z_{d4o}^4$$
$$\geq \theta_{\min,o}^{So1} \sum_{i=1}^{m} \left[\lambda v_i^{\prime} + (1-\lambda) v_i^{\prime\prime}\right] x_{io}$$

And for the last constraint, there is:

$$\sum_{d2=1}^{D2} \left[\lambda w_{d2}^{2\prime} + (1-\lambda) w_{d2}^{2\prime\prime}\right] z_{d2o}^2 + \sum_{d3=1}^{D3} \left[\lambda w_{d3}^{3\prime} + (1-\lambda) w_{d3}^{3\prime\prime}\right] z_{d3o}^3$$
$$+ \sum_{d4=1}^{D4} \left[\lambda w_{d4}^{4\prime} + (1-\lambda) w_{d4}^{4\prime\prime}\right] z_{d4o}^4$$
$$= \theta_o^{Sup*} \sum_{i=1}^{m} \left[\lambda v_i^{\prime} + (1-\lambda) v_i^{\prime\prime}\right] x_{io}$$

Therefore, for every $(d2 = 1, \ldots, D2)$, $(d3 = 1, \ldots, D3)$, $(d4 = 1, \ldots, D4)$,$(i = 1, \ldots, m)$, there is:

$$\left(\lambda w_{d2}^{2\prime} + (1-\lambda) w_{d2}^{2\prime\prime}, \lambda w_{d3}^{3\prime} + (1-\lambda) w_{d3}^{3\prime\prime},\right.$$
$$\left.\lambda w_{d4}^{4\prime} + (1-\lambda) w_{d4}^{4\prime\prime}, \lambda v_i^{\prime} + (1-\lambda) v_i^{\prime\prime}\right) \in S$$

which is equal to:

$$\lambda\left(w_1^{2\prime}, \ldots, w_{D2}^{2\prime}, w_1^{3\prime}, \ldots, w_{D3}^{3\prime}, w_1^{4\prime}, \ldots, w_{D4}^{4\prime}, v_1^{\prime}, \ldots, v_i^{\prime}\right)$$
$$+ (1-\lambda)\left(w_1^{2\prime\prime}, \ldots, w_{D2}^{2\prime\prime}, w_1^{3\prime\prime}, \ldots, w_{D3}^{3\prime\prime}, w_1^{4\prime\prime}, \ldots,\right.$$
$$\left.w_{D4}^{4\prime\prime}, v_1^{\prime\prime}, \ldots, v_i^{\prime\prime}\right) \in S$$

Hence, the feasible set S is convex.

Appendix B Indicator selection survey questionnaire

Introduction

Thank you for agreeing to help us use your experience to select proper measures for the supply chain sustainability of the company. As you know, we are evaluating the sustainability efficiency of your company's supply chain with a focus on supplier and manufacturer stages to determine the current status and see if we can Identify improvement initiatives. For this purpose, we have provided an attachment, which is the list of measures that have been collected through the literature review.

Please answer the following questions by writing your answer in your own words in the box provided. If you have any questions about this questionnaire, don't hesitate to contact us.

Name:	
Department:	Job position:
Date of employment:	Total work experience:
Highest education certification:	Field of Study:

Directions

1. Please indicate four questions as below:

   Q1: Is the indicator aligned with goals and strategies?
   Q2: Does the indicator have computational complexity?
   Q3: Is the indicator actionable?
   Q4: Is there reliable data to calculate the indicator?

2. Please select at least ten measures in each stage of the supply chain
3. Please sort them by priority and Note in the table below:

Name:

Selected Sustainability indicator

Supplier stage:

Economic indicators	Environmental indicators	Social indicators

Manufacturer stage:

Economic indicators	Environmental indicators	Social indicators

Description:

