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A Novel Sustainable Multi-objective Optimization Model for Steel Supply Chain Design Considering Technical and Managerial Issues: a Case Study

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Abstract

The iron and steel industry is one of the most resource-intensive and pollutant industries that creates the highest value across all mining and metal industries. While the recent studies provide recommendations to improve sustainable development in this industry, the complexity of the socio-environmental impacts of activities in this industry due to its multi-tier and multi-supply chain structures has given rise to the problem of sustainable steel supply chain network design. This work proposes a new multi-objective mixed-integer linear programming model to integrate sustainability factors with managerial and technical restrictions. The total economic profitability is maximized, while environmental pollution is minimized. There is also a focus on the social and environmental compliance. Accordingly, a novel sustainability assessment system is proposed. The managerial restrictions are also satisfied by maximizing the demand fulfillment priority using a new method. The augmented ε-constraint method is applied to tackle the mathematical problem under study. Finally, a real case study is used. The results obtained 35% and 41% reductions in CO2 and particulate matter emissions, respectively, while the total profit decreases up to 15%. A sensitivity analysis is also performed. In addition, several managerial insights are discussed based on the results.

Table of abbreviations

Abbreviation	Full description	Abbreviation	Full description
Augmented ε-constraint method	AUGMECON2	Multiobjective mixed-integer linear programming	MOMILP
Blast Furnace-Basic Oxygen Furnace	BF-BOF	Net present value	NPV
Central management group	CMG	Particulate matter	PM
Direct Reduction-Electric Arc Furnace	DR-EAF	Prioritization of demand fulfilment	PDF
Environmental pollution	EP	Socio-environmental compliances	SEC
Expert group judgment	EGJ	Steel supply chain network	SSCN
External relationships	ExS	Supply chain	SC
Gross domestic product	GDP	Supply chain network	SCN
Group analytical hierarchy process	GAHP	Supply chain network design	SCND
Inter-supply chains	IeS	Sustainability assessment	SA
Intra-supply chain	IaS	Sustainability assessment	SA
Iron and steel industry	ISI	Sustainable indicators	SIs
Key performance indicators	KPIs	Sustainable supply chain management	SSCM
Multi-criteria decision-making	MCDM	Technique for order preference by similarity to ideal solution	TOPSIS

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1. Introduction

The iron and steel industry (ISI) includes several activities, from extracting natural resources to processing and refining materials. All these processes are operated through the partnership of several companies in a multi-tier and multi-supply chain (SC) structure regarding geographical and geopolitical considerations. The length and complexity of such a supply chain network (SCN) can be driven to deal with many issues such as market flexibility and better response to risk [1]. It also significantly impacts the sustainable development criteria [2]. All attempts in this framework should be carried out to draw a "development that meets the needs of the present without compromising the ability of future generations to meet their needs" [3], although global climate warming, resource scarcity, and related social and environmental tensions have been turned into major concerns to reach this idea [4], [5]. In this regard, global agreements such as "Kyoto Protocol [6]" and then the "Paris Agreement [7]" were adopted to limit and reduce these impacts [4]. ISI by using resource-intensive processes causes future environmental concerns with a high depletion rate of known reserves and decreasing ore grades that increase costs in steel enterprises as well [8], [9]. This industry is also the most significant contributor to CO_2 emission among all industries (about 7-9% of global emission) and causes many undesired local sustainability challenges such as water contaminations, solid wastes, emissions of air pollutants, especially dust (or particulate matter (PM)), resulting from production and bulk transportation operations [10], [11]. At the same time, this industry creates the highest value across all mining and metal industries [9]. Consequently, ISI, which is directly connected to the energy and transportation systems and supplies the necessary materials for buildings, infrastructure, agriculture, and many others, is at the heart of delivering solutions for this issue [12], [13]. Regarding all these matters, the most effective way forward for each industry such as ISI is a move toward sustainable development via adopting cleaner production and sustainable logistics and being more committed to promoting social responsibility [14], [15]. It is more crucial for the developing countries that have not yet faced rigorous emission regulations, while, there is a possibility of imposing carbon tariffs in these countries for exports to the developed countries [16]. Hence, the preparation approach to deal with global carbon reduction restrictions seems necessary for these countries. A systematic approach based on sustainable supply chain management (SSCM) is appropriate for dealing with this issue. Accordingly, SSCM in ISI can be interpreted as managing intra- and inter-organizational flows committed to a balanced approach to the triple-bottom-line (TBL) of economic, social, and environmental dimensions [17], [18]. Such a collaborative approach requires a holistic view spanning all existing parts of the multi-tier and multi-SC structure of the steel supply chain network (SSCN) to create a sustainable value [19], [20].

Since SSCM is now recognized as a key issue in industrial sustainability, many researchers have discussed manifold enablers, including sustainable product design, lifecycle assessment systems, adoption of green technology, satisfying the triple bottom line, green logistics, and many others to implement this concept [21]. In this way, several research works like [22], [23] proposed the multi-objective mixed-integer linear programming (MOMILP) models for a sustainable supply chain network design (SCND) by minimizing the environmental impacts, reducing operating costs, meeting customer needs, and related economic criteria [21]. However, the researchers have mainly focused on optimizing economic and environmental dimensions, usually by minimizing emissions, energy, and utility consumptions and maximizing profit and job creation in separate objective functions [22], [24], [25]. This approach has been also applied to develop sustainable SCND optimization models in ISI [26], [27]. Hajisoltani *et al*. generated a bi-objective model to meet a practical and greener production and distribution planning of mineral products in the supply chain network [28]. Differently, a multi-objective optimization model has been presented to minimize energy consumption, various types of emissions, and the costs to improve environmental management in ISI [29]. Some researchers such as Chen and Anderson [30] presented a multi-objective programming model that jointly minimizes costs, emissions, and employee injuries in a supply chain. Subsequently, a novel integrated multi-objective optimization model has been applied in coal mining industry by minimizing costs, maximizing sustainability attributes along with efficiency scores using the multi-criteria decision-making (MCDM) [31]. However, integration of MCDM and multi-objective optimization framework was mostly applied for decisions such as supplier evaluation and order allocation [32], [33]. However, this study attempts to go one step further than the previous research works. A new method has been examined, in which a sustainability assessment (SA) system is applied to create a proper sustainable-related objective function. This proposed structure investigates the combined influences of social and environmental aspects on economic planning by ranking the production facilities in each level of SSCN. In this regard, an applicable SA system must be defined to help the managers have a comprehensive perception [34]. For this purpose, major global mining and steel institutions [35], [36] have highlighted this concept to understand the importance of achieving sustainability in their business activities [37]. Meanwhile, many researchers investigated the application of suggested sustainable indicators (SIs) by evaluating the performance of mines and ISI companies (e.g. [38], [39]) or comparing steel companies to other industries [40]. Some researchers have also suggested categories by adding the integrated SIs (e.g. [41]), improving the analysis by considering inner dependencies between criteria (e.g. [42], [43]) or defining the new criteria to investigate technical and organizational governance performances (e.g. [44]). However, the literature still provides limited findings for developing practical measurement indicators that help sustainable operations management, considering the intra- and inter-organizational relationships [43], [45].

Alternatively, integrating the chain's parties and managing the flow of material/product throughout the network plays an essential role in the SCN performance and competitiveness [46]. This matter becomes even more prominent by implementing this concept in extended multi-tier and multi-SC structures such as SSCNs [47]. Accordingly, systematic managerial monitoring seems necessary to lead the production and logistics operations. This matter is highlighted in this study by the new applicable mathematical structure that implements the priorities of a central management group (CMG) on logistics operations. Furthermore, there are specific technical considerations when dealing with a multi-tier SSCN, which depend on the nature of each process. To the best of our knowledge, the study of Valderama *et al*. [48] is among the few publications that have considered some of the technical issues in designing the environmental iron ore mining SC (part of the iron and steel SC). However, others have either considered these issues in separate problems (e.g. [49]) or ignored internal processes in the SSCN problem (e.g. [50]). Accordingly, the studies that integrate all these mentioned aspects, specifically in a multi-SC framework, are hardly found. On the other hand, activities like reducing the environmental and social impacts by adjusting operational activities and material flow, improving efficiency, and developing advanced products have been known as practical solutions to implementing sustainability in ISI [13], [51]. Among mentioned issues, adjusting operational activities is an applicable way for developing countries to implement social commitments and prepare themselves to follow the global obligations that will be imposed on them in the future [51]. Therefore, to fill the gap in the literature and develop the applicable structure, the MOMILP model has been presented in this paper. The proposed model develops a sustainable optimal material flow in a multi-tier and multi-SC structure of SSCN consisting of regional and tactical perspectives. For this purpose, the influences of maximizing the socio-environmental compliances and minimizing the environmental pollution to maximize economic profitability are investigated. Maximizing the managerial priorities is also considered to create more flexible conditions to meet customers' demands. The specific technical issues are included in this study to create more conformity with inevitable real-world complexities. Four primary contributions are provided in this study. First, a comprehensive mathematical model is developed to optimize the sustainability of production and logistics operations in the multi-tier and multi-SC structures of ISI. Secondly, a novel hierarchical SA system is developed to investigate the influences of socio-environmental performances on the optimization of SCN sustainability. Thirdly, the managerial restrictions are reflected in the mathematical modelling by defining a new objective function to maximize demand fulfilment. Fourthly, the specific technical issues in ISI are considered to model a real-world condition. The rest of this paper is organized as follows. In Section 2, the problem is described in detail. Section 3 explains the sustainability assessment method. The mathematical formulation is explained in Section 4. The case study applied to study the performance of the proposed model is described in Section 5. The results and discussion are presented in Section 6, and conclusions and future works are stated in Section 7.

2. Problem Description

Generally, there are two main categories for steel production, namely primary and secondary steel production pathways [12]. The former pathway refers to the operations in which iron ore is the main raw material (by around 80% share of global steel production), while in the latter one, recycled scrap steel plays the essential role in producing steel [52]. Two main attributed routes to the primary steel production pathway named the BF-BOF (Blast Furnace-Basic Oxygen Furnace) and the DR-EAF (Direct Reduction-Electric Arc Furnace) are considered in this study [53]. These pathways can be started by *iron ore mining,* followed by a series of production processes grouped as *concentration*, *agglomeration*, *ironmaking*, and *steelmaking* processes [12]. The multi-tier production plants are placed in these processes according to their functionality: concentration plants (in concentration process) and pelletizing plants (in agglomeration) exist in both pathways, sintering (in agglomeration), BF (in ironmaking), and BOF (in steelmaking) plants as one integrated steelwork unit (in short, BOF) belong to the first route, and DR (in ironmaking), and EAF (in steelmaking) are for the second route [54]. These routes can be decomposed into two sections based on the nature of the processes. The primary duties in the 1st section are enriching the purity (iron content) and removing the impurities of supplied iron ores. The "blending" zone should be considered here to meet the desired quality and quantity of the product by providing an appropriate mix of different types of supplied iron ore [48]. In comparison, the aims of processes in the 2nd section are to enhance the iron content of all intermediate and final products besides reaching the proper chemical and physical properties of products. To meet the second aim, the "proportioning process" is applied to prepare the standard combination of supplied raw materials (including intermediate and additive materials) in each process [55]. Moreover, reducing oxygen from iron ore must be done along this section, which requires a significant amount of energy, mainly in the forms of natural gas in the DR-EAF route and metallurgical coke in the BF-BOF process [56]. Note that monitoring the size distribution (in short, size) should be done in both sections.

The SSCN structure in this study encompasses three types of focal entities, which include iron ore mines (in short, mines), conventional and ISI-specific warehouses (or blending beds), and multi-tier production plants (in short, plants). Meanwhile, a multi-SC framework is defined where the managerial factors are applied to prioritize the logistics operations in "within SC" or intra-supply chain (IaS), "between SCs" or inter-supply chains (IeS), and "external interactions with the SCN" or external (ExS) relationships (Figure 1). The major decisions in this study are resource allocation, production planning, flow and process management, inventory management, and demand management. Regarding the various aspects of managerial and technical issues in this structure, the MOMILP model has been developed that determines the sustainable optimal material flow in the SSCN. Accordingly, besides maximizing the economic profitability (net present value; NPV), the prioritization of demand fulfilment (PDF), and the socio-environmental compliances (SEC) objective functions, the total environmental pollution (EP) in the production and transportation systems is minimized. The augmented ε-constraint method (AUGMECON2), a well-known and practical solution method for multiobjective optimization, is applied to solve the proposed model [57]. The GAHP-TOPSIS method (a hybrid of "group analytical hierarchy process" and "technique for order preference by similarity to ideal solution") is also linked to the primary solution method to derive the appropriate coefficients for the SEC objective function. The research methodology, shown in Figure 2, summarizes the steps of developing the MOMILP model by applying the SA system, evaluating the model performance compared to a real case, analyzing the sustainable planning, discussing the sensitivity analysis, and interpreting the managerial insights. In the following sections, the sustainability assessment method, the mathematical modeling, and the applied case study description are explained.

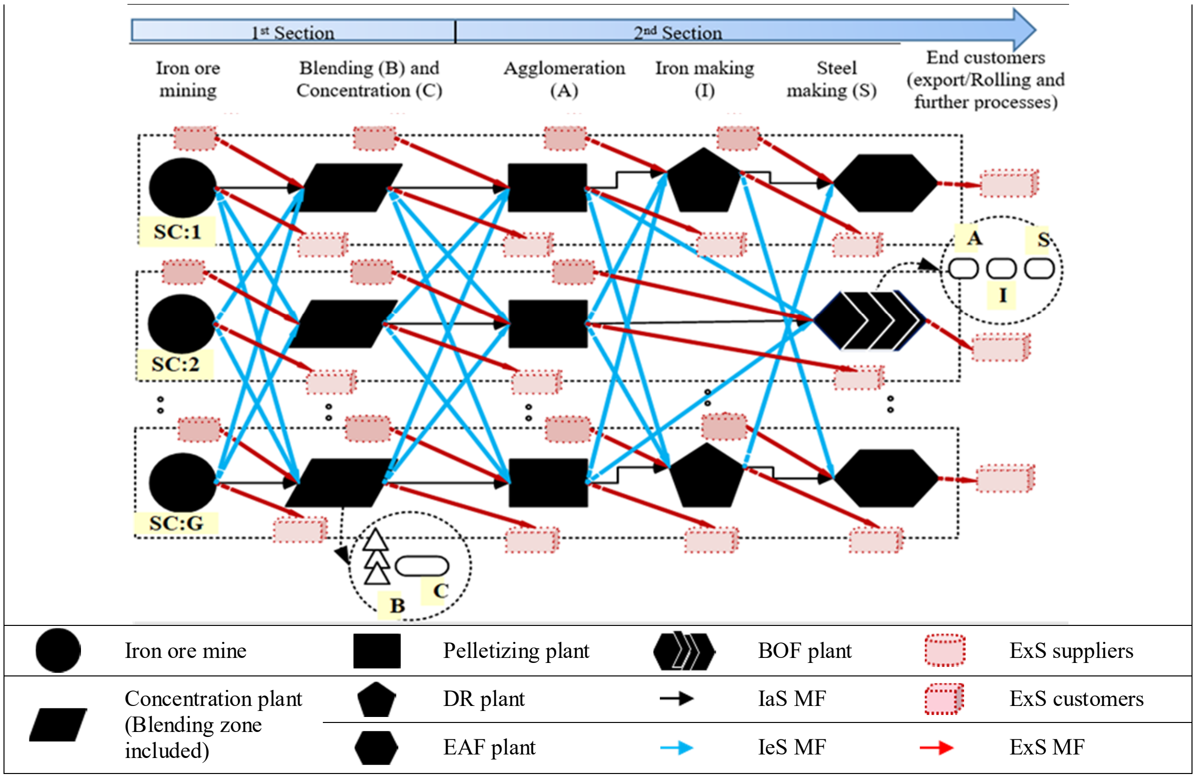

Figure 1. Framework of the proposed SSCN.

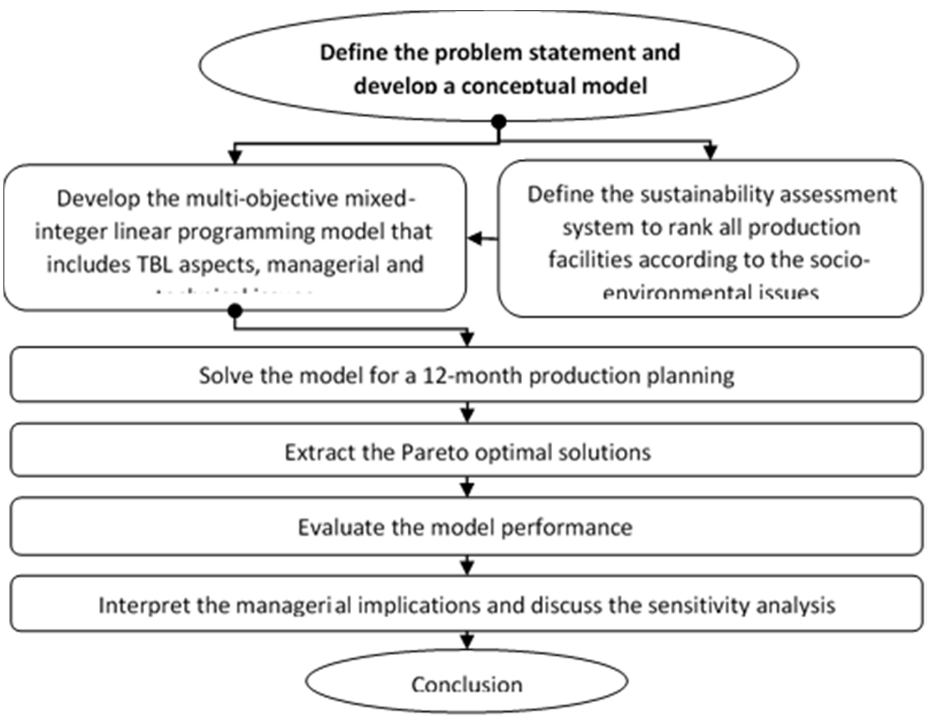

Figure 2. Scheme of research methodology.

3. Sustainability Assessment Method

This section presents a novel hierarchical SA system for ISI. Numerous comprehensive SA frameworks have been presented that were mentioned in the introduction section, although few studies have addressed all three aspects of sustainability in sufficient and quantifiable indicators [22]. Meanwhile, studies show that differences occur in implementing sustainable criteria in various links along the SCN [43]. Hence, the main goal of this system is to rank the set of production facilities in each level of SSCN including the mines and multi-tier production plants, applying the critical environmental and social indicators. The proposed SA in such a way helps mine and mineral industry managers, specifically in ISI, to have a holistic outlook and make supply chain decisions easily and efficiently. The applied criteria (SIs) have been defined based on reviewing the existing literature and the knowledge of experienced experts in ISI. The results of the mentioned ranking are then applied as the coefficients of the third objective function in the mathematical optimization problem to make a reliable structure for maximizing the socio-environmental compliances in the SSCN (see Section 4.1.3.). The profitability indicator, which has a crucial role in the economic dimension of sustainability, is used individually as the primary objective function in this study. The TOPSIS method is applied to rank the criteria, while criteria weighting is implemented by the AHP method. The description of this process is beyond the scope of this study, and the interested readers can refer to [58] and [59] for more information. Table 1 and Table 2 refer to the social and environmental criteria, respectively, and Figure 3 illustrates the hierarchical SA system.

Table 1. Social criteria.

Goal	Socio-environmental ranking of production facilities	
Criterion	**Social indicators (SoI)**	
Sub-criteria	Internal social effects (ISE)	External social effects (ESE)
Sub-sub criteria	Internal stakeholders' satisfaction (ISS) [41], [44]	External stakeholders' satisfaction (ESS) [42], [60]
	Health and safety (HS) [30], [38]	Investment in the community (IC) [41], [61]
	Employee training (ET) [35], [42]	

Table 2. Environmental criteria.

Goal	Socio-environmental ranking of production facilities	
Criterion	**Environmental indicators (EnI)**	
Sub-criteria	Raw material quality (RQ)	Utility consumption (UC) [38]
Sub-sub criteria	Chemical component (CC) [62]	Energy consumption (ECo)
	Size (S) [63]	Water consumption (WCo)
Sub-criteria	Yield and combination (YC) [62]	Waste management (WM) [64], [65]
Sub-sub criteria	Yield (Y)	Water reuse (WR)
	Combination (C)	Solid recycle (SR)
Sub-criteria	Green design (GD) [32], [60]	Process redesign (PR)
Sub-sub criteria	Water reuse equipment (WRE)	Modification in primary process (MPP)
	Emission controller equipment (ECE)	New installation (NI)
Sub-criteria	Environmental impacts monitoring (EIM)[66]	Land use (LU) [60], [67]
Sub-sub criteria	Measurement devices (MD)	Proximity to residential and protected areas (PRP) [39]
	Environmental competent staff (ECS)	Occupied area (OA) [40]
	Self-declared reports (SDR)	

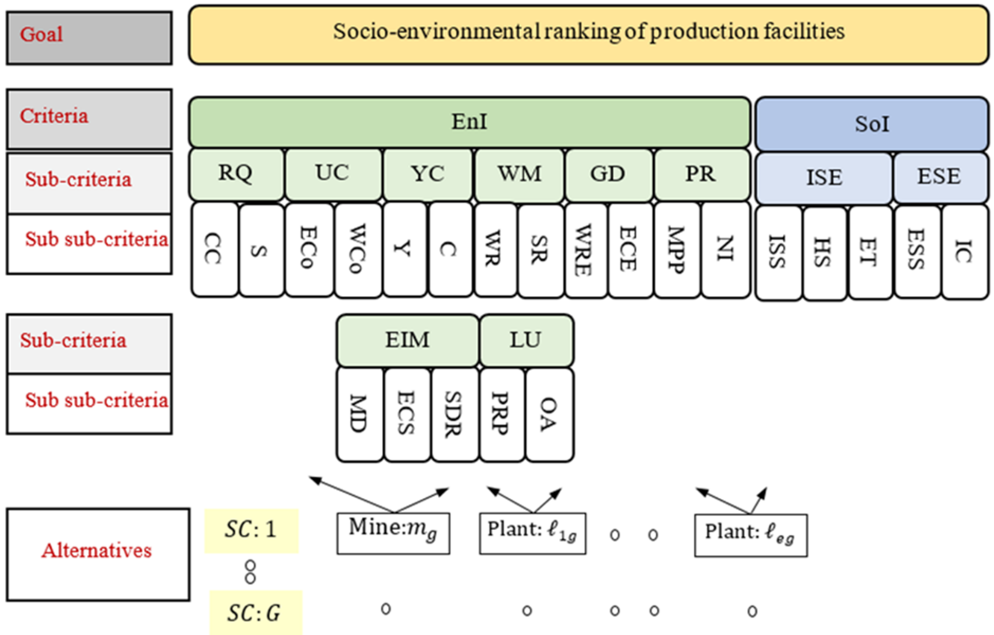

Figure 3. Hierarchical SA system for ISI (The mentioned symbols have been used in the mathematical model).

4. Mathematical Modeling

To solve the proposed MOMILP problem, one must find Pareto optimal solutions to the problem. According to this, the decision-makers (DMs) are looking for the most preferred solutions usually takes the form of a trade-off curve instead of an optimal solution to a single objective problem [68], [69]. Various solution methodologies have been developed for solving multi-objective mathematical optimization models that can be classified into priori, posteriori or generation, and interactive categories [57]. The most applicable methods in these categories are the weighting method, goal programming, and goal attainment for the first, AUGMECON and AUGMECON2 for the second, and interactive fuzzy solution methodologies for the third category, respectively. Given the complexity of MOMILP problems, metaheuristics such as evolutionary algorithms have also been applied to solve large scale and complex problems [57], [69]. The AUGMECON2 method is applied in this study. This exact method is a modified version of the conventional ε-constraint approach [70] which has been widely applied in sustainable SCND problems [22]. Based on this method, a multi-objective optimization problem decomposes into several problems that optimizes one objective function and limits the values of the other functions by ε-constraints in the form of inequality constraints [71], [72]. There are two main advantages to use the AUGMECON2 method in compare to other mentioned exact based methods: avoiding the production of weakly or infeasible Pareto optimal solutions and accelerating the whole process by skipping the redundant iterations [73], [74]. The steps of implementing this method are explained more in Section 6.2.

The proposed SCND model includes four objective functions: maximization of NPV, maximization of PDF, maximization of SEC, and minimization of EP. The constraints are grouped into capacity, flow conservation, blending, proportioning, demand, and non-negativity sets. The mathematical formulation is mentioned below, and the related notations are presented in Appendix Tables A.1- A.6. The proposed model is based on the following assumptions:

- The location of facilities is known and fixed.
- All suppliers, mines, and plants are considered single-product facilities.
- There is no material flow between the facilities of the same level [75].
- Each SC has its own outbound suppliers and customers.
- The blending zone in each concentration plant has a large enough space to stock separately any types of supplied iron ores [76].
- Production plants are considered hybrid facilities that perform production and storage functions [77].
- Transportation is done by trucks.

4.1. Objective functions

The main target of this model is to optimize the sustainable material flow in the SSCN regarding management considerations. For this purpose, four objective functions are defined.

4.1.1. Maximizing the NPV

The first objective function (1) maximizes the NPV in a specific production planning period. Equations from (2) to (6) present the modeling of this objective function in a disaggregated manner. Equation (2) corresponds to the calculation of the total sales revenue, and Equations (3) to (6) determine total purchase and transportation costs (PTC^t), total storage costs (SC^t), total fixed and variable costs (FVC^t), and total cost of unfulfilled demand for the final product (UC^t).

$$Max\ \text{NPV} = \sum_{t\in T} \frac{\left((Rev^t - PTC^t - SC^t - FVC^t - UC^t)\right)}{(1+dr)^t} \quad (1)$$

$$Rev^t = \sum_{g\in SC}\sum_{i\in I}\sum_{o\in O_{ig}}\sum_{g'\in SC}\sum_{i'\in I}\sum_{d\in D_{i'g'}}\left(Xp_o^t \times \left(Pr_{o,d}^t - Cm_{o,d}^t\right)\right) + \sum_{g\in SC}\sum_{i\in I}\sum_{o\in O_{ig}}\sum_{i'\in I}\sum_{d'\in Dx_{i'g}}\left(Xp_o^t \times \left(Pr_{o,d'}^t - Cm_{o,d'}^t\right)\right) \quad (2)$$

$$PTC^t = \sum_{g'\in SC}\sum_{i\in I}\sum_{o\in O_{ig'}}\sum_{g\in SC}\sum_{i'\in I}\sum_{d\in D_{i'g}}\left(Xt_{o,d}^t \times \left(Cp_{o,d}^t + Ct_{o,d}^t\right)\right) + \sum_{g\in SC}\sum_{i\in I}\sum_{o'\in Ox_{ig}}\sum_{i'\in I}\sum_{d\in D_{i'g}}\left(Xt_{o',d}^t \times \left(Cp_{o',d}^t + Ct_{o',d}^t\right)\right) \quad (3)$$

$$SC^t = \sum_{g\in SC}\sum_{i\in I}\sum_{o\in O_{ig}}\left(Xs_o^t \times Cs_o^t\right) \quad (4)$$

$$FVC^t = \sum_{g\in SC}\sum_{i\in I}\sum_{o\in O_{ig}}\left(Cf_o^t + (Xp_o^t \times Cv_o^t)\right) \quad (5)$$

$$UC^t = \sum_{g\in SC}\sum_{d\in Cx_{eg}}\left(Xu_d^t \times Cu_d^t\right) \quad (6)$$

4.1.2. Maximizing the prioritization of demand fulfilment

The second objective function (7) maximizes the desired strategy of CMG to prioritize the demand fulfilment of different types of customers. This objective function allows the CMG to manage the relationships between facilities by assigning the corresponding factors to the IaS ($Df1_o^t$), IeS ($Df2_o^t$), and ExS ($Df3_o^t$) customers. Here, $Df1_o^t + Df2_o^t + Df3_o^t = 1$, $\sum_{g\in SC}\sum_{i\in I}\sum_{o\in O_{ig}} \alpha d_o = 1$, and $i < i'$.

$$Max\ \text{PDF} = \sum_{g\in SC}\sum_{i\in I}\sum_{o\in O_{ig}} \alpha d_o \times \sum_{t\in T}\left(Df1_o^t \times \left(\sum_{i'\in I}\sum_{d\in C_{i'g}:(o,d)\in Ac} Xt_{o,d}^t\right) + Df2_o^t \times \left(\sum_{\substack{g'\in SC \\ g'\neq g}}\sum_{i'\in I}\sum_{d'\in C_{i'g'}:(o,d')\in Ac} Xt_{o,d'}^t\right) + Df3_o^t \times \left(\sum_{i'\in I}\sum_{d''\in cx_{i'g}:(o,d'')\in Ac} Xt_{o,d''}^t\right)\right) \quad (7)$$

4.1.3. Maximizing socio-environmental compliance

The third objective function (8) maximizes the environmental and social compliance for all production facilities in the SSCN. Accordingly, the socio-environmental ranking factor Sw_o is applied as the SEC objective function coefficients for each production facility. The applied scores in this objective function have been derived by a mentioned SA system in Section 3.

Here, $Sw_o = \frac{Sc_o}{\max Sc_o}$. Note, $\sum_{g\in SC}\sum_{o\in O_{ig}} Sc_o = 1\ \forall i \in I$, and $\sum_{i\in I} \alpha s_i = 1$.

$$Max\,\text{SEC} = \sum\nolimits_{i\in I} \alpha s_i \times \sum\nolimits_{t\in T}\sum\nolimits_{g\in SC}\sum\nolimits_{o\in O_{ig}} (Sw_o \times Xp_o^t) \tag{8}$$

4.1.4. Minimizing environmental pollution

The last objective function (9) minimizes the environmental pollution in production processes (Eq. 10), and the transportation of all products (Eqs. 11 and 12), and raw materials (Eqs. 13 and 14) along all routes applying the standard unit amount of environmental pollution Ep_o^h in the production process at location o and in transportation Et^h in the unit of distance. Max^h and Min^h are the maximum and minimum pollution amounts of h emitted throughout the production and transportation processes in the SSCN applied to scale the different types of pollutants in Eq. (9). Here, $\sum_{h\in H} \alpha e^h = 1$.

$$Min\,\text{EP} = \sum_{h\in H} \alpha e^h \times \left(\frac{\left(\sum_{t\in T}\left(PPE^t + \left(Et^h \times (TPE^t + TPEx^t + TRE^t + TREx^t)\right)\right)\right) - Min^h}{Max^h - Min^h}\right) \tag{9}$$

In which:

$$PPE^t = \sum\nolimits_{g\in SC}\sum\nolimits_{i\in I}\sum\nolimits_{o\in O_{ig}} (Ep_o^h \times Xp_o^t) \tag{10}$$

$$TPE^t = \sum\nolimits_{g\in SC}\sum\nolimits_{i\in I}\sum\nolimits_{o\in O_{ig}}\sum\nolimits_{g'\in SC}\sum\nolimits_{i'\in I}\sum\nolimits_{d\in D_{i'g'}} \left(Xt_{o,d}^t \times Ds_{o,d}\right) \tag{11}$$

$$TPEx^t = \sum\nolimits_{g\in SC}\sum\nolimits_{i\in I}\sum\nolimits_{o\in O_{ig}}\sum\nolimits_{i'\in I}\sum\nolimits_{d'\in Dx_{i'g}} \left(Xt_{o,d'}^t \times Ds_{o,d'}\right) \tag{12}$$

$$TRE^t = \sum\nolimits_{g\in SC}\sum\nolimits_{i'\in I}\sum\nolimits_{d''\in D_{i'g}}\sum\nolimits_{g'\in SC}\sum\nolimits_{i\in I}\sum\nolimits_{o'\in O_{ig'}} \left(Xt_{o',d''}^t \times Ds_{o',d''}\right) \tag{13}$$

$$TREx^t = \sum\nolimits_{g\in SC}\sum\nolimits_{i'\in I}\sum\nolimits_{d''\in D_{i'g}}\sum\nolimits_{i\in I}\sum\nolimits_{o''\in Ox_{ig}} \left(Xt_{o'',d''}^t \times Ds_{o'',d''}\right) \tag{14}$$

4.2. Capacity constraints

Constraints (15) limit the maximum iron ore transported from each mine at location o to the ExS customers cx_{ig} or IaS and IeS customers (facilities) $c_{ig'}$ according to the mine production capacity in each period. Constraints (16) also impose the supply capacity of raw material k for each ExS supplier sx_{ig}^k. Constraints (17) enforce minimum and maximum limits on production amount in each plant $\ell_{\bar{\imath}g}$. Here, Te_o^t is a technical factor that resulted from changes in production planning strategies. Constraints (18) state the storage capacity of products in each plant $\ell_{\bar{\imath}g}$. Here, Xs_o^0 can be applied for the initial level of the storage.

$$\left(\sum_{i\in I}\sum_{d\in Cx_{ig}:(o,d)\in Ac} Xt_{o,d}^t\right) + \left(\sum_{g'\in SC}\sum_{i\in I}\sum_{d'\in C_{ig'}:(o,d')\in Ac} Xt_{o,d'}^t\right) \le \overline{Qy}_o^t \quad \forall o \in M_g, g \in SC, t \in T \tag{15}$$

$$\sum_{i' \in I} \sum_{d \in D_{i'g}:(o,d) \in Ac} Xt_{o,d}^{t} \leq \overline{Qy}_{o}^{t} \tag{16}$$
$$\forall o \in Sx_{ig}^{k}, k \in R \cup A, i \in I(i < i')$$
$$g \in SC, t \in T$$

$$\underline{Qp}_{o}^{t} \leq Xp_{o}^{t} \leq \overline{Qp}_{o}^{t} \times Te_{o}^{t} \tag{17}$$
$$\forall o \in l_{\bar{\imath}g}, \bar{\imath} \in \bar{I}, g \in SC, t \in T$$

$$Xs_{o}^{t} \leq \overline{Qs}_{o}^{t} \tag{18}$$
$$\forall o \in l_{\bar{\imath}g}, \bar{\imath} \in \bar{I}, g \in SC, t \in T$$

4.3. Flow conservation constraints

Constraints (19) guarantee the flow conservation of products in each production facility at location o.

$$Xp_{o}^{t} + Xs_{o}^{(t-1)} - Xs_{o}^{t} = \sum_{i' \in I} \sum_{d \in Cx_{i'g}:(o,d) \in Ac} Xt_{o,d}^{t} + \sum_{g' \in SC} \sum_{i' \in I} \sum_{d' \in C_{i'g'}:(o,d') \in Ac} Xt_{o,d'}^{t} \tag{19}$$
$$\forall o \in O_{ig} \backslash \{B_{\ell_{1g}}^{m_{g'}}\}, i \in I\ (i < i'), g \in SC, t \in T$$

4.4. Blending constraints

Blending is an essential process in the 1st section of SSCN to meet the appropriate product (iron concentrate). Three constraints are defined to deploy this process in the mathematical model. In the first set, the quality of supplied iron ores is checked. Accordingly, constraints (20) state that the properties of supplied iron ore n should not be more/less than a given maximum/minimum level Ar_{d}^{nf}. The second set guarantees the flow conservations of all supplied iron ores that have been transported from mines $M_{g'}$ in constraints (21) and mines Mx_{g} in constraints (22) to the assigned blending beds in each plant ℓ_{1g}. Lastly, in the third set, the amount of iron concentrate is calculated in balance with the desired amount of consumed iron ores that have been transported from the blending beds (constraints (23)). For this purpose, the recovery ratio $Re_{\ell_{1g}}^{Fet}$ and the expected Fe of iron concentrate $Rt_{\ell_{1g}}^{Fet}$ determine the quality and quantity of supplied iron ores from blending beds [49], [50].

$$Xt_{o,d}^{t} \times Rt_{o}^{ft} \geq Xt_{o,d}^{t} \times Ar_{d}^{nf} \times k^{f} \quad \forall f \in F, n \in R, o \in M, d \in B_{\ell_{1g}}^{o}, \ell_{1g} \in l_{\bar{\imath}g}, g \in SC, t \in T \tag{20}$$

$$\sum_{g' \in SC} \sum_{o' \in M_{g'}} \sum_{d \in B_{\ell_{1g}}^{o'}:(o',d) \in Ac} Xt_{o',d}^{t} + \sum_{g' \in SC} \sum_{o' \in M_{g'}} \sum_{d \in B_{\ell_{1g}}^{o'}} Xs_{d}^{(t-1)} - \sum_{g' \in SC} \sum_{o' \in M_{g'}} \sum_{d \in B_{\ell_{1g}}^{o'}} Xs_{d}^{t} = \sum_{g' \in SC} \sum_{o' \in M_{g'}} \sum_{o \in B_{\ell_{1g}}^{o'}} Xt_{o,\ell_{1g}}^{t} \tag{21}$$
$$\forall \ell_{1g} \in l_{\bar{\imath}g}, g \in SC, t \in T$$

$$\sum_{o' \in Mx_{g}} \sum_{d \in B_{\ell_{1g}}^{o'}:(o',d) \in Ac} Xt_{o',d}^{t} + \sum_{o' \in Mx_{g}} \sum_{d \in B_{\ell_{1g}}^{o'}} Xs_{d}^{(t-1)} - \sum_{o' \in Mx_{g}} \sum_{d \in B_{\ell_{1g}}^{o'}} Xs_{d}^{t} = \sum_{o' \in Mx_{g}} \sum_{o \in B_{\ell_{1g}}^{o'}} Xt_{o,\ell_{1g}}^{t} \tag{22}$$
$$\forall \ell_{1g} \in l_{\bar{\imath}g}, g \in SC, t \in T$$

$$\sum_{g' \in SC} \sum_{o' \in M_{g'}} \sum_{o \in B_{\ell_{1g}}^{o'}} \left(Xt_{o,\ell_{1g}}^{t} \times Rt_{o}^{Fet}\right) + \sum_{o''' \in Mx_{g}} \sum_{o'' \in B_{\ell_{1g}}^{o'''}} \left(Xt_{o'',\ell_{1g}}^{t} \times Rt_{o''}^{Fet}\right) = \frac{\left(Xp_{\ell_{1g}}^{t} \times Rt_{\ell_{1g}}^{Fet}\right)}{Re_{\ell_{1g}}^{Fet}} \tag{23}$$
$$\forall Fe \in f, \ell_{1g} \in l_{\bar{\imath}g}, g \in SC, t \in T$$

4.5. Proportioning constraints

The proportioning process as the standard combination of raw materials in the 2nd section of SSCN can be modelled by four sets of constraints. The first set limits the maximum demand of each intermediate material r by constraints (24) and additive material a by constraints (25). The second set controls the supply capacity of all required materials, which is generally denoted by the constraints (15)-(18). The third set imposes the standard combination of raw materials to produce desired products. Accordingly, the proportioning ratios Pp_d^{rt} for intermediate materials and Pp_d^{at} for additive materials are applied in constraints (26) and (27). Finally, the quality of each supplied intermediate material r is checked by constraints (28) as the last set of constraints.

$$\sum_{g'\in SC}\sum_{i\in I\setminus\{B\}}\sum_{o\in S_{ig'}^{r}:(o,d)\in Ac} Xt_{o,d}^{t}+\sum_{i\in I}\sum_{o'\in Sx_{ig}^{r}:(o',d)\in Ac} Xt_{o',d}^{t}\le Dm_d^{rt} \quad \forall r\in R, d\in l_{\bar{\imath}g}, \bar{\imath}\in \bar{\bar{I}}\ (i<\bar{\imath}), g\in SC, t\in T \tag{24}$$

$$\sum_{i\in I}\sum_{o\in Sx_{ig}^{a}:(o,d)\in Ac} Xt_{o,d}^{t}\le Dm_d^{at} \quad \forall a\in A, d\in l_{\bar{\imath}g}, \bar{\imath}\in \bar{\bar{I}}(i<\bar{\imath}), g\in SC, t\in T \tag{25}$$

$$\sum_{g'\in SC}\sum_{i\in I\setminus\{B\}}\sum_{o\in S_{ig'}^{r}:(o,d)\in Ac} Xt_{o,d}^{t}+\sum_{i\in I}\sum_{o'\in Sx_{ig}^{r}:(o',d)\in Ac} Xt_{o',d}^{t}= Xp_d^t\times Pp_d^{rt} \quad \forall r\in R, d\in l_{\bar{\imath}g}, \bar{\imath}\in \bar{\bar{I}}(i<\bar{\imath}), g\in SC, t\in T \tag{26}$$

$$\sum_{i\in I}\sum_{o\in Sx_{ig}^{a}:(o,d)\in Ac} Xt_{o,d}^{t}= Xp_d^t\times Pp_d^{at} \quad \forall a\in A, d\in l_{\bar{\imath}g}, \bar{\imath}\in \bar{\bar{I}}\ (i<\bar{\imath}), g\in SC, t\in T \tag{27}$$

$$Xt_{o,d}^{t}\times Rt_o^{ft}\ge Xt_{o,d}^{t}\times Ar_d^{rf}\times k^f \quad \forall f\in F, r\in R, o\in S_{ig'}^{r}\cup Sx_{ig}^{r}, d\in l_{\bar{\imath}g}, \bar{\imath}\in \bar{\bar{I}}(i<\bar{\imath}), g'\&g\in SC, t\in T \tag{28}$$

4.6. Demand constraints

The ultimate constraints determine the limitation of the customer demand (spot market), excluding the demand of final product customers, by constraints (29) and compute the unfulfilled demand Xu_d^t of the final product for each contract customer cx_{eg} by constraints (30).

$$\sum_{i\in I}\sum_{o\in O_{ig}\setminus\{\ell_{eg}\}:(o,d)\in Ac} Xt_{od}^{t}\le Dm_d^{t} \quad \forall d\in Cx_{i'g}, i'\in I(i<i'), g\in SC, t\in T \tag{29}$$

$$Xt_{\ell_{eg}d}^{t}= Dm_d^t+Xu_d^t \quad \forall d\in Cx_{eg}, \ell_{eg}\in \ell_{\bar{\imath}g}, g\in SC, t\in T \tag{30}$$

4.7. Non-negativity constraints

Finally, constraints (31) define the non-negativity conditions of decision variables.

$$Xp_o^t, Xp_d^t, Xt_{o,d'}^t, Xt_{o',d}^t, Xs_o^t, Xu_d^t\ge 0 \tag{31}$$

5. Case Study

The model was implemented in a large steel production holding in Iran. This firm produces at least 25 million tons of solid waste, 6 million tons of CO_2, and 40 thousand tons of PM at nominal capacity. It also accounts for 10% of the country's steel production and has 18% and 21% shares of total CO_2 and PM emissions in the domestic steel industry. The SSCN includes three SCs with three iron ore mines, two concentration plants, three pelletizing plants, two DR plants, and three steel plants (two EAF plants and one BOF plant) (Figure 4). The production capacity and emission factors are mentioned in Tables 3 and 4, respectively. Other related information has been summarized in Tables S.1-S.6 of the supplement file.

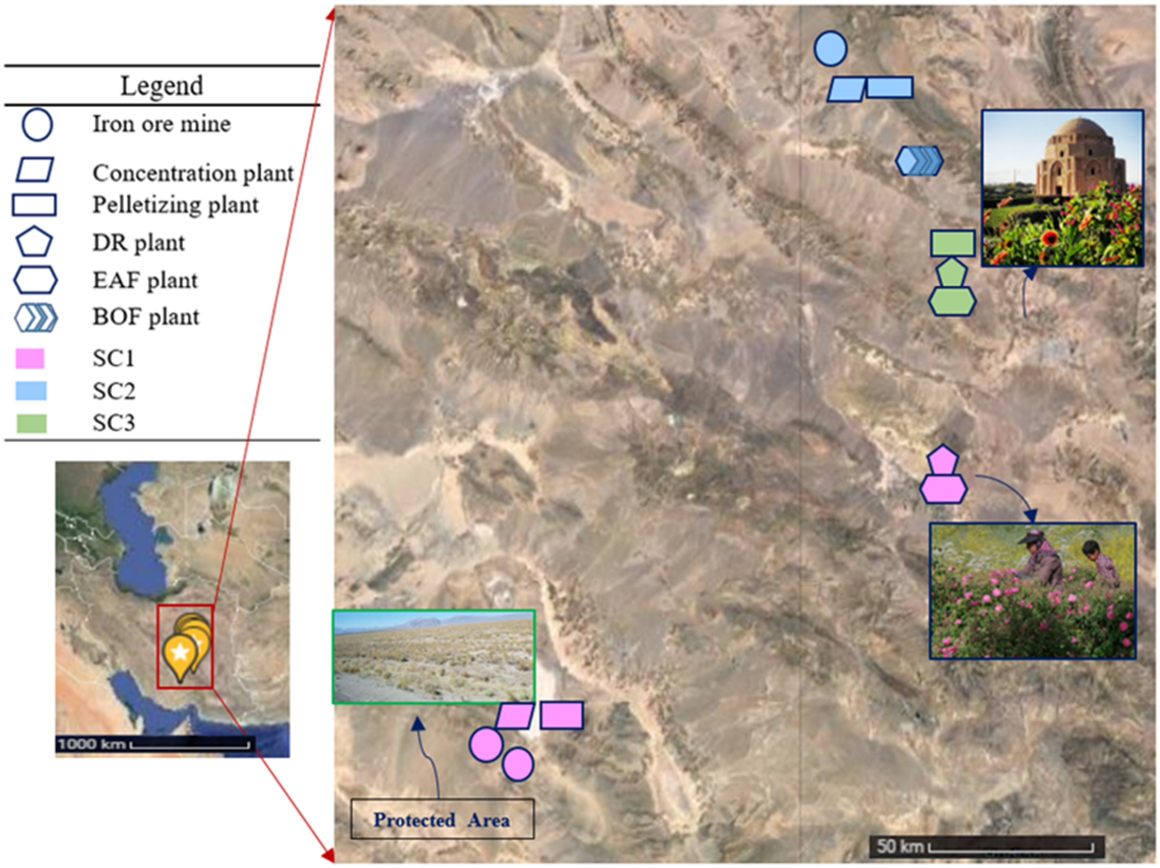

Figure 4. Location of facilities in the case study.

Table 3. Production capacity (Mt).

Facilities		SC1	SC2	SC3
Mines	No.1	2.41	4.29	-
	No.2	1.05	-	-
Concentration plants		4	4	-
Pelletizing plants		2.5	2.5	2.5
DR plants		1	-	2
EAF plants		1	-	1.5
BOF plant		-	1.7	-

Table 4. Amount of emission factors in production (kg/t) and transportation (kg/tkm) processes.

Processes	PM_{10}	CO_2	References
Mining [(a)]	0.04075	6.8	[78], [79]
Concentration [(b)]	0.0766	10.2	
Pelletizing	0.94	30	[78], [80]
DR	0.64	700	
EAF	3.11	80	
BOF [(c)]	13.64	1727	
Heavy-bulk Road transportation	13×10^{-6}	13×10^{-2}	[81]

(a): Stripping ratio: 1.5

(b): Blending zone included

(c): Sinter, BF, BOF plants integrated

6. Results and Discussion

Today, sustainability concerns in the industrial SCNs require a comprehensive approach beyond solely economic considerations [24]. Furthermore, applying non-optimal solutions depending on practical experiences is still the prevailing traditional vision [17]. These challenges are discussed in this section by comparing the results of the proposed model against the actual planning. In the following, the sustainable planning model is explained and analyzed. Ultimately, the sensitivity analysis and the managerial insights are presented.

6.1. Evaluation of proposed model performance against actual planning

A bi-objective mathematical optimization model including the NPV and PDF objective functions was applied to evaluate the optimal solution against the actual planning. Before comparing the results, general conditions are mentioned. There are assigned external customers for each related facility of SCs, in the spot market for intermediate products, and end customers for the final product (steel). After satisfying the intra-SC customers' demand, each facility can sell its product to either the inter-SC or external customers, although, in terms of the geographical distributions, the similar facilities of other SCs may be closer to the mentioned supplier. The number of external iron ore mines to compensate for the production shortage in the mines owned by each SC is limited. As the main raw material in the SSCN, the iron ore supply shortage raises the necessity of optimal planning analysis. The proposed model consequences showed adequate conformity by the mentioned managerial priority to satisfy the demands of the intra-SC customers. Besides, the economic optimized flow pattern enforces the whole system to transport the intermediate materials toward the inter and intra-facilities instead of selling the surplus products to spot markets in each period. This modified flow pattern leads to the production of more value-added products. Meanwhile, defining the proper blending constraints in the model imposes the appropriate material handling to use all available iron ore capacity for more production. Figure 5 also demonstrates the material flow from iron ore mines owned by the SCs to the related blending bed in each concentration plant, for instance. Consequently, the comparison results indicate a 6% and 4% increase in the final product and total profit, respectively. Table 5 and Figure 7, parts a and b show the related findings.

Table 5. Annual production and supply in the economic planning *vs.* actual planning (Mt).

Description \ Conditions		SC1		SC2		SC3		Total	
		Actual plan.	Econom ic plan.	Actual plan.	Economic plan.	Actual plan.	Economic plan.	Actual plan.	Economic plan.
Mines production	No.1	2.41	2.41	4.29	4.29	-	-	12.26	12.26
	No.2	1.05	1.05	-	-	-	-		
Ore from ExS suppliers to concentration plant		1.13	1.13	1.32	1.32	-	-		
Ore from ExS suppliers to BOF plant		-	-	2.06	2.06	-	-		
Concentration plants		2.7	2.7	2.68	2.71	-	-	5.38	5.4
Pelletizing plants		2.3	2.49	2.3	2.5	0.25	0.0035	4.85	4.99
DR plants		0.9	1	-	-	1.8	1.98	2.7	2.98
EAF plants		0.75	0.98	-	-	1.5	1.5	3.95	4.18
BOF plant		-	-	1.7	1.7	-	-		
Profit in SCs (M$)		236	257	327	333	162	163	725	753

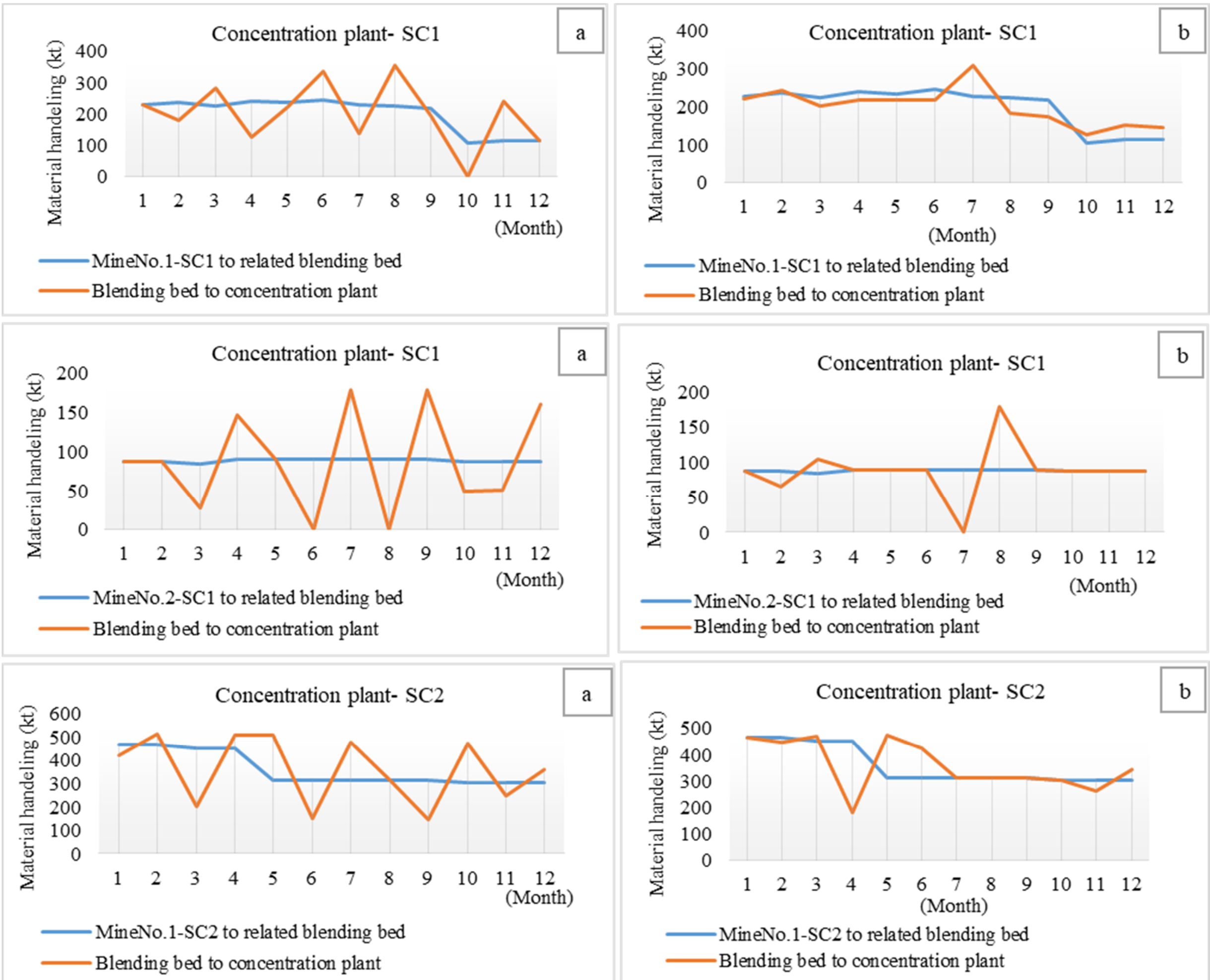

Figure 5. Iron ore handling in blending beds: a) Economic planning *vs.* b) Actual planning.

6.2. Results of sustainable planning

The results of sustainable modelling are presented here. The NPV objective function is maximized in this model, while the remaining objective functions, PDF, SEC, and EP are included as constraints by implementing the ε-constraint method. These objective functions configure the manageable structure in the SSCN. The PDF objective function deploys the CMG strategies on flow patterns by assigning the appropriate factors to different types of relationships between facilities. Regarding three distinct SCs in the case study, this objective function prioritizes the demand fulfillment of IaS facilities compared to other customers via assigning 1 to the factor $Df1_o^t$ and 0 to others, meanwhile, maximizing the SEC objective function controls the entire production system to have the highest socio-environmental compliance in the SSCN. For this purpose, the holistic SA system was applied to rank all facilities at each production level. The derived rankings (scores) for the facilities applied in the objective coefficients (factors) are mentioned in Table 6. Ultimately, the EP objective function minimizes the environmental pollution caused by transportation and production activities. The critical impacts of CO_2 emissions, as a global concern, and PM emissions, as a local hazard, were considered in the mentioned objective function (see Table 4). ILOG IBM CPLEX 12.9 was used to solve the model for a 12-month time frame.

Table 6. Socio-environmental scores and coefficients derived from the SA system.

Facilities / Derived rankings (scores)	Mines			Concentration plants		Pelletizing plants			DR plants		Steel plants		
											EAF	BOF	
	SC1		SC2	SC1	SC2	SC1	SC2	SC3	SC1	SC3	SC1	SC3	SC2
	No.1	No.2											
Socio-environmental scores (rankings)	0.25	0.35	0.4	0.55	0.45	0.35	0.4	0.25	0.55	0.45	0.5	0.4	0.1
Socio-environmental factors (coefficients)	0.63	0.88	1	1	0.82	0.88	1	0.63	1	0.82	1	0.8	0.2

The process of extracting the appropriate Pareto optimal solutions for the proposed MOMILP model begins by developing the lower bounds and ranges for at least p-1 objective functions (here p-1=3) that are included as constraints [68]. For this purpose, the proper payoff table is calculated applying the lexicographic optimization method to skip the redundant iterations. Accordingly, the AUGMECON2 method can be applied to obtain the Pareto optimal set based on defined grid points on the feasible region. The payoff table and ranges of the series of objective functions that have been considered as constraints are illustrated in Table 7.

Table 7. Payoff table obtained by the lexicographic optimization.

Conditions	PDF (kt)	SEC (kt)	EP (D*)
Max. PDF	1,680.12	3,769.29	201
Max. SEC	924.99	3,888.38	210
Min. EP	203.32	538.25	1.04
Range	1,476.79	3,350.12	208.76

*Dimensionless

Moreover, two more restrictions were set by DMs to reach the final preferred solutions in the case study. The first is to admit the solutions that meet the CMG priorities to fulfil the demands of IaS facilities. The second is to accept the solutions that make a total profit more than the minimum amount approved by the CMG (Eq. 32).

$$\sum_{t\in T}\left((Rev_t - PTC_t - SC_t - FVC_t - UC_t)\right) \geq MDP \qquad (32)$$

Accordingly, the final Pareto optimal set is derived and compared in pairwise charts in Figure 6. Pareto point number 14 meets the desired conditions after consulting with experts and based on the resulted values for objective functions and selected for the following analysis.

6.3. Discussion

Analysis of the sustainable planning results indicate the different patterns of logistics operations and productions along the SSCN, while the PDF objective function maximizes the demand of intra-SC customers (IaS). This matter begins by changing the periodical transportation of stocked iron ores toward the downstream facilities in the blending beds. In the following, the SEC objective function maximizes the socio-environmental compliances in the entire production system. The EP objective function also conducts the system to meet the most desired sustainable conditions by minimizing the emissions in production and transportation systems. The alterations of flow patterns between sustainable and economic planning results are presented in Figure7, parts b, and c. Additionally, proper compromises arise between maximizing the socio-environmental compliances and minimizing the emissions while a pollutant facility reaches the appropriate socio-environmental score. Among all facilities in the SSCN, the BOF plant, as the most polluting system with the least assigned socio-environmental score, must endure the significant production reduction to obey the sustainable planning requirement. Consequently, the transportation costs and CO_2 emissions in production and transportation processes also decrease considerably. However, the EAF plants can continue their production regularly because of significantly less emission and better socio-environmental scores (Figure 8).

Ultimately, four key performance indicators (KPIs) including the total profit, the total final product (steel) as the product with the most added-value, CO_2, and PM emissions were defined to summarize the findings. As shown in Table 8, the comparison results of sustainable planning versus economic planning show a 35% and 41% reduction in CO_2 and PM emissions. Thus, the final product amount and the total profit of SSCN decreased by 27% and 15%. These findings align with a proactive approach that resulted from operational adjustments, without necessarily costly investments in carbon-reducing technologies [16], [51]. Integrating sustainable principles into the strategic and tactical SCND decisions can be considered as a step towards the implementation of social and environmental responsibilities of any organization as well [51]. Tables S.7 and S.8 in the supplement file present additional details about the results.

Table 8. Comparison of economic and sustainable planning results on KPIs.

Problem type	Total profit (M$)	Total final production (Mt)	Total CO_2 emission (Mt)	Total PM emission (kt)
Economic planning	753	4.18	6.09	38.30
Sustainable planning	637	3.04	3.97	22.59

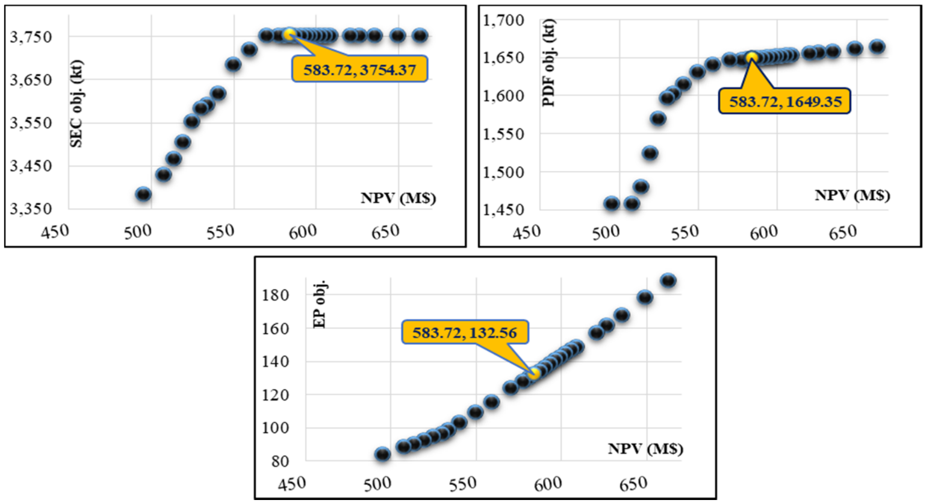

Figure 6. Pairwise comparison charts for different objective functions.

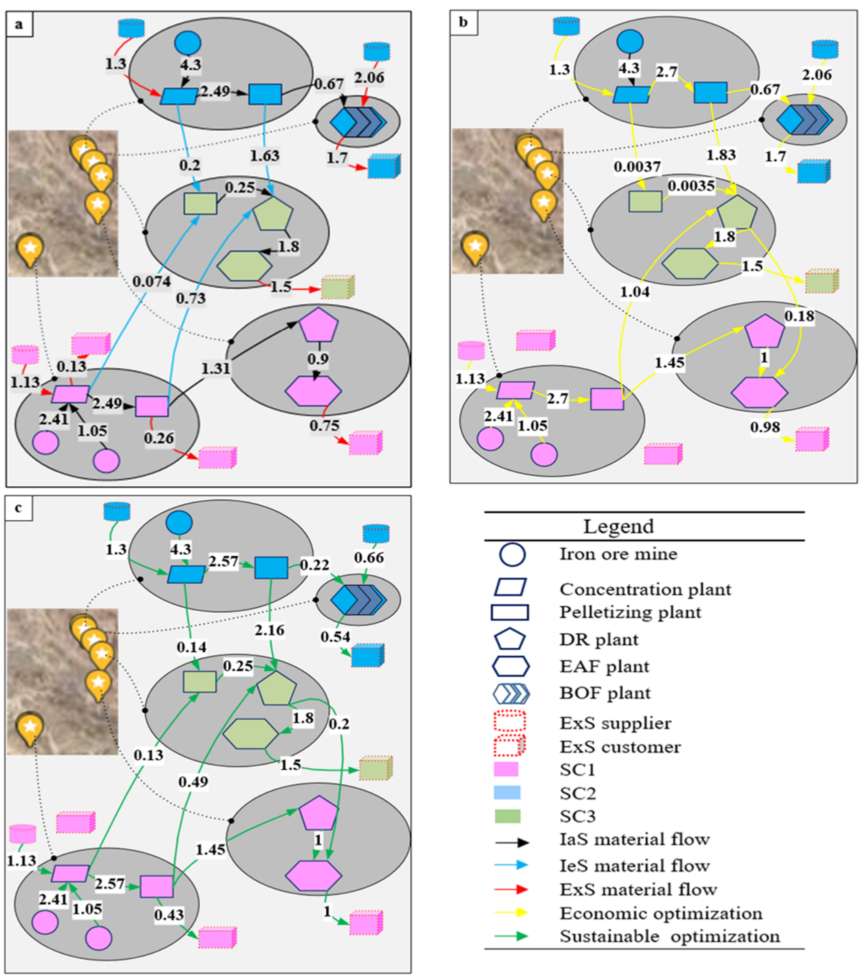

Figure 7. Annual material flow (Mt): a) Actual planning, b) Economic planning, c) Sustainable planning.

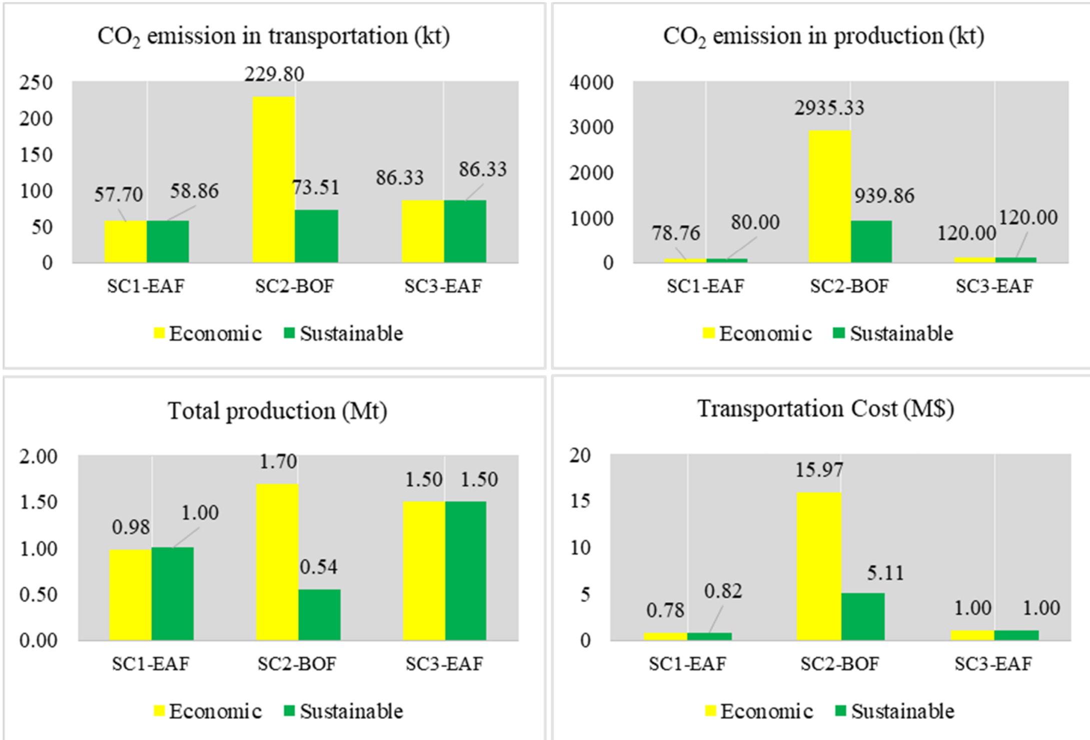

Figure 8. Findings in sustainable planning *vs.* economic planning in Steel plants.

6.4. Sensitivity analysis

The steel price and the value of all material inputs, especially intermediate materials, fluctuate during the global crisis or economic growth. Understanding the influences of this price volatility allows managers to plan based on changes in the supply chain performance. To investigate these effects, a reasonable variation in prices of steel and other intermediate materials was considered in this study. Accordingly, a reasonable variation in the prices of these materials was considered to analyze the sensitivity of the entire SSCN performance. The findings show that a 10% fall in prices results in a 16% reduction in total profit without any significant variations in the final production rate. Consequently, the CO_2 and PM emissions remain almost constant. However, a 20% reduction in prices yields the system to decrease 33% of profits by a 4% reduction in final production. This matter caused 6% and 8% fewer emissions of CO_2 and PM. In another way, a 10% and 20% increase in prices motivates the whole system to raise the steel production rate by 4% and 7%. Moreover, the total profit grows by 18% and 37% respectively. At the same time, total emissions of CO_2 increased by 6% and 10%, and PM emissions rise by 7% and 13%. Therefore, rising environmental pressures and social impacts are expected. Figure 9 shows the results of the sensitivity analysis on KPIs.

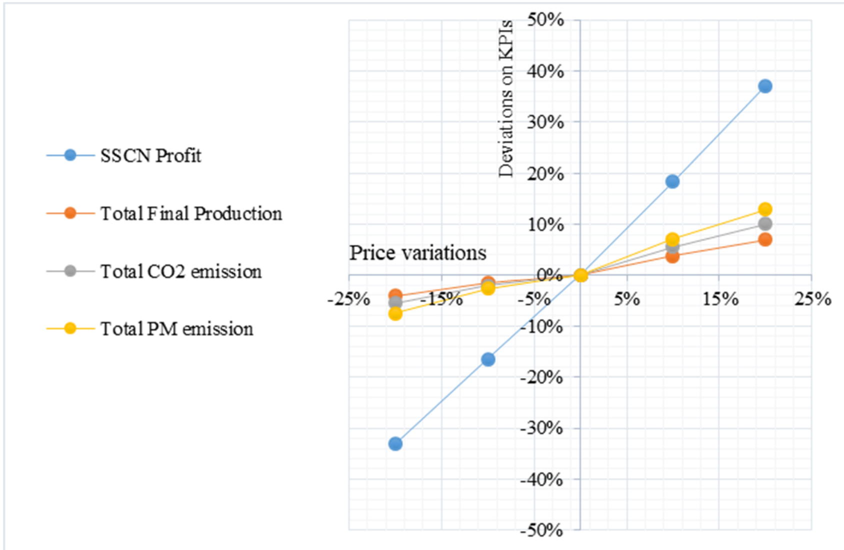

Figure 9. Sensitivity analysis.

6.5. Managerial insights

The computational results provided several valuable insights for managers of steel supply chain networks as follows:

- The model structure can demonstrate the influences of technological constraints on optimized conditions. Among them, blending constraints impose the proper material handling operations between mines and concentration plants to use all available iron ore capacity, resulting in higher total profitability by improving production planning.
- Applying the proposed sustainability assessment system results in the model provides ISI managers with a tool for making tactical and operational decisions that are more in line with sustainable development goals. In addition, it could ease the continuous monitoring of sustainable corrective actions.
- Considering the only economic planning approach in SSCNs, moves the planning toward using more facilities with lower production costs. However, sustainable planning motivates the system to alter the usage of some facilities more than the previous strategy to better adapt to environmental and social issues. The proposed model guides managers to have a clear vision of comparing these two perspectives and implementing production and transportation planning in such conditions.
- Maximizing the prioritization of demand fulfillment as a new objective function is a practical tool for the management group to analyze the various production-transportation policies between SCs, to project the most overall desired profit along SSCN.
- Although boosting the intermediate and final products prices motivates the system to raise the production on a steeper slope, environmental threats such as increasing emissions arise more drastically. Therefore, accelerating efforts to improve energy and emissions efficiency seems necessary to provide the opportunity to keep profitability.
- Studies show that improving the quality of input materials leads to a significant reduction in pollution. For instance, a 1% increase in the iron content of supplied iron ores decreases the coke consumption by 1.5% to 2% in the BF-BOF route, which has a critical role in CO_2 emission [56]. Consequently, this model can guide managers to analyze the effects of raw materials quality on improving the regional sustainability footprints.

7. Conclusions

The iron and steel industry (ISI) has a vital role in improving the welfare of local and national society. Unfortunately, it is also a source of environmental pollution due to the large consumption of fossil energy, water, electricity, and natural raw materials. These issues create a need for a proper approach to guide the managers in thinking beyond the economic benefits of production processes and consider the whole system's environmental and social effects. For this purpose, a multi-objective mixed-integer linear programming (MOMILP) model was proposed in this study. This framework had been developed in a multi-tier structure and promoted by a multi-supply chain (SC) system. This model also included specific technical restrictions to conform to inevitable real-world complexities. Maximizing the net present value (NPV) was the primary objective function in this model. The following objective function aims to implement the desired managerial priorities in fulfilling the demands. Meanwhile, besides the environmental pollution minimization function, a new socio-environmental objective function was defined, conducting the whole system to cleaner productions and sustainable logistics operations. In this regard, a hierarchical sustainability assessment (SA) system was applied to derive the objective coefficients by ranking the mines and multi-tier production plants at each production level.

To find out the most preferred solutions for this model, the Pareto optimal set was generated using the augmented ε-constraint method (AUGMECON2) implemented in ILOG CPLEX. An actual case study in Iran has been chosen to test the model. According to the economic and sustainable planning results and the sensitivity analysis of price fluctuations for iron-based materials, the proposed model can help managers identify the most sustainable productions and logistics operations. The comparison results of sustainable planning versus economic planning showed a 35% and 41% reduction in CO_2 and PM emissions that result from a 27% and 15% decrease in the final product amount and the total profit of SSCN. Additionally, there are valuable areas to consider for further research such as (i) considering the uncertainty of price, iron content of raw materials, and recovery ratio, (ii) integrating this model with other supportive supply chain networks such as the coke supply chain as one of the most pollutant related supply chains to ISI, (iii) combining the model with a closed-loop supply chain via adding the collection centers of scrap and other recyclable materials, and (IV) generalizing the problem into a global optimization model, to assess the sustainable footprints at the macro-economic level.

Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A.1. Description of sets and indices.

Items	Definition
T	Time periods
SC	Numbers of SCs in the SSCN
M, B, L	Set of mines M, blending beds B, and multi-tier plants L in the SSCN
M_g, Mx_g	Subset of mines M_g belonging to the SSCN and outbound iron ore suppliers Mx_g for each SC $g \in$ SC ($M_g \cup Mx_g \subseteq M$)
I	Set of echelons include mines M, blending beds B, and multi-tier plants L in the SSCN ($M \cup B \cup L \subseteq I$)
$\bar{I}$	Set of tiers of plants in the SSCN: $\bar{I} = \{1,2,\dots,e-1,e\}$
$\bar{\bar{I}}$	Set of tiers of plants in the 2nd section of the SSCN: $\bar{\bar{I}} = \bar{I}\backslash\{1\}$
$l_{\bar{\imath}g}$	Subset of plants in each tier $\bar{\imath} \in \bar{I}$ and SC $g \in$ SC : $l_{\bar{\imath}g} = \{\ell_{1g}, \ell_{2g}, \cdots, \ell_{(e-1)g}, \ell_{eg}\} \subseteq L$
$B_{\ell_{1g}}^{m_{g'}}$	Subset of blending beds $B_{\ell_{1g}}^{m_{g'}} \subseteq B$ where stock the supplied iron ore from mine $m_{g'} \in M$ ($g' \in$ SC) at each plant $\ell_{1g} \in l_{\bar{\imath}g}$ ($g \in$ SC)
R, A, P	Set of supplied raw materials: intermediate materials R, additive materials A, and products P
S, C	Set of all suppliers S and customers C
S_{ig}^k, Sx_{ig}^k	Subset of suppliers S_{ig}^k belonging to the SSCN and outbound suppliers Sx_{ig}^k in each echelon $i \in I$ and SC $g \in$ SC to supply $k \in R \cup A$
C_{ig}, Cx_{ig}	Subset of customers C_{ig} belonging to the SSCN and outbound customers Cx_{ig} in each echelon $i \in I$ and SC $g \in$ SC
F	Set of chemical and physical properties include the purity Fe, impurities, and size Z: $F = \{Fe, S, P, SiO_2, Al_2O_3, MgO, Z\}$
H	Set of pollutants $H = \{CO_2, SO_2, NO_x, PM, Co, Ni, \dots\}$
O, D	Set of all origins O and destinations D
O_{ig}, D_{ig}	Subset of origins $O_{ig} \subset O$ and destinations $D_{ig} \subset D$ belonging to the SSCN in each echelon $i \in I$ and SC $g \in$ SC
Ox_{ig}, Dx_{ig}	Subset of outbound origins $Ox_{ig} \subset O$ and destinations $Dx_{ig} \subset D$ in each echelon $i \in I$ and SC $g \in$ SC
Ac	Set of all arcs presented in the problem network

Table A. 2. Parameters related to capacity.

Items	Definition
$\overline{Qy}_o^t$	The supply capacity at location $o \in O_{ig}$ during the period $t \in T$ ($i \in I, g \in$ SC)
$\underline{Qp}_o^t, \overline{Qp}_o^t$	The lower and upper production limits at location $o \in O_{ig}$ during the period $t \in T$ ($i \in I, g \in$ SC)
$\overline{Qs}_o^t$	Maximum storage capacity at location $o \in O_{ig}$ during the period $t \in T$ ($i \in I, g \in$ SC)
Te_o^t	The technical factor for production process at location $o \in O_{ig}$ during the period $t \in T$ ($i \in I, g \in$ SC)
Dm_d^{kt}	Demand limit of raw material $k \in R \cup A$ at location $d \in D_{ig}$ during the period $t \in T$ ($i \in I, g \in$ SC)
Dm_d^t	The product demand at location $d \in D_{ig}$ during the period $t \in T$ ($i \in I, g \in$ SC)

Table A. 3. Parameters related to blending and proportioning processes.

Items	Definition
Rt_o^{ft}	Ratio of properties $f \in F$ of material at location $o \in O_{ig}$ during the period $t \in T$ ($i \in I, g \in$ SC)
Re_d^{Fet}	Recovery ratio of $Fe \in F$ retrieved after processing at location $d \in D_{ig}$ during the period $t \in T$ ($i \in I, g \in$ SC)
Ar_d^{rf}	Minimum (for purity) or maximum (for impurity or size) acceptable ratio of $f \subseteq F$ in supplied materials $r \in R$ for location $d \in D_{ig}$ ($i \in I, g \in$ SC)
$k^f \begin{cases} +1 \\ -1 \end{cases}$	If $f \in F$ appears as purity (Fe) If $f \in F$ appears as impurity or size
Pp_d^{kt}	Planned proportioning ratio for each raw material $k \in R \cup A$ at location $d \in D_{ig}$ during the period $t \in T$ ($i \in I, g \in$ SC)

Table A. 4. Parameters related to objective functions.

Parameter	Definition
dr	Discount rate
$Df1_o^t, Df2_o^t$ $Df3_o^t$	Demand prioritization factors at location $o \in O_{ig}$ during the period $t \in T$ $(i \in I, g \in \text{SC})$
αd_o	The expert group judgment (EGJ) for location $o \in O_{ig}$ in PDF obj. function $(i \in I, g \in \text{SC})$
Sc_o	The socio-environmental score for each location $o \in O_{ig}$ $(i \in I, g \in \text{SC})$
αs_i	The EGJ factor for echelon $i \in I$ in SEC obj. function
Ep_o^h	The amount of pollution $h \in H$ per unit of production at location $o \in O_{ig}$ $(i \in I, g \in \text{SC})$
Et^h	The amount of pollution of $h \in H$ for material transportation
$Ds_{o,d}$	Distance between $o \in O_{ig'}$ and $d \in D_{i'g}$ $(i'\&i \in I, g'\&g \in \text{SC}, i < i')$
Min^h	Minimum pollution of $h \in H$ in the SSCN
Max^h	Maximum pollution of $h \in H$ in the SSCN
αe^h	EGJ factor for each type of pollutants $h \in H$ in EP obj. function
MDP	Minimum desired total profit of the productions in the SSCN

Table A. 5. Parameters related to cost and revenue.

Items	Definition
$Pr_{o,d}^t$	The selling price per unit of production from location $o \in O_{ig}$ to customer $d \in D_{i'g'} \cup Dx_{i'g}$ during the period $t \in T$ $(i'\&i \in I, g'\&g \in \text{SC}, i < i')$
$Cm_{o,d}^t$	Cost of risks* per unit of production, added in the price of product sold from location $o \in O_{ig}$ to customer $d \in D_{i'g'} \cup Dx_{i'g}$ during the period $t \in T$ $(i'\&i \in I, g'\&g \in \text{SC}, i < i')$
$Cp_{o,d}^t$	Purchase cost per unit of supplied raw material from supplier $o \in O_{ig'} \cup Ox_{ig}$ to location $d \in D_{i'g}$ during the period $t \in T$ $(i'\&i \in I, g'\&g \in \text{SC}, i < i')$
$Ct_{o,d}^t$	Transportation cost per unit of supplied raw materials from supplier $o \in O_{ig'} \cup Ox_{ig}$ to location $d \in D_{i'g}$ during the period $t \in T$ $(i'\&i \in I, g'\&g \in \text{SC}, i < i')$
Cs_o^t	Storage cost per unit of production at location $o \in O_{ig}$ $(i \in I, g \in \text{SC})$ during the period $t \in T$
Cf_o^t	Fixed costs for producing at location $o \in O_{ig}$ during the period $t \in T$ $(i \in I, g \in \text{SC})$
Cv_o^t	Variable cost per unit of production at location $o \in O_{ig}$ during the period $t \in T$ $(i \in I, g \in \text{SC})$
Cu_d^t	The unfulfilled cost per unit of final product sold to $d \in Dx_{eg}$ during the period $t \in T$ $(e \in \bar{I}, g \in \text{SC})$

*Note: The cost for (transfer of) risk means extra costs, which are included as sellers' or buyers' obligations according to the agreement between the parties (Refer to https://incodocs.com).

Table A. 6. Decision variables.

Items	Definition
Xp_o^t, Xp_d^t	Amount of product produced at location $o \in O_{ig}$ or $d \in D_{ig}$ during the period $t \in T$ $(i \in I, g \in \text{SC})$
$Xt_{o,d'}^t$	Flow of product from $o \in O_{ig}$ to $d' \in D_{i'g'} \cup Dx_{i'g}$ during the period $t \in T$ $(i'\&i \in I, g'\&g \in \text{SC}, i < i')$
$Xt_{o',d}^t$	Flow of raw material from $o' \in O_{ig'} \cup Ox_{ig}$ to $d \in D_{i'g}$ during the period $t \in T$ $(i'\&i \in I, g'\&g \in \text{SC}, i < i')$
Xs_o^t, Xs_d^t	Amount of product stored at location $o \in O_{ig}$ or $d \in D_{ig}$ during the period $t \in T$ $(i \in I, g \in \text{SC})$
Xu_d^t	The shortage of demand at location $d \in Dx_{eg}$ during the period $t \in T$ $(e \in \bar{I}, g \in \text{SC})$

ارائه یک مدل بهینه سازی چندهدفه پایدار جدید برای طراحی زنجیره تأمین فولاد با در نظرگرفتن ملاحظات فنی و مدیریتی: مطالعه موردی

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چکیده:

صنعت آهن و فولاد از جمله صنایع منبع‌بر و آلاینده محسوب شده و در عین حال بالاترین ارزش را نیز در بین همه صنایع معدنی و فلزی خلق می‌کند. اگرچه مطالعات اخیر پیشنهاداتی را برای ارتقاء توسعه پایداری در این صنعت ارائه کرده‌اند، اما پیچیدگی اثرات اجتماعی-محیط زیستی ناشی از فعالیت‌های این صنعت به‌دلیل ساختار چندرده‌ای و چندزنجیره‌ای آن هنوز هم به صورت یک مسئله اساسی در طراحی شبکه زنجیره تأمین پایدار در این حوزه باقی مانده است. از این‌رو، در این تحقیق، یک مدل برنامه ریزی خطی عدد صحیح مختلط چند هدفه جهت یکپارچگی عوامل پایداری با محدودیت‌های فنی و مدیریتی ارائه شد. در این مدل سودآوری اقتصادی کل بیشنه شده درحالیکه میزان آلاینده‌های محیط زیستی کمینه شد. همچنین در این مدل پیاده‌سازی تعهدات اجتماعی و محیط زیستی نیز مد نظر قرار گرفت. اعمال محدودیت‌های مدیریتی در برآورده کردن تقاضا نیز از طریق یک روش جدید بیشینه شد. برای حل مدل از روش اپسیلون محدودیت ارتقاء یافته استفاده شد. درنهایت، مدل با استفاده از داده‌های واقعی یک مطالعه موردی حل شد. نتایج مدل حاکی از کاهش ۳۵٪ و ۴۱٪ به‌ترتیب در میزان انتشار کربن دی اکسید و ذرات گرد و غبار بود که به واسطه آن سود کلی به میزان ۱۵٪ کاهش یافت. آزمون تحلیل حساسیت نیز بر روی نتایج مدل انجام شد. به علاوه، موارد مربوط به بینش مدیریتی ناشی از نتایج مدل مورد بحث قرار گرفت.

کلمات کلیدی: صنعت آهن و فولاد، طراحی شبکه زنجیره تأمین، سیستم ارزیابی پایداری، الویت برآورده کردن تقاضا، بهینه سازی چندهدفه.