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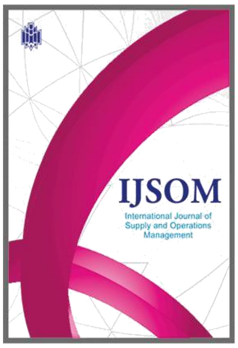

Bi-objective Stochastic Programming Model for Green Closed-loop Supply Chain Network Design in Presence of Sale and Leaseback Transactions

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Abstract

The need for effective use of assets has become more important in the design of supply chain networks in today's competitive environment. Sale and leaseback (SLB) agreements are one of the appropriate tools to achieve this important goal. The proper use of these agreements increases the liquidity of assets, and provides financial resources required for other activities. However, the consideration of SLB possibility in a Closed-Loop Supply Chain (CLSC) that aims to minimize CO_2 emissions as well as maximizing profit has never studied before. Therefore, this paper proposes a bi-objective two-stage stochastic program for designing a CLSC network considering SLB agreements. The objective functions are: to maximize profit after tax and to minimize CO_2 emissions of the supply chain. To assess the performance of the proposed model, 30 different-sized test problems are generated and solved by both LP-metric and max-min methods. Finally, sensitivity analysis is performed to assess the impact of SLB related parameters (the safety stock coefficient, the fair value of the leased asset, the interest rate implicit in the lease, and the lessee's incremental borrowing rate) on the objectives. The results show significant superiority of the proposed model over which do not consider SLB possibility. Outcomes also indicates that Lp-metric method provides better solutions for the problem. Finally, some managerial insights are suggested.

Keywords: Closed-loop supply chain network design (CLSC); Scenario-based stochastic optimization; Sale and leaseback (SLB); CO_2 emissions; Multi-objective optimization.

1. Introduction

Nowadays competitive conditions, legal requirements and environmental concerns have made organizations responsible for collecting End-of-Life (EoL) products to reuse, remanufacture, and recycle or environmentally friendly dispose of them. Therefore, reverse logistics is a necessity to reduce environmental impacts as well as costs and to enhance performance of the chain. In the forward supply chain, activities such as production and distribution planning are performed. Nevertheless, in the reverse supply chain, activities such as product collection and recovery (reuse, remanufacture, recycle) planning, defective product separation, repair or disposal take place. Merging the reverse logistics with forward chains has changed the structure of traditional supply chains. Since the performance of forward and reverse supply chains are significantly correlated, proper integration is essential to protect seamless forward and backward flows in a Closed-Loop Supply Chain (CLSC) (Vahdani et al., 2012). In addition to ordinary supply chain activities, a CLSC considers the flow of EoL products, their recovery and dispatching to the production cycle. The main purpose is to determine the flow of materials (raw, under construction and finished product, returned, recovered) between all supply chain nodes, so that the costs of transportation, recovering and supply of materials are minimized, or equivalently, profits are maximized.

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Sometimes, CLSC issues are referred to as environmentally friendly supply chain issues. The purpose of such issues is to minimize waste of materials over the product life cycle (Pishvaee and Torabi, 2010). The interaction of forward and reverse paths varies according to the type of product. For products like jewelry which have very rare or expensive raw materials, the dependency is high and almost all new products are produced from recycled ones. Another most promising solution for environmental impacts in a supply chain, that is widely used, is the CO_2 emissions indicator (Soleimani et al., 2017).

A new practical concept in supply chain that has been widely adopted and used worldwide, is utilization of financial aspects, especially after the 2008 financial crisis. In this regard, Sales and Leaseback (SLB) is a concept in financial management, whereby supply chain managers can solve liquidity problems, and provide monetary resources for future activities at an acceptable level. A SLB transaction involves selling the asset and leasing it by the seller. This method can be an efficient financing method in situation of liquidity shortage and inability to borrow. Rental amounts and asset sale prices are usually interdependent, as both are negotiated simultaneously. Since the mid-1990s, as the number and distribution of industries have increased, more attention has been focused on these transactions. Many studies suggest that paying attention to SLB has added value, and is a good source of financing that improves liquidity and shows the hidden value of a company's assets. In a supply chain, plants, warehouses, distribution centers, and other facilities throughout the chain occupy large amounts of capital. Therefore, the budget allocated to non-productive assets prevents the investment growth in other short- and medium-term projects. The integration of SLB financing and supply chain techniques helps Decision Makers (DM) to sell their assets, if needed, and re-renting them, using their liquidity for other value-added activities.

On the other hand, the complicated and dynamic nature of today’s supply chains made planning and decision making more complex. Thus, considering the uncertainty of key input parameters, like demand, results in developing more realistic models which increase the applicability of them.

This study extends the model presented by Longinidis and Georgiadis in 2014 to include more practical considerations (Longinidis and Georgiadis, 2014). More precisely, a bi-objective two-stage stochastic program is presented for a multi-period, multi-product, CLSC in the presence of the possibility of SLB for fixed assets. To the best of our knowledge, the above-mentioned financial approach, has not been considered in case of an uncertain CLSC, in which reverse logistics activities including collecting, inspecting, repairing or dismantling products are integrated with forward logistics.

The remainder of this paper is organized as follows. Section 2 introduces the research background and the literature review. Section 3 describes problem statement and mathematical formulation. Section 4 is devoted to computational results, validation, sensitivity analysis and managerial insights. Finally, section 5 concludes the paper and suggestions for future research are presented.

2. Research background and literature review

In order to review the relevant studies, this section presents the literature review in three main parts: (1) CLSC network design; (2) SLB in supply chain management; (3) CO_2 emissions management in a supply chain.

2.1. CLSC network design

Regarding the importance of critical environmental issues like resource depletion and CO_2 emissions, less use of raw materials is considered as one of the most efficient solutions. Thus, governments are focusing on drivers for product recovery to bring them into manufacturing cycle again.

Although returning products is usual since the early days of trade, the reverse logistics debate has attracted researchers’ attention, since the early 1990s. The related studies are ranging from simple models of facility deployment to complex multi-purpose models (Pishvaee et al., 2009). It can be seen in the supply chain literature that since 2005, reverse logistics has been the important topic of many studies in this area (Pokharel et al., 2009). In this regard, a large body of literature has developed on CLSC network design problems and several review papers have been published (Haddad-Sisakht and Ryan, 2018; Govindan et al., 2017).

Fleischmann et al. (2001) showed that simultaneous optimization of the forward and reverse networks, compared to their separate design, results in significant cost savings. Salema et al. (2007) extended the model proposed by Fleischman et al. (2001) into a capacitated multi-product reverse distribution network under demand uncertainty and the possibility of product return. Lu and Bostel (2007) presented a binary mixed integer program to integrate design of forward and reverse networks considering their mutual interactions. To solve the proposed model, an algorithm based on Lagrangian heuristics was presented. Qin and Ji (2009) used fuzzy mathematical programming to design the reverse logistic networks. They used a hybrid algorithm based on genetic algorithm and fuzzy simulation to solve the problem. El-Sayed et al. (2010) presented a multi-stage stochastic mixed integer program for the multi-level, multi-period forward-reverse logistics network design, to maximize the expected total profit. Mitra (2012) formulated the deterministic and stochastic two-echelon CLSC with correlated demands and returns considering holding and shortage costs of inventories. Garg et al. (2015) formulated a bi-objective integer nonlinear program for CLSC network design problem with four echelons in the forward chain and five echelons in reverse chain, considering the environmental issues. They proposed an interactive multi- objective programming approach algorithm to solve the problem. Rumin et al. (2016) proposed a robust multi-objective mixed integer nonlinear program to deal with the environmental CLSC design. They used the LP-metrics method to solve the problem. Badri et al. (2017) presented a two-stage stochastic program for designing a value-based supply chain network in a three-level, multi-product, multi-period setting. Yan Yan Kui et al. (2017) presented a mixed integer program to cope with CLSC design problem involving several manufacturers, intermediary manufacturers and customer centers. In addition, the demand uncertainty and the possibility of returning products were considered. Finally, a bee colony optimization algorithm was used to solve the problem. Haddad-Sisakht and Ryan (2018) formulated a CLSC assuming stochastic demands, multi-mode transportation, and governmental carbon emission regulations. Kamlesh Pant et al. (2018) formulated a CLSC network design model, consisting of four forward and six backward levels in the form of a Mixed Integer Linear Program (MILP). They solved the problem using a branch and bound method. Zhen et al. (2019) proposed a sustainable CLSC network design, considering environmental concerns, demand uncertainty and returned product quality. They proposed a bi-objective MILP model, to minimize the total cost and emissions. Asim et al. (2019) developed a multi-echelon, multi-item integrated production-transportation CLSC model under uncertain supply and demand. The proposed model includes three objective functions, namely minimizing cost, defective items and delivery time. Fuzzy goal programming was used and a real-life case study was applied to test the model. Taleizadeh et al. (2019) presented a model to decide on pricing and discount in a sustainable CLSC network. They incorporated the remanufacturing abilities of the plants and secondary market for selling the recovered materials. Alegoz et al. (2020) proposed a two-stage stochastic program to study economic and environmental impacts in CLSCs regarding uncertain product quality and rate of return. Mohtashami et al. (2020) considered the waiting time of the transportation fleet in a network and designed a green CLSC network that decreases the energy consumption and environmental impacts via loading, unloading, and production rates. Wen et al. (2020) developed a model that determines primary pricing and collection rate based on consumers' environmental responsibility in a CLSC. Santander et al. (2020) applied a MILP-based optimization method to design a green CLSC network for local and distributed plastic recycling. Diabat and Jebali (2020) studied take-back legislation in a CLSC and concluded that the total chain's profitability can be improved by applying penalty-reward mechanism. Khorshidvand et al. (2021a) developing a two-stage model for a sustainable CLSC taking into account pricing, green quality, and advertising. In the first stage, pricing, greening, and advertising decisions are made, while in the second stage, a fuzzy multi-objective Mixed Integer Linear Program is used to maximize the total profit, reduce CO_2 emissions, and improve social impacts. They also proposed a Lagrangian relaxation method for solving large-scale instances. Khorshidvand et al. (2021b) proposed a new hybrid method, in which supply chain coordination decisions and CLSC network design objectives are involved together. The approach, first, makes price, greenness, and advertisement decisions, and then maximizes profit and minimizes CO_2 emission. A robust optimization method is used to cope with uncertainty in demand and large-scale instances were solved by a Lagrangian relaxation algorithm. Yozgat and Erol (2021) presented a review paper on sustainable factors for supply chain network design under uncertainty. Their studies carried out on CLSCs taking into account sustainability factors. Sustainability sub-factors are also included in their study.

2.2. SLB in supply chain management

Despite the critical role of financial aspects in supply chain management, few researchers have addressed this issue. Guillén et al. (2007) presented a mathematical model to simultaneously optimize supply chain operational and financial activities. Puigjaner et al. (2008) optimized a supply chain at the operational level by taking into account financial considerations such as investment, interest rates, account receivables, payments, cash and debt. Sodhi and Tang (2009) extended the linear programming model of deterministic supply-chain planning to take demand uncertainty and cash flows into account for the medium term. Due to the similarity of the resulting stochastic programming model to the asset–liability management, they surveyed various modeling and solution choices developed in the asset–liability management literature, and discussed their applicability to supply-chain planning. Naraharisetti et al. (2008) proposed a MILP for asset management and capital budgeting in the supply chain redesign context, aiming to make decisions about facility location, relocation, investment, disinvestment, technology upgrade, production–allocation, distribution, supply contracts, capital generation, etc. Longinidis and Georgiadis (2011) presented a scenario-based stochastic mixed integer program to integrate financial considerations with supply chain design decisions under demand uncertainty. Nickel et al. (2012) presented a multi-stage stochastic MILP to cope with a multi-period supply chain network design problem considering uncertain demand and interest rates. Their proposed model includes many practical considerations like those related with the financial decisions, in order to maximize the financial benefit. Ramezani et al. (2014) incorporated some financial aspects (i.e., current and fixed assets and liabilities) in the CLSC network design problem, as well as a set of budgetary constraints representing balances of cash, debt, securities, payment delays, and discounts. The main goal of the proposed model was to optimize the change in equity, rather than profit/cost. Longinidis and Georgiadis (2014) introduced a multi-objective mixed integer nonlinear program (moMINLP) that improves financial performance of a supply chain by incorporating economic value added (EVA™) and credit solvency via a valid credit scoring model (Altman's Z-score).

Mohammadi et al. (2017) studied the design of a four-echelon supply chain network considering both operational and financial dimensions at the tactical and strategic levels. The aim of their proposed model was to simultaneously optimize corporate value, change in equity and economic value added. Arani and Torabi (2018) developed a bi-objective mixed possibilistic-stochastic model for a comprehensive supply chain master planning problem, integrating physical/material and financial tactical plans by accounting for the reciprocal effects of supply chain's functions and flows. In addition, a mixture of fuzzy and random fuzzy variables was incorporated into the model to handle the uncertainty of the problem. Yang et al. (2019) examined financing and pricing decisions in a supply chain in which a common retailer is supplied by an incumbent manufacturer and a capital-constrained new entrant manufacturer. They identified the conditions under which the retailer should offer financing directly to the new entrant manufacturer, and showed how the retailer sets an interest rate that is either forward-looking or short-sighted. Seiler et al. (2020) combined local networks of companies in a supply chain and designed a single, extended network, where, position of focal companies is characterized by social network analysis. They used regression analysis to study the impact of these characteristics on financial performance.

SLB is a financial transaction in which one sells an asset and leases it back from the buyer. By releasing stagnant capital from low-liquid fixed assets, SLB may have a valuable role in financing the supply chain. Despite importance and widely usage in financial contract, SLB has received less attention in the supply chain area. Ling (2012) investigated the perception of investors and corporation companies in SLB transactions in Malaysia, in terms of factors that influence the corporate firm to be involved in SLB transactions, and its benefits and disadvantages. Longinidis and Georgiadis (2014) incorporated demand and real estate market uncertainty within a MINLP where SLB technique was integrated with supply chain network design decisions.

2.3. CO_2 Emissions management in a supply chain

As the integration of supply chain management with environment protection considerations can help pollution reduction, many studies have paid special attention to this subject. Thereupon, a new research field was created: Green Supply Chain Management (GSCM). In this area, a remarkable number of studies has focused on the reverse logistics and CLSC (2014). Fareeduddin et al. (2015) mentioned three common regulatory policies, namely strict carbon caps, carbon tax, and carbon cap-and-trade in their study and proposed mathematical models to capture tradeoffs between costs and emissions. Their models help policy makers to predict the impact of regulatory policies on overall emissions in a supply chain operation. Fareeduddin et al. (2017) proposed an optimization model for designing and planning a multi-period, multi-product CLSC with carbon footprint consideration under uncertain demands and returns. Again, the proposed model captures trade-offs between supply chain total cost and carbon emissions. Hemmati and Pasandideh (2020) proposed a MINLP for a two-echelon supply chain that focuses on supplier location, supplier selection and order allocation with green constraints. Their bi-objective model aimed to coordinate inventory and transportation among suppliers and warehouses and simultaneously to meet targets for total costs and CO_2 emissions of transportations. Keshavarz-Ghorbani and Arshadi Khamseh (2021) presented a repair process to improve the virtual age of used products and integrated it to forward flows as a CLSC. They estimated the optimal number of EoL products return and repair to maximize profit. The price of selling new products, the cost of acquiring EoL products, and the warranty period are determined in order to motivate the customers to bring back EoL products and to increase the demand for products.
Investigating the literature, the current paper is the first to develop a bi-objective stochastic optimization model for a multi-period, multi-product, CLSC that considers possibility of SLB for fixed assets. The main contributions of the present study are as follows:

- Considering profit and CO_2 emissions as objective functions, using a two-stage stochastic program
- Simultaneously considering forward and backward product flows in the network as a CLSC.

3. Problem description and mathematical modeling

As previously mentioned, in this paper, the multi-product, multi-period CLSC network design is considered. The forward chain comprises four echelons: Plants (P), warehouses (W), distribution centers (DC) and customers (C). The backward chain includes three echelons: collection centers (CC), repair centers (RC) and disposal centers (DPC). Figure 1 illustrates schematic of assumed network. Plants produce several types of products that move from warehouses to distribution centers. In order to meet anticipated demand, products are transferred from distribution centers to customers. Products delivered to customers may have defects for some reasons, so they should be transferred to collection centers. Then, products that are reproducible and repairable are separated and completely defective ones are transferred to disposal centers. Reproducible products are transferred to plants, and repairable ones are transferred to repair centers and then are sent to distribution centers. Locations of plants, customers and disposal centers are considered to be predetermined. However, establishment of other facilities, namely warehouses, distribution centers, collection centers and repair centers, is decided by the presented model. The purpose of the proposed model is to maximize the expected value of supply chain network's profit in a stochastic environment over the planning horizon. The planning horizon determined based on the Economic Life (EL) of fixed assets. As considered by Longinidis and Georgiadis (2014), a SLB term (T) should be at least 75% of asset's EL, and should be completed by the end of asset's EL. At the end of each time period, the status of the SLB is reviewed. The SLB process begins and continues until the end of the period if it has added value. To deal with the inherent uncertainty of the problem, a scenario-based approach is used. Figure 2 (Longinidis and Georgiadis, 2014) shows the planning horizon and the scenario tree representation. The number of scenarios is determined based on the planning horizon, which is 75% of the EL of the asset, and is determined by the relation $(2^{\frac{EL}{4}-1})$. The probability of each scenario is considered as Ψ_s, $(\sum_{S=1}^{2^{\frac{EL}{4}-1}} \Psi_s = 1)$. The uncertain parameters, whose values are specified by the DM(s), are as follows (see section 3.1 for detailed description of the notations):

- demand for products ($\mathrm{DM}_{ict}^{[s]}$)
- fair values of assets ($FV_{mt}^{[s]}$, $\mathrm{FV}_{kt}^{[s]}$, $\mathrm{FV}_{nt}^{[s]}$, $\mathrm{FV}_{rt}^{[s]}$)
- lessee’s incremental borrowing rates ($\mathrm{LIBR}_{mt}^{[s]}$, $\mathrm{LIBR}_{kt}^{[s]}$, $\mathrm{LIBR}_{nt}^{[s]}$, $\mathrm{LIBR}_{rt}^{[s]}$)
- interest rate implicit in the lease for fixed assets ($\mathrm{IRIL}_{mt}^{[s]}$, $\mathrm{IRIL}_{kt}^{[s]}$, $\mathrm{IRIL}_{nt}^{[s]}$, $\mathrm{IRIL}_{rt}^{[s]}$)
- product’s return ratio ($RR_{it}^{[s]}$), repair ratio ($\mathrm{RP}_{it}^{[s]}$)
- reproduction ratio ($\mathrm{RM}_{it}^{[s]}$).

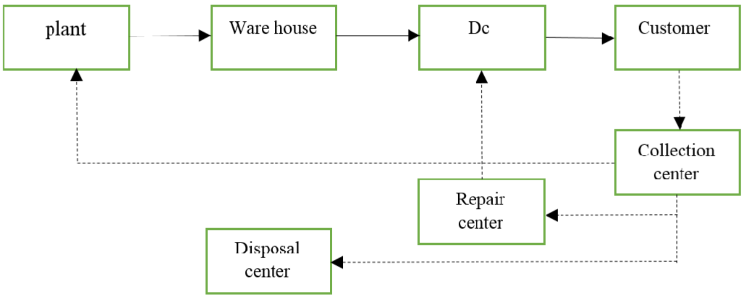

Figure 1. The product flow in a CLSC

Fair value (FV) is the amount at which an asset can be exchanged between knowledgeable and interested people in a contract. The Interest Rate Implicit in the Lease ($IRIL$) is the discount rate that makes the present value of the minimum lease payments equal to the FV of the leased asset at the beginning of the lease term. The Lessee’s Incremental Borrowing Rate ($LIBR$) is the interest rate that the borrower will pay on a similar lease. If this rate cannot be recognized, then the interest rate is replaced, which is the lessee should pay to borrow the necessary funds for purchasing the asset over a similar period at the beginning of the lease. The difference between the FV and the nominal value is the unrealized profit of the SLB. The depreciation policies of the leased back assets must be consistent with those of assets owned (Longinidis and Georgiadis, 2014).

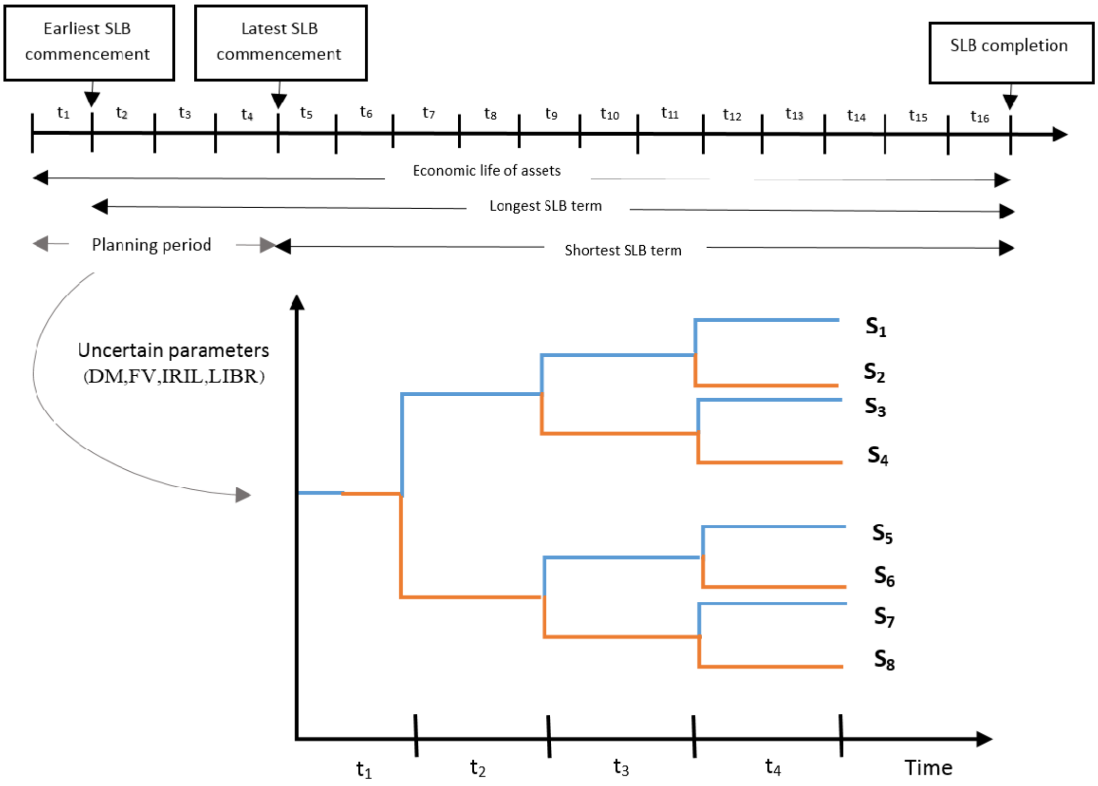

Figure 2. Planning horizon and scenario tree representation

An SLB transaction can be done regardless of the FV and present value of the minimum lease payments. However, corporations prefer the FV to be higher than the present value of the minimum lease payment. This helps them yield a positive net present value. The basic conditions for a value-creating SLB transaction for each fixed asset at any time period is as follows (Longinidis and Georgiadis, 2014):

$$\mathrm{FV} \geq \mathrm{PVLP} \qquad \leftrightarrow$$

$$\mathrm{FV} \geq \mathrm{PMT} \times \frac{1-(1+\mathrm{LIBR})^{-\mathrm{T}}}{\mathrm{LIBR}} \qquad \leftrightarrow$$

$$\mathrm{FV} \geq \frac{\mathrm{FV}}{(1-(1+\mathrm{IRIL})^{-\mathrm{T}})/\mathrm{IRIL}} \times \frac{1-(1+\mathrm{LIBR})^{-\mathrm{T}}}{\mathrm{LIBR}} \qquad (1)$$

By factoring the term FV in both sides, inequality (1) can be rewritten as inequality (2).

$$0 \geq \mathrm{FV}\left(\frac{(1-(1+\mathrm{LIBR})^{-\mathrm{T}})/\mathrm{LIBR}}{(1-(1+\mathrm{IRIL})^{-\mathrm{T}})/\mathrm{IRIL}} - 1\right) \qquad (2)$$

Inequality (2) holds for negative right side. Since FV, $LIBR$, and $IRIL$ are positive, *t* the ratio of discount factors should be smaller than one. This condition is stated in inequality (3), which is prerequisite for the SLB occurrence (Longinidis and Georgiadis, 2014).

$$1 \geq \frac{\mathrm{DF}_{\mathrm{T}}^{\mathrm{LIBR}}}{\mathrm{DF}_{\mathrm{T}}^{\mathrm{IRIL}}} \qquad (3)$$

The benefit from SLB is measured by Unearned Profit on SLB (UPSLB), which is the difference between the FV and the Book Value (BV) of an asset. The value of UPSLB for each fixed asset at any given time period is calculated as follows (Longinidis and Georgiadis, 2014).

$$\mathrm{UPSLB} = \mathrm{FV} - \mathrm{BV} \qquad \leftrightarrow$$

$$\mathrm{UPSLB} = \mathrm{FV} - (\mathrm{ECST} - \mathrm{ACDPR}) \quad \leftrightarrow$$

$$\mathrm{UPSLB} = \mathrm{FV} - (\mathrm{ECST} - \tau\mathrm{DRECST}) \tag{4}$$

3.1. Notations

The following sub-sections are devoted to clarify the notations used for modeling in this study. For brevity reasons, parameters are mentioned in the appendix.

3.1.1. Sets and indices

Sets and indices

E	Set of production resources, indexed by e, $(e \in E)$
I	Set of products, indexed by i, $(i \in I)$
J	Set of plants, indexed by j, $(j \in J)$
M	Set of candidate warehouses, indexed by m, $(m \in M)$
K	Set of candidate distribution centers, indexed by k, $(k \in K)$
C	Set of customers, indexed by c, $(c \in C)$
N	Set of candidate collection centers, indexed by n, $(n \in N)$
R	Set of candidate repair centers, indexed by r, $(r \in R)$
L	Set of disposal centers, indexed by l, $(l \in L)$
T	Set of time periods, indexed by t, $(t \in T)$
S	Set of scenarios, indexed by s, $(s \in S)$

3.1.2. Variables

Continuous variables

W_m	Capacity of warehouse m
DC_k	Capacity of distribution center k
CC_n	Capacity of collection center n
RC_r	Capacity of repair center r
$Q_{1ijmt}^{[s]}$	Quantity of product i transferred during time period t from plant j to warehouse m under
$Q_{2imkt}^{[s]}$	Quantity of product i transferred from warehouse m to distribution center k during time period t under scenario s
$Q_{3ikct}^{[s]}$	Quantity of product i transferred from distribution center k to customer c during time period t under scenario s
$Q_{4icnt}^{[s]}$	Quantity of product i transferred from customer c to collection center n during time period t under scenario s
$Q_{5inrt}^{[s]}$	Quantity of product i transferred from collection center n to repair center r during time period t under scenario s
$Q_{6injt}^{[s]}$	Quantity of product i transferred from collection center n to plant j during time period t under scenario s
$Q_{7inlt}^{[s]}$	Quantity of product i transferred from collection center n to disposal center l during time period t under scenario s
$Q_{8irkt}^{[s]}$	Quantity of product i transferred from repair center r to distribution center k during time period t under scenario s
$P_{ijt}^{[s]}$	Production rate of product i in plant j during time period t under scenario s
$I_{1ijt}^{[s]}$	Inventory level of product i held at plant j at the end of time period t under scenario s
$I_{2imt}^{[s]}$	Inventory level of product i held at warehouse m at the end of time period t under scenario s
$I_{3ikt}^{[s]}$	Inventory level of product i held at distribution center k at the end of time period t under
$PMT_{1m}^{[s]}$	Minimum lease payments for sold and leased back warehouse m under scenario s
$PMT_{2k}^{[s]}$	Minimum lease payments for sold and leased back distribution center k under scenario s
$PMT_{3n}^{[s]}$	Minimum lease payments for sold and leased back collection center n under scenario s
$PMT_{4r}^{[s]}$	Minimum lease payments for sold and leased back repair center r under scenario s
$PVLP_{1m}^{[s]}$	Present value of minimum lease payments for sold and leased back warehouse m under
$PVLP_{2k}^{[s]}$	Present value of minimum lease payments for sold and leased back distribution center k under scenario s
$PVLP_{3n}^{[s]}$	Present value of minimum lease payments for sold and leased back collection center n under scenario s

$PVLP_{4r}^{[s]}$	Present value of minimum lease payments for sold and leased back repair center r under

Binary variables

$LPW_{mt}^{[s]}$	1 if warehouse m is sold and leased back during time period t under scenario s, 0 otherwise
$LPDC_{kt}^{[s]}$	1 if distribution center k is sold and leased back during time period t under scenario s, 0
$LPCC_{nt}^{[s]}$	1 if collection center n is sold and leased back during time period t under scenario s, 0
$LPRC_{rt}^{[s]}$	1 if repair center r is sold and leased back during time period t under scenario s, 0 otherwise
$OPW_{mt}^{[s]}$	1 if warehouse m is owned during time period t under scenario s, 0 otherwise
$\mathrm{OPDC}_{\mathrm{kt}}^{[s]}$	1 if distribution center k is owned during time period t under scenario s, 0 otherwise
$OPCC_{nt}^{[s]}$	1 if collection center n is owned during time period t under scenario s, 0 otherwise
$OPRC_{rt}^{[s]}$	1 if repair center r is owned during time period t under scenario s, 0 otherwise
PW_m	1 if warehouse m is established, 0 otherwise
PDC_k	1 if distribution center k is established, 0 otherwise
PCC_n	1 if collection center n is established, 0 otherwise
PRC_r	1 if repair center r is established, 0 otherwise
$PW.DC_{mk}$	1 In case of product transfer from warehouse m to distribution center k, 0 otherwise
$PDC.C_{kc}$	1 if product is to be transferred from distribution center k to customer c, 0 otherwise
$PC.CC_{cn}$	1 if product is to be transferred from customer c to collection center n, 0 otherwise
$PCC.RC_{nr}$	1 if product is to be transferred from collection center n to repair center r, 0 otherwise
$\mathrm{PCC.P}_{\mathrm{nj}}$	1 if product is to be transferred from collection center n to plant j, 0 otherwise
$\mathrm{PCC.DPC}_{\mathrm{nl}}$	1 if product is to be transferred from collection center n to disposal center l, 0 otherwise
$\mathrm{PRC.DC}_{\mathrm{rk}}$	1 if product is to be transferred from repair center r to distribution center k, 0 otherwise

Auxiliary variables

$\mathrm{PMT\_LPW}_{\mathrm{mt}}^{[s]}$	The product of $\mathrm{PMT}_{\mathrm{m}}^{[s]}$ and $\mathrm{LPW}_{\mathrm{mt}}^{[s]}$
$\mathrm{PMT}_{\mathrm{LPW1}}{}_{\mathrm{mt}}^{[s]}$	Auxiliary variable for linearization
$\mathrm{PMT\_LPDC}_{\mathrm{kt}}^{[s]}$	The product of $\mathrm{PMT}_{\mathrm{k}}^{[s]}$ and $\mathrm{LPDC}_{\mathrm{kt}}^{[s]}$
$\mathrm{PMT\_LPDC1}_{\mathrm{kt}}^{[s]}$	Auxiliary variable for linearization
$\mathrm{PMT\_LPCC}_{\mathrm{nt}}^{[s]}$	The product of $\mathrm{PMT}_{\mathrm{n}}^{[s]}$ and $\mathrm{LPCC}_{\mathrm{nt}}^{[s]}$
$\mathrm{PMT\_LPCC1}_{\mathrm{nt}}^{[s]}$	Auxiliary variable for linearization
$\mathrm{PMT\_LPRC}_{\mathrm{rt}}^{[s]}$	The product of $\mathrm{PMT}_{\mathrm{r}}^{[s]}$ and $\mathrm{LPRC}_{\mathrm{rt}}^{[s]}$
$\mathrm{PMT\_LPRC1}_{\mathrm{rt}}^{[s]}$	Auxiliary variable for linearization
$\mathrm{PVLP\_LPW}_{\mathrm{mt}}^{[s]}$	The product of $\mathrm{PVLP}_{\mathrm{m}}^{[s]}$ and $\mathrm{LPW}_{\mathrm{mt}}^{[s]}$
$\mathrm{PVLP\_LPW1}_{\mathrm{mt}}^{[s]}$	Auxiliary variable for linearization
$\mathrm{PVLP\_LPDC}_{\mathrm{kt}}^{[s]}$	The product of $\mathrm{PVLP}_{k}^{[s]}$ and $\mathrm{LPDC}_{\mathrm{kt}}^{[s]}$
$\mathrm{PVLP\_LPDC1}_{\mathrm{kt}}^{[s]}$	Auxiliary variable for linearization
$\mathrm{PVLP\_LPCC}_{\mathrm{nt}}^{[s]}$	The product of $\mathrm{PVLP}_{\mathrm{n}}^{[s]}$ and $\mathrm{LPCC}_{\mathrm{nt}}^{[s]}$
$\mathrm{PVLP\_LPCC1}_{\mathrm{nt}}^{[s]}$	Auxiliary variable for linearization
$\mathrm{PVLP\_LPRC}_{\mathrm{rt}}^{[s]}$	The product of $\mathrm{PVLP}_{\mathrm{r}}^{[s]}$ and $\mathrm{LPRC}_{\mathrm{rt}}^{[s]}$
$\mathrm{PVLP\_LPRC1}_{\mathrm{rt}}^{[s]}$	Auxiliary variable for linearization

3.2. The objective functions

$$\mathrm{Obj1} = \max \sum_{t=1}^{\frac{EL}{4}} \sum_{S=1}^{2^{\frac{EL}{4}-1}} \Psi_s * \ [(1 - TR)(\underbrace{\sum_i \sum_c PRICE_{ict}^{[s]} DM_{ict}^{[s]}}_{1} - \underbrace{\sum_i \sum_j C_{ij}^{P} P_{ijt}^{[s]}}_{2} - \underbrace{\sum_i \sum_j \sum_m C_{ijm}^{TR} Q_{1ijmt}^{[s]}}_{3} - \sum_i \underbrace{\sum_m \sum_k C_{imk}^{TR} Q_{2imkt}^{[s]}}_{4} - \sum_i \underbrace{\sum_k \sum_c C_{ikc}^{TR} Q_{3ikct}^{[s]}}_{5} -$$

$$\sum_i \underbrace{\sum_c \sum_n C_{icn}^{TR} Q_{4icnt}^{[s]}}_{6} - \sum_i \underbrace{\sum_n \sum_j C_{inj}^{TR} Q_{6injt}^{[s]}}_{7} - \sum_i \underbrace{\sum_n \sum_r C_{inr}^{TR} Q_{5inrt}^{[s]}}_{8} - \sum_i \underbrace{\sum_n \sum_l C_{inl}^{TR} Q_{7inlt}^{[s]}}_{9} - \sum_i \underbrace{\sum_r \sum_k C_{irk}^{TR} Q_{8irkt}^{[s]}}_{10} -$$

$$\underbrace{\sum_i \sum_m C_{im}^{WH} \sum_j Q_{1ijmt}^{[s]}}_{11} - \sum_i \underbrace{\sum_k C_{ik}^{DH} \sum_m Q_{2imkt}^{[s]}}_{12} -$$

$$\sum_i \underbrace{\sum_j C_{ij}^{I} \frac{(I_{1ijt}^{[s]}+I_{1ij,t-1}^{[s]})}{2}}_{13} - \sum_i \underbrace{\sum_m C_{im}^{I} \frac{(I_{2imt}^{[s]}+I_{2im,t-1}^{[s]})}{2}}_{14} - \sum_i \underbrace{\sum_k C_{ik}^{I} \frac{(I_{3ikt}^{[s]}+I_{3ik,t-1}^{[s]})}{2}}_{15} -$$

$$\sum_i \underbrace{\sum_n C_{in}^{ins} \sum_c Q_{4icnt}^{[s]}}_{16} - \sum_i \underbrace{\sum_r C_{ir}^{rep} \sum_n Q_{5inrt}^{[s]}}_{17} - \sum_i \underbrace{\sum_l C_{il}^{dis} \sum_n Q_{7inlt}^{[s]}}_{18} - \sum_i \underbrace{\sum_j C_{ij}^{rem} \sum_n Q_{6injt}^{[s]}}_{19} -$$

$$\underbrace{\sum_m DR_m C_m^{W} OPW_{mt}^{[s]}}_{20} - \underbrace{\sum_m DR_m PVLP_{1m}^{[s]} LPW_{mt}^{[s]}}_{21} - \underbrace{\sum_k DR_k C_k^{DC} OPDC_{kt}^{[s]}}_{22} - \underbrace{\sum_k DR_k PVLP_{2k}^{[s]} LPDC_{kt}^{[s]}}_{24} -$$

$$\underbrace{\sum_n DR_n C_n^{CC} OPCC_{nt}^{[s]}}_{25} - \underbrace{\sum_n DR_n PVLP_{3n}^{[s]} LPCC_{nt}^{[s]}}_{26} - \underbrace{\sum_r DR_r C_r^{RC} OPRC_{rt}^{[s]}}_{27} - \underbrace{\sum_r DR_r PVLP_{4r}^{[s]} LPRC_{rt}^{[s]}}_{28} -$$

$$\underbrace{\sum_m PMT_{1m}^{[s]} LPW_{mt}^{[s]}}_{29} - \underbrace{\sum_k PMT_{2k}^{[s]} LPDC_{kt}^{[s]}}_{30} - \underbrace{\sum_n PMT_{3n}^{[s]} LPCC_{nt}^{[s]}}_{31} - \underbrace{\sum_r PMT_{4r}^{[s]} LPRC_{rt}^{[s]}}_{32}) + \ +mmm \ +$$

$$\underbrace{\sum_m (FV_{mt}^{[s]} - (1 - TP_t DR_m) C_m^{W})(LPW_{mt}^{[s]} - LPW_{m,t-1}^{[s]})}_{33} + \underbrace{\sum_k (FV_{kt}^{[s]} - (1 - TP_t DR_k) C_k^{DC})(LPDC_{kt}^{[s]} - LPDC_{k,t-1}^{[s]})}_{34} +$$

$$\underbrace{\sum_n (FV_{n*t}^{[s]} - (1 - TP_t DR_n) C_n^{CC})(LPCC_{nt}^{[s]} - LPCC_{n,t-1}^{[s]}) + \sum_r (FV_{rt}^{[s]} - (1 - TP_t DR_r) C_r^{RC})(LPRC_{rt}^{[s]} - LPRC_{r,t-1}^{[s]})]}_{35} \tag{5}$$

The purpose of the proposed model is to maximize the expected value of profit during the planning horizon under different scenarios. The objective function is composed of two parts: Net Operating Profit After Taxes (NOPAT) and the Unearned Profit from SLB (UPSLB). The former and latter are calculated based on the income statement and accounting standards for capital/finance leases, respectively.

To calculate the first part, net sales are calculated by summing the multiplication of products' prices and demands (1). Then, various costs are subtracted and finally, the result is multiplied by $(1 - TR)$ to obtain the net profit after tax for each time period under all scenarios. The costs include: cost of production (2), cost of transportation from plants to warehouses (3), warehouses to distribution centers (4), distribution centers to customers (5), customers to collection centers (6), collection centers to plants (7), collection centers to repair centers (8), collection centers to disposal centers (9) and repair centers to distribution centers (10), internal transfer cost of products in warehouses (11) and distribution centers (12), inventory cost at plants (13), warehouses (14) and distribution centers (15), inspection cost at collection centers (16), repair cost at repair centers (17), disposal cost at disposal centers (18), reproduction cost at plants (19), depreciation cost for both owned warehouses (20) and sold and leased-back ones (21), owned distribution centers (22) and sold and leased-back ones (23), owned collection centers (24) and sold and leased-back ones (25), owned repair services (26) and sold and leased-back ones (27), lease payments for sold and leased back warehouses (28), distribution centers (29), collection centers (30) and repair centers (31).

The depreciation cost is divided into two periods, the period when the asset is owned, and the period when the asset is sold and leased-back. For the owned fixed assets, the depreciation cost is calculated as the product of depreciation rate and establishment/historical cost of them. For the sold and leased back assets, the depreciation cost is calculated as the product of depreciation rate and the present value of minimum lease payments for them. Leasing cost is the minimum lease payments, and annual interest paid is the amount of interest a company pays to serve its loans (Longinidis and Georgiadis, 2014).

As mentioned above, the second part of the first objective function is UPSLB, measured as the difference between the FV and the BV of the fixed asset at the beginning of the SLB transaction. The UPSLB is calculated for warehouses (32), distribution centers (33), collection centers (34) and repair centers (35).

$$\text{Obj2} = \min \sum_{t=1}^{\frac{EL}{4}} \sum_{s=1}^{2^{\frac{EL}{4}-1}} \Psi_s * [\sum_{i.j} \underbrace{M_{ijm} . Q_{1ijmt}^{[s]}}_{1} + \underbrace{\sum_{i.m.k} M_{imk} . Q_{2imkt}^{[s]}}_{2} + \underbrace{\sum_{i.k.c} M_{ikc} . Q_{3ikct}^{[s]}}_{3} + \sum_{i.c.n} \underbrace{M_{icn} . Q_{4icnt}^{[s]}}_{4} +$$

$$\underbrace{\sum_{i.n.j} M_{inj} . Q_{6injt}^{[s]}}_{5} + \underbrace{\sum_{i.n.r} M_{inr} . Q_{5inrt}^{[s]}}_{6} + \underbrace{\sum_{i.n.l} M_{inl} . Q_{7inlt}^{[s]}}_{7} + \underbrace{\sum_{i.r.k} M_{irk} . Q_{8irkt}^{[s]}}_{8} + \sum_{i.j} \underbrace{M_{ij} . P_{ijt}^{[s]}}_{9} + \underbrace{\sum_{i.n.j} M_{ij}^{rem} Q_{6injt}^{[s]}}_{10} \tag{6}$$

The second objective is to minimize the CO_2 emissions produced by the movement of vehicles between centers (expressions 1 to 8) as well as production (expression 9) and reproduction (expression 10) processes.

3.3. Constraints

The constraints of the proposed model can be classified into ten categories as follows.

3.3.1. Constraints pertaining to connecting points

$$\mathrm{PW.DC}_{mk} \leq \mathrm{PW}_m \qquad \forall m \in M, \forall k \in K \qquad (7)$$

$$\mathrm{PW.DC}_{mk} \leq \mathrm{PDC}_k \qquad \forall m \in M, \forall k \in K \qquad (8)$$

$$\mathrm{PDC.C}_{kc} \leq \mathrm{PDC}_k \qquad \forall k \in K, \forall c \in C \qquad (9)$$

$$\mathrm{PC.CC}_{cn} \leq \mathrm{PCC}_n \qquad \forall c \in C, \forall n \in N \qquad (10)$$

$$\mathrm{PCC.RC}_{nr} \leq \mathrm{PCC}_n \qquad \forall n \in N, \forall r \in R \qquad (11)$$

$$\mathrm{PCC.RC}_{nr} \leq \mathrm{PRC}_r \qquad \forall n \in N, \forall r \in R \qquad (12)$$

$$\mathrm{PCC.P}_{nj} \leq \mathrm{PCC}_n \qquad \forall n \in N, \forall j \in J \qquad (13)$$

$$\mathrm{PRC.DC}_{rk} \leq \mathrm{PRC}_r \qquad \forall r \in R, \forall k \in K \qquad (14)$$

$$\mathrm{PRC.DC}_{rk} \leq \mathrm{PDC}_k \qquad \forall r \in R, \forall k \in K \qquad (15)$$

$$\mathrm{PCC.DPC}_{nl} \leq \mathrm{PCC}_n \qquad \forall n \in N, \forall l \in L \qquad (16)$$

Constraints (7) - (16) state that a connection between two points (i.e., distribution centers, warehouses, customers, collection centers, repair centers, plants and disposal centers) is possible only when the related two points are established.

3.3.2. Constraints bounding quantities transferred

$$Q^{[s]}_{1ijmt} \leq Q^{max}_{ijm} \;.\; \mathrm{PW}_m \qquad \forall i \in I, \forall j \in J, \forall m \in M, \forall t \in T, \forall s \in S \qquad (17)$$

$$Q^{[s]}_{2imkt} \leq Q^{max}_{imk} \;.\; \mathrm{PWDC}_{mk} \qquad \forall i \in I, \forall m \in M, \forall k \in K, \forall t \in T, \forall s \in S \qquad (18)$$

$$Q^{[s]}_{3ikct} \leq Q^{max}_{ikc} \;.\; \mathrm{PDCC}_{kc} \qquad \forall i \in I, \forall k \in K, \forall c \in C, \forall t \in T, \forall s \in S \qquad (19)$$

$$Q^{[s]}_{4icnt} \leq Q^{max}_{icn} \;.\; \mathrm{PC.CC}_{cn} \qquad \forall i \in I, \forall c \in C, \forall n \in N, \forall t \in T, \forall s \in S \qquad (20)$$

$$Q^{[s]}_{5inrt} \leq Q^{max}_{inr} \;.\; \mathrm{PCC.RC}_{nr} \qquad \forall i \in I, \forall n \in N, \forall r \in R, \forall t \in T, \forall s \in S \qquad (21)$$

$$Q^{[s]}_{6injt} \leq Q^{max}_{inj} \;.\; \mathrm{PCC.P}_{nj} \qquad \forall i \in I, \forall n \in N, \forall j \in J, \forall t \in T, \forall s \in S \qquad (22)$$

$$Q^{[s]}_{7inlt} \leq Q^{max}_{inl} \;.\; \mathrm{PCC.DPC}_{nl} \qquad \forall i \in I, \forall n \in N, \forall l \in L, \forall t \in T, \forall s \in S \qquad (23)$$

$$Q^{[s]}_{8irkt} \leq Q^{max}_{irk} \;.\mathrm{PRC.DC}_{rk} \qquad \forall i \in I, \forall r \in R, \forall k \in K, \forall t \in T, \forall s \in S \qquad (24)$$

Constraints (17) - (24) ensure that the quantities of products transferred between two echelons are limited to a predefined maximum quantity. Indeed, these constraints apply capacity limitations. Moreover, they ensure that products are transferred between two echelons only when a connection is established between them. The above-mentioned echelons are plants and warehouses (Constraint (17)), warehouses and distribution centers (Constraint (18)), distribution centers and customers (Constraint (19)), customers and collection centers (Constraint (20)), collection centers and repair centers (Constraint (21)), collection centers and plants (Constraint (22)), collection centers and disposal centers (Constraint (23)) and repair centers and distribution centers (Constraint (24)).

$$\textstyle\sum_i Q^{[s]}_{1ijmt} \geq Q^{min}_{jm} \;.\; \mathrm{PW}_m \qquad \forall j \in J, \forall m \in M, \forall t \in T, \forall s \in S \qquad (25)$$

$$\textstyle\sum_i Q^{[s]}_{2imkt} \geq Q^{min}_{mk} \;.\; \mathrm{PWDC}_{mk} \qquad \forall m \in M, \forall k \in K, \forall t \in T, \forall s \in S \qquad (26)$$

$$\textstyle\sum_i Q^{[s]}_{3ikct} \geq Q^{min}_{kc} \;.\; \mathrm{PDCC}_{kc} \qquad \forall k \in K, \forall c \in C, \forall t \in T, \forall s \in S \qquad (27)$$

$$\textstyle\sum_i Q^{[s]}_{4icnt} \geq Q^{min}_{cn} \;.\; \mathrm{PC.CC}_{cn} \qquad \forall c \in C, \forall n \in N, \forall t \in T, \forall s \in S \qquad (28)$$

$$\textstyle\sum_i Q^{[s]}_{5inrt} \geq Q^{min}_{nr} \;.\; \mathrm{PCC.RC}_{nr} \qquad \forall n \in N, \forall r \in R, \forall t \in T, \forall s \in S \qquad (29)$$

$$\textstyle\sum_i Q^{[s]}_{6injt} \geq Q^{min}_{nj} \;.\; \mathrm{PCC.P}_{nj} \qquad \forall n \in N, \forall j \in J, \forall t \in T, \forall s \in S \qquad (30)$$

$$\textstyle\sum_i Q^{[s]}_{7inlt} \geq Q^{min}_{nl} \;.\; \mathrm{PCC.DPC}_{nl} \qquad \forall n \in N, \forall l \in L, \forall t \in T, \forall s \in S \qquad (31)$$

$$\textstyle\sum_i Q^{[s]}_{8irkt} \geq Q^{min}_{rk} \;.\; \mathrm{PRC.DC}_{rk} \qquad \forall r \in R, \forall k \in K, \forall t \in T, \forall s \in S \qquad (32)$$

Constraints (25) - (32) define lower bounds on the quantities of products transferred between two echelons of the supply chain. The lower bounds are defined for plants and warehouses (Constraint (25)), warehouses and distribution centers (Constraint (26)), distribution centers and customers (Constraint (27)), customers and collection centers (Constraint (28)), collection centers and repair centers (Constraint (29)), collection centers and plants (Constraint (30)), collection centers and disposal centers (Constraint (31)) and repair centers and distribution centers (Constraint (32)).

3.3.3. Balance constraints

$$I^{[s]}_{1ijt} = I^{[s]}_{i1j,t-1} + \left(P^{[s]}_{ijt} - \sum_m Q^{[s]}_{1ijmt} + \sum_n Q^{[s]}_{6injt}\right) \qquad \forall i \in I, \forall j \in J, \forall t \in T, \forall s \in S \tag{33}$$

$$I^{[s]}_{2imt} = I^{[s]}_{2im,t-1} + \left(\sum_j Q^{[s]}_{1ijmt} - \sum_k Q^{[s]}_{2imkt}\right) \qquad \forall i \in I, \forall m \in M, \forall t \in T, \forall s \in S \tag{34}$$

$$I^{[s]}_{3ikt} = I^{[s]}_{3ik,t-1} + \left(\sum_m Q^{[s]}_{2imkt} - \sum_c Q^{[s]}_{3ikct} + \sum_r Q^{[s]}_{8irkt}\right) \qquad \forall i \in I, \forall k \in K, \forall t \in T, \forall s \in S \tag{35}$$

$$\sum_k Q^{[s]}_{3ikct} = DM^{[s]}_{ict} \qquad \forall i \in I, \forall c \in C, \forall t \in T, \forall s \in S \tag{36}$$

$$\sum_n Q^{[s]}_{4icnt} = RR^{[s]}_{it}.\ DM^{[s]}_{ict} \qquad \forall i \in I, \forall c \in C, \forall t \in T, \forall s \in S \tag{37}$$

$$\sum_j Q^{[s]}_{6injt} = RM^{[s]}_{it}\ .\ \sum_c Q^{[s]}_{4icnt} \qquad \forall i \in I, \forall n \in N, \forall t \in T, \forall s \in S \tag{38}$$

$$\sum_r Q^{[s]}_{5inrt} = RP^{[s]}_{it}\ .\ \sum_c Q^{[s]}_{4icnt} \qquad \forall i \in I, \forall n \in N, \forall t \in T, \forall s \in S \tag{39}$$

$$\sum_l Q^{[s]}_{7inlt} = \left(RR^{[s]}_{it} - RM^{[s]}_{it} - RP^{[s]}_{it}\right).\sum_c Q^{[s]}_{4icnt} \qquad \forall i \in I, \forall n \in N, \forall t \in T, \forall s \in S \tag{40}$$

$$\sum_j Q^{[s]}_{6injt} + \sum_r Q^{[s]}_{5inrt} + \sum_l Q^{[s]}_{7inlt} = \sum_c Q^{[s]}_{4icnt} \qquad \forall i \in I, \forall n \in N, \forall t \in T, \forall s \in S \tag{41}$$

$$\sum_n Q^{[s]}_{5inrt} = \sum_k Q^{[s]}_{8irkt} \qquad \forall i \in I, \forall r \in R, \forall t \in T, \forall s \in S \tag{42}$$

Constraint (33), (34) and (35) represent inventory balance constraints at plants, warehouses and distribution centers, respectively. Constraint (36) states that the quantity of products transferred from all distribution centers to each customer must be equal to the customer's demand. Constraint (37) guarantees that the quantity of products transferred to all collection centers are proportionate to costumers' demand. Constraint (38) balances between the input amounts of a collection center and the quantity of products transferred from that collection center to all plants. Constraint (39) states that the quantity of products transferred from any collection center to repair centers is equal to the input amounts of that collection center. Constraint (40) assures that the quantity of products transferred from any collection center to disposal centers is proportionate to the input amounts of that collection center. Constraint (41) guarantees that the quantity of products transferred to all plants, repair and disposal centers from any collection center must be equal to the input amounts of that collection center. Constraint (42) states that the total amounts of products transferred from all collection centers to any repair center must be transferred to distribution centers.

3.3.4. Constraints on capacity of facilities

$$P^{min}_{ijt} \leq P^{[s]}_{ijt} \leq P^{max}_{ijt} \qquad \forall i \in I, \forall j \in J, \forall t \in T, \forall s \in S \tag{43}$$

$$\sum_i \rho_{ije}.P^{[s]}_{ijt} \leq R_{je} \qquad \forall j \in J, \forall e \in E, \forall t \in T, \forall s \in S \tag{44}$$

$$W^{min}_m.PW_m \leq W_m \leq W^{max}_m.PW_m \qquad \forall m \in M \tag{45}$$

$$DC^{min}_k.PDC_k \leq DC_k \leq DC^{max}_k.PDC_k \qquad \forall k \in K \tag{46}$$

$$CC^{min}_n.PCC_n \leq CC_n \leq CC^{max}_n.PCC_n \qquad \forall n \in N \tag{47}$$

$$RC^{min}_r.PRC_r \leq RC_r \leq RC^{max}_r\ .PRC_r \qquad \forall r \in R \tag{48}$$

$$\sum_i \gamma_{im}.I^{[s]}_{2imt} \leq W_m \qquad \forall m \in M, \forall t \in T, \forall s \in S \tag{49}$$

$$\sum_i \gamma_{ik}.I^{[s]}_{3ikt} \leq DC_k \qquad \forall k \in K, \forall t \in T, \forall s \in S \tag{50}$$

$$\sum_m Q^{[s]}_{1ijmt} \leq P^{s}_{ijt} \qquad \forall i \in I, \forall j \in J, \forall t \in T, \forall s \in S \tag{51}$$

$$\sum_i \sum_k Q^{[s]}_{2imkt} \leq W_m \qquad \forall m \in M, \forall t \in T, \forall s \in S \tag{52}$$

$$\sum_i \sum_c Q^{[s]}_{3ikct} \leq DC_k \qquad \forall k \in K, \forall t \in T, \forall s \in S \tag{53}$$

$$\sum_i \sum_j Q^{[s]}_{6injt} + \sum_i \sum_r Q^{[s]}_{5inrt} + \sum_i \sum_l Q^{[s]}_{7inlt} \leq CC_n\ .PCC_n \qquad \forall n \in N, \forall t \in T, \forall s \in S \tag{54}$$

$$\sum_i \sum_k Q^{[s]}_{8irkt} \leq RC_r \,.\, PRC_r \qquad \forall r \in R, \forall t \in T, \forall s \in S \qquad (55)$$

Constraint (43) sets lower and upper bounds on the production rate of plants. Constraint (44) restricts the use of shared resources with regard to their associated availability in each plant. Constraint (45), (46), (47) and (48) sets lower and upper bounds on the capacity of warehouses, distribution centers, collection centers and repair centers, respectively. Constraint (49) states that the capacity of a warehouse cannot be less than the total volume of inventory holdings. Constraint (50) guarantees that the capacity of a distribution center cannot be less than the total amount of inventory holdings. Constraint (51) states that the quantities of products transferred from each plant cannot not exceed the production quantity of that product in each time period. Constraint (52) ensures that the quantity of all products transferred from each warehouse cannot exceed the storage capacity. Constraint (53) ensures that the quantity of all products transferred from each distribution center cannot exceed the capacity of the distribution center. Constraint (54) ensures that the quantity of all products transferred from each collection center cannot exceed the capacity of the collection center. Constraint (55) ensures that the quantity of all products transferred from each repair center cannot exceed the capacity of the repair center.

3.3.5. Constraints bounding inventories

$$I^{[s]}_{1ijt} \geq I^{[s],min}_{1ijt} \qquad \forall i \in I, \forall j \in J, \forall t \in T, \forall s \in S \qquad (56)$$

$$I^{[s]}_{2imt} \geq I^{[s],min}_{2imt} . PW_m \qquad \forall i \in I, \forall m \in M, \forall t \in T, \forall s \in S \qquad (57)$$

$$I^{[s]}_{3ikt} \geq I^{[s],min}_{3ikt} . PDC_k \qquad \forall i \in I, \forall k \in K, \forall t \in T, \forall s \in S \qquad (58)$$

$$I^{[s],min}_{1ijt} = \delta_{ij} \,.\, \sum_m Q^{[s]}_{1ijmt} \qquad \forall i \in I, \forall j \in J, \forall t \in T, \forall s \in S \qquad (59)$$

$$I^{[s],min}_{2imt} = \delta_{im} \,.\, \sum_k Q^{[s]}_{2imkt} \qquad \forall i \in I, \forall m \in M, \forall t \in T, \forall s \in S \qquad (60)$$

$$I^{[s],min}_{3ikt} = \delta_{ik} \,.\, \sum_c Q^{[s]}_{3ikct} \qquad \forall i \in I, \forall k \in K, \forall t \in T, \forall s \in S \qquad (61)$$

Constraints (56) – (58) set lower bounds on inventory holdings in plants, warehouses and distribution centers, respectively. Based on constraint (59) – (61), the corresponding lower bounds are determined as a proportion of products delivered by plants, warehouses and distribution centers, respectively.

3.3.6. SLB constraints

$$PW_m = OPW^{[s]}_{mt} + LPW^{[s]}_{mt} \qquad \forall m \in M, \forall t \in T, \forall s \in S \qquad (62)$$

$$PDC_k = OPDC^{[s]}_{kt} + LPDC^{[s]}_{kt} \qquad \forall k \in K, \forall t \in T, \forall s \in S \qquad (63)$$

$$PCC_n = OPCC^{[s]}_{nt} + LPCC^{[s]}_{nt} \qquad \forall n \in N, \forall t \in T, \forall s \in S \qquad (64)$$

$$PRC_r = OPRC^{[s]}_{rt} + LPRC^{[s]}_{rt} \qquad \forall r \in R, \forall t \in T, \forall s \in S \qquad (65)$$

$$LPW^{[s]}_{m,t-1} \leq LPW^{[s]}_{mt} \qquad \forall m \in M, \forall t \in T, \forall s \in S \qquad (66)$$

$$LPDC^{[s]}_{k,t-1} \leq LPDC^{[s]}_{kt} \qquad \forall k \in K, \forall t \in T, \forall s \in S \qquad (67)$$

$$LPCC^{[s]}_{n,t-1} \leq LPCC^{[s]}_{nt} \qquad \forall n \in N, \forall t \in T, \forall s \in S \qquad (68)$$

$$LPRC^{[s]}_{r,t-1} \leq LPRC^{[s]}_{rt} \qquad \forall r \in R, \forall t \in T, \forall s \in S \qquad (69)$$

Constraints (62), (63), (64) and (65) state that established warehouses, distribution centers, collection centers and repair centers should be either owned or sold and leased back at any time period under each scenario, respectively. Constraints (66), (67), (68) and (69) state that when warehouses, distribution centers, collection centers and repair centers are sold and leased back at any time period under each scenario, they cannot be owned again in later time periods.

3.3.7. Simplifying constraints

$$\frac{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{LIBR}_{\mathrm{mt}}^{[\mathrm{s}]}}}{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{IRIL}_{\mathrm{mt}}^{[\mathrm{s}]}}}=\frac{1-(1+LIBR_{mt}^{[s]})^{-\mathrm{T}}\Big/\mathrm{LIBR}_{\mathrm{mt}}^{[\mathrm{s}]}}{1-(1+\mathrm{IRIL}_{\mathrm{mt}}^{[\mathrm{s}]})^{-\mathrm{T}}\Big/\mathrm{IRIL}_{\mathrm{mt}}^{[\mathrm{s}]}} \tag{70}$$

$$\frac{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{LIBR}_{\mathrm{kt}}^{[\mathrm{s}]}}}{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{IRIL}_{\mathrm{mt}}^{[\mathrm{s}]}}}=\frac{1-(1+\mathrm{LIBR}_{\mathrm{kt}}^{[\mathrm{s}]})^{-\mathrm{T}}\Big/\mathrm{LIBR}_{\mathrm{kt}}^{[\mathrm{s}]}}{1-(1+\mathrm{IRIL}_{\mathrm{kt}}^{[\mathrm{s}]})^{-\mathrm{T}}\Big/\mathrm{IRIL}_{\mathrm{kt}}^{[\mathrm{s}]}} \tag{71}$$

$$\frac{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{LIBR}_{\mathrm{nt}}^{[\mathrm{s}]}}}{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{IRIL}_{\mathrm{nt}}^{[\mathrm{s}]}}}=\frac{1-(1+\mathrm{LIBR}_{\mathrm{nt}}^{[\mathrm{s}]})^{-\mathrm{T}}\Big/\mathrm{LIBR}_{\mathrm{nt}}^{[\mathrm{s}]}}{1-(1+\mathrm{IRIL}_{\mathrm{nt}}^{[\mathrm{s}]})^{-\mathrm{T}}\Big/\mathrm{IRIL}_{\mathrm{nt}}^{[\mathrm{s}]}} \tag{72}$$

$$\frac{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{LIBR}_{\mathrm{rt}}^{[\mathrm{s}]}}}{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{IRIL}_{\mathrm{rt}}^{[\mathrm{s}]}}}=\frac{1-(1+\mathrm{LIBR}_{\mathrm{rt}}^{[\mathrm{s}]})^{-\mathrm{T}}\Big/\mathrm{LIBR}_{\mathrm{rt}}^{[\mathrm{s}]}}{1-(1+\mathrm{IRIL}_{\mathrm{rt}}^{[\mathrm{s}]})^{-\mathrm{T}}\Big/\mathrm{IRIL}_{\mathrm{rt}}^{[\mathrm{s}]}} \tag{73}$$

Constraints (70), (71), (72) and (73) calculate some proportions used to simplify other constraints for warehouses, distribution centers, collection centers and repair centers, respectively.

3.3.8. Constraints activating binary variables

$$(\mathrm{LPW}_{\mathrm{mt}}^{[\mathrm{s}]}-\mathrm{LPW}_{\mathrm{m,t-1}}^{[\mathrm{s}]})\Big(1-\frac{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{LIBR}_{\mathrm{mt}}^{[\mathrm{s}]}}}{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{IRIL}_{\mathrm{mt}}^{[\mathrm{s}]}}}\Big)\geq \mathrm{M}(\mathrm{LPW}_{\mathrm{mt}}^{[\mathrm{s}]}-1) \qquad \forall \mathrm{m}\in \mathrm{M}, \forall \mathrm{t}\in \mathrm{T}, \forall \mathrm{s}\in \mathrm{S} \tag{74}$$

$$(\mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}-\mathrm{LPDC}_{\mathrm{k,t-1}}^{[\mathrm{s}]})\Big(1-\frac{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{LIBR}_{\mathrm{kt}}^{[\mathrm{s}]}}}{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{IRIL}_{\mathrm{kt}}^{[\mathrm{s}]}}}\Big)\geq \mathrm{M}(\mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}-1) \qquad \forall \mathrm{k}\in \mathrm{K}, \forall \mathrm{t}\in \mathrm{T}, \forall \mathrm{s}\in \mathrm{S} \tag{75}$$

$$(\mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}-\mathrm{LPCC}_{\mathrm{n,t-1}}^{[\mathrm{s}]})\Big(1-\frac{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{LIBR}_{\mathrm{nt}}^{[\mathrm{s}]}}}{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{IRIL}_{\mathrm{nt}}^{[\mathrm{s}]}}}\Big)\geq \mathrm{M}(\mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}-1) \qquad \forall \mathrm{n}\in \mathrm{N}, \forall \mathrm{t}\in \mathrm{T}, \forall \mathrm{s}\in \mathrm{S} \tag{76}$$

$$(\mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}-\mathrm{LPRC}_{\mathrm{r,t-1}}^{[\mathrm{s}]})\Big(1-\frac{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{LIBR}_{\mathrm{rt}}^{[\mathrm{s}]}}}{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{IRIL}_{\mathrm{rt}}^{[\mathrm{s}]}}}\Big)\geq \mathrm{M}(\mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}-1) \qquad \forall \mathrm{r}\in \mathrm{R}, \forall \mathrm{t}\in \mathrm{T}, \forall \mathrm{s}\in \mathrm{S} \tag{77}$$

Constraints (74), (75), (76) and (77) activate binary variables, if warehouses, distribution centers, collection centers and repair centers are sold and leased back at any time period under each scenario, respectively.

3.3.9. Constraints pertaining to minimum lease payments

$$\mathrm{PMT}_{1\mathrm{m}}^{[\mathrm{s}]}=\sum_{\mathrm{t=1}}^{\mathrm{EL}/4}\Big[\Big(\frac{\mathrm{FV}_{\mathrm{mt}}^{[\mathrm{s}]}}{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{IRIL}_{\mathrm{mt}}^{[\mathrm{s}]}}}\Big)(\mathrm{LPW}_{\mathrm{mt}}^{[\mathrm{s}]}-\mathrm{LPW}_{\mathrm{m,t-1}}^{[\mathrm{s}]})\Big] \qquad \forall \mathrm{m}\in \mathrm{M}, \forall \mathrm{s}\in \mathrm{S} \tag{78}$$

$$\mathrm{PMT}_{2\mathrm{k}}^{[\mathrm{s}]}=\sum_{\mathrm{t=1}}^{\mathrm{EL}/4}\Big[\Big(\frac{\mathrm{FV}_{\mathrm{kt}}^{[\mathrm{s}]}}{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{IRIL}_{\mathrm{kt}}^{[\mathrm{s}]}}}\Big)(\mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}-\mathrm{LPDC}_{\mathrm{k,t-1}}^{[\mathrm{s}]})\Big] \qquad \forall \mathrm{k}\in \mathrm{K}, \forall \mathrm{s}\in \mathrm{S} \tag{79}$$

$$\mathrm{PMT}_{3\mathrm{n}}^{[\mathrm{s}]}=\sum_{\mathrm{t=1}}^{\mathrm{EL}/4}\Big[\Big(\frac{\mathrm{FV}_{\mathrm{nt}}^{[\mathrm{s}]}}{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{IRIL}_{\mathrm{nt}}^{[\mathrm{s}]}}}\Big)(\mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}-\mathrm{LPCC}_{\mathrm{n,t-1}}^{[\mathrm{s}]})\Big] \qquad \forall \mathrm{n}\in \mathrm{N}, \forall \mathrm{s}\in \mathrm{S} \tag{80}$$

$$\mathrm{PMT}_{4\mathrm{r}}^{[\mathrm{s}]}=\sum_{\mathrm{t=1}}^{\mathrm{EL}/4}\Big[\Big(\frac{\mathrm{FV}_{\mathrm{rt}}^{[\mathrm{s}]}}{\mathrm{DF}_{\mathrm{T=EL-t}}^{\mathrm{IRIL}_{\mathrm{rt}}^{[\mathrm{s}]}}}\Big)(\mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}-\mathrm{LPRC}_{\mathrm{r,t-1}}^{[\mathrm{s}]})\Big] \qquad \forall \mathrm{r}\in \mathrm{R}, \forall \mathrm{s}\in \mathrm{S} \tag{81}$$

$$\mathrm{PVLP}_{1m}^{[s]} = \sum_{t=1}^{EL/4}[(\frac{\mathrm{FV}_{mt}^{[s]}}{\mathrm{DF}_{T=EL-t}^{\mathrm{IRIL}_{mt}^{[s]}}})(\mathrm{DF}_{T=EL-t}^{\mathrm{LIBR}_{mt}^{[s]}})(\mathrm{LPW}_{mt}^{[s]} - \mathrm{LPW}_{m,t-1}^{[s]})] \qquad \forall m \in M, \forall s \in S \qquad (82)$$

$$\mathrm{PVLP}_{2k}^{[s]} = \sum_{t=1}^{EL/4}[(\frac{\mathrm{FV}_{kt}^{[s]}}{\mathrm{DF}_{T=EL-t}^{\mathrm{IRIL}_{kt}^{[s]}}})(\mathrm{DF}_{T=EL-t}^{\mathrm{LIBR}_{kt}^{[s]}})(\mathrm{LPDC}_{kt}^{[s]} - \mathrm{LPDC}_{k,t-1}^{[s]})] \qquad \forall k \in K, \forall s \in S \qquad (83)$$

$$\mathrm{PVLP}_{3n}^{[s]} = \sum_{t=1}^{EL/4}[(\frac{\mathrm{FV}_{nt}^{[s]}}{\mathrm{DF}_{T=EL-t}^{\mathrm{IRIL}_{nt}^{[s]}}})(\mathrm{DF}_{T=EL-t}^{\mathrm{LIBR}_{nt}^{[s]}})(\mathrm{LPCC}_{nt}^{[s]} - \mathrm{LPCC}_{n,t-1}^{[s]})] \qquad \forall n \in N, \forall s \in S \qquad (84)$$

$$\mathrm{PVLP}_{4r}^{[s]} = \sum_{t=1}^{EL/4}[(\frac{\mathrm{FV}_{rt}^{[s]}}{\mathrm{DF}_{T=EL-t}^{\mathrm{IRIL}_{rt}^{[s]}}})(\mathrm{DF}_{T=EL-t}^{\mathrm{LIBR}_{rt}^{[s]}})(\mathrm{LPRC}_{rt}^{[s]} - \mathrm{LPRC}_{r,t-1}^{[s]})] \qquad \forall r \in R, \forall s \in S \qquad (85)$$

Constraint (78), (79), (80) and (81) calculate the minimum lease payments for sold and leased back warehouses, distribution centers, collection centers and repair centers under each scenario, respectively. Constraint (82), (83), (84) and (85) calculate the present value of minimum lease payments for sold and leased back warehouses, distribution centers, collection centers and repair centers under each scenario, respectively.

3.3.10. Constraints on CO_2 emissions

$$\mathrm{M}_{ijm}.\,\mathrm{Q}_{1ijmt}^{[s]} \leq \mathrm{M}_{MAX} \qquad i \in I, \forall j \in J, \forall m \in M, \forall t \in T, \forall s \in S \qquad (86)$$

$$\mathrm{M}_{imk}.\,\mathrm{Q}_{2imkt}^{[s]} \leq \mathrm{M}_{MAX} \qquad \forall i \in I, \forall m \in M, \forall k \in K, \forall t \in T, \forall s \in S \qquad (87)$$

$$\mathrm{M}_{ikc}.\,\mathrm{Q}_{3ikct}^{[s]} \leq \mathrm{M}_{MAX} \qquad \forall i \in I, \forall k \in K, \forall c \in C, \forall t \in T, \forall s \in S \qquad (88)$$

$$\mathrm{M}_{icn}.\,\mathrm{Q}_{4icnt}^{[s]} \leq \mathrm{M}_{MAX} \qquad \forall i \in I, \forall c \in C, \forall n \in N, \forall t \in T, \forall s \in S \qquad (89)$$

$$\mathrm{M}_{inr}.\,\mathrm{Q}_{5inrt}^{[s]} \leq \mathrm{M}_{MAX} \qquad \forall i \in I, \forall n \in N, \forall r \in R, \forall t \in T, \forall s \in S \qquad (90)$$

$$\mathrm{M}_{inj}.\,\mathrm{Q}_{6injt}^{[s]} \leq \mathrm{M}_{MAX} \qquad \forall i \in I, \forall n \in N, \forall j \in J, \forall t \in T, \forall s \in S \qquad (91)$$

$$\mathrm{M}_{inl}.\,\mathrm{Q}_{7inlt}^{[s]} \leq \mathrm{M}_{MAX} \qquad \forall i \in I, \forall n \in N, \forall l \in L, \forall t \in T, \forall s \in S \qquad (92)$$

$$\mathrm{M}_{irk}.\,\mathrm{Q}_{8irkt}^{[s]} \leq \mathrm{M}_{MAX} \qquad \forall i \in I, \forall r \in R, \forall k \in K, \forall t \in T, \forall s \in S \qquad (93)$$

$$\mathrm{M}_{ij}.\,\mathrm{P}_{ijt}^{[s]} \leq \mathrm{M}_{MAX} \qquad \forall i \in I, \forall j \in J, \forall t \in T, \forall s \in S \qquad (94)$$

$$\sum_{n} \mathrm{M}_{ij}^{rem}\mathrm{Q}_{6injt}^{[s]} \leq \mathrm{M}_{MAX} \qquad \forall i \in I, \forall j \in J, \forall t \in T, \forall s \in S \qquad (95)$$

Constraint (86) - (93) guarantees that the amount of CO_2 emissions due