……………………………………………………………………………………………

Appendix C Table of the results

Results of SCN sustainability efficiency

	The first scenario (cooperative model)									The second scenario (non-cooperative model)								
DMU	θ_o^{OC}	θ_o^{Sup*}	θ_o^{Man*}	θ_o^{Ec1}	θ_o^{En1}	θ_o^{So1}	θ_o^{Ec2}	θ_o^{En2}	θ_o^{So2}	θ_o^{ON}	θ_o^{Sup*}	θ_o^{Man*}	θ_o^{En1}	θ_o^{So1}	θ_o^{Ec2}	θ_o^{En2}	θ_o^{So2}	θ_o^{En1}
1	0.89	0.42	1.00	0.46	0.40	0.40	0.60	0.51	1.00	1.0	1.0	1.0	1.00	1.00	0.64	0.24	0.47	0.99
2	1.00	0.53	1.00	0.56	0.52	0.52	0.79	0.54	0.99	0.9	0.8	1.0	0.72	0.71	0.82	0.87	0.50	0.98
3	0.83	0.70	0.86	0.71	0.69	0.69	0.45	0.50	0.84	0.9	0.8	1.0	0.65	0.65	0.75	0.57	0.46	1.00
4	0.79	0.87	0.71	0.86	0.87	0.87	0.00	0.68	0.58	1.0	1.0	1.0	0.84	0.86	0.99	0.77	0.68	0.89
5	0.82	0.81	0.78	0.80	0.81	0.81	0.19	0.79	0.55	1.0	0.9	1.0	0.77	0.79	0.91	0.00	0.91	0.61
6	0.85	0.74	0.88	0.74	0.74	0.74	0.00	0.84	0.71	0.9	0.8	1.0	0.64	0.65	0.75	0.00	0.81	0.82
7	0.85	0.52	0.96	0.54	0.51	0.52	0.00	0.92	0.78	0.9	0.8	1.0	0.69	0.69	0.80	0.00	0.81	0.82
8	0.86	0.83	0.73	0.83	0.83	0.83	0.01	0.70	0.59	0.9	0.9	1.0	0.72	0.73	0.85	0.37	0.67	0.82
9	0.91	0.86	0.85	0.85	0.86	0.86	0.00	0.82	0.69	1.0	1.0	1.0	0.83	0.86	0.99	0.98	0.78	0.82
10	0.88	0.86	0.85	0.86	0.85	0.85	0.41	0.91	0.53	1.0	1.0	1.0	0.84	0.86	0.99	0.55	0.93	0.58
11	0.86	0.62	0.97	0.63	0.61	0.62	0.00	1.00	0.66	0.9	0.8	1.0	0.71	0.72	0.83	0.00	0.86	0.72
12	1.00	0.75	1.00	0.75	0.75	0.75	0.00	0.96	0.81	1.0	1.0	1.0	0.82	0.84	0.97	0.29	0.81	0.82
13	1.00	0.89	0.83	0.87	0.89	0.89	0.00	0.72	0.54	1.0	1.0	1.0	0.83	0.87	1.00	0.37	0.66	0.59
14	1.00	0.74	0.95	0.73	0.74	0.74	0.00	0.60	0.83	1.0	0.9	1.0	0.79	0.82	0.94	0.00	0.55	0.91
15	0.94	0.98	0.81	0.97	0.98	0.98	0.50	0.78	0.66	1.0	1.0	1.0	0.84	0.86	0.99	0.81	0.85	0.74
16	1.00	1.00	0.82	0.99	1.00	1.00	0.00	0.78	0.66	1.0	1.0	1.0	0.84	0.86	0.99	0.47	0.81	0.82
17	0.95	0.72	0.97	0.73	0.72	0.72	1.00	0.49	0.72	1.0	1.0	1.0	0.84	0.86	0.99	1.00	0.45	0.79
18	0.94	0.71	0.92	0.71	0.70	0.71	0.70	0.65	0.68	1.0	1.0	1.0	0.84	0.86	0.99	0.71	0.60	0.75
19	0.78	0.56	0.78	0.57	0.56	0.56	0.07	0.73	0.64	0.9	0.9	1.0	0.72	0.74	0.85	0.88	0.67	0.77
20	0.94	0.77	0.82	0.76	0.77	0.77	0.21	0.84	0.57	1.0	1.0	1.0	0.83	0.86	1.00	0.02	0.87	0.62
21	1.00	0.68	1.00	0.69	0.67	0.67	0.72	0.96	0.81	1.0	1.0	1.0	0.84	0.86	0.99	0.00	0.81	0.82
22	0.96	0.81	0.94	0.81	0.80	0.80	0.00	0.71	0.84	1.0	1.0	1.0	0.85	0.86	0.99	0.27	0.66	0.90
23	1.00	0.70	1.00	0.71	0.70	0.70	0.00	0.67	0.87	0.9	0.8	1.0	0.71	0.72	0.83	0.00	0.61	0.92
24	0.96	0.71	0.96	0.72	0.70	0.70	0.00	0.92	0.77	1.0	0.9	1.0	0.78	0.79	0.91	0.00	0.81	0.82
25	0.99	0.71	0.99	0.72	0.70	0.70	0.67	0.98	0.75	1.0	0.9	1.0	0.80	0.81	0.93	0.29	0.81	0.82
26	0.96	0.61	1.00	0.61	0.60	0.61	0.10	0.96	0.81	1.0	1.0	1.0	0.81	0.84	0.97	0.55	0.81	0.82
27	0.90	0.51	1.00	0.51	0.50	0.50	0.00	0.95	0.81	1.0	1.0	1.0	0.84	0.86	0.99	0.00	0.81	0.82
28	0.96	0.85	0.80	0.85	0.84	0.84	0.00	0.77	0.65	1.0	1.0	1.0	0.85	0.86	0.99	0.00	0.81	0.82
29	1.00	0.70	0.91	0.72	0.69	0.69	0.00	0.94	0.63	1.0	1.0	1.0	0.85	0.85	0.98	0.24	0.87	0.68
30	1.00	0.71	0.87	0.73	0.70	0.70	0.07	0.85	0.69	1.0	1.0	1.0	0.85	0.86	0.99	0.06	0.84	0.76
31	1.00	0.29	0.95	0.32	0.27	0.28	0.57	0.91	0.77	1.0	1.0	1.0	0.85	0.86	0.99	0.59	0.81	0.82
32	1.00	0.70	0.86	0.70	0.69	0.69	0.14	0.86	0.63	1.0	0.9	1.0	0.79	0.80	0.93	0.72	0.87	0.69
33	1.00	0.65	0.93	0.65	0.64	0.64	0.01	0.89	0.75	1.0	0.9	1.0	0.79	0.81	0.93	0.00	0.81	0.82

continued

	The first scenario (cooperative model)									The second scenario (non-cooperative model)								
DMU	θ_o^{OC}	θ_o^{Sup*}	θ_o^{Man*}	θ_o^{Ec1}	θ_o^{En1}	θ_o^{So1}	θ_o^{Ec2}	θ_o^{En2}	θ_o^{So2}	θ_o^{ON}	θ_o^{Sup*}	θ_o^{Man*}	θ_o^{En1}	θ_o^{So1}	θ_o^{Ec2}	θ_o^{En2}	θ_o^{So2}	θ_o^{En1}
34	0.99	0.62	0.90	0.64	0.61	0.61	0.13	0.79	0.76	1.0	1.0	1.0	0.85	0.86	0.99	0.37	0.72	0.86
35	1.00	1.00	0.64	1.00	0.99	1.00	0.02	0.68	0.40	1.0	1.0	1.0	0.85	0.85	0.99	0.21	1.00	0.44

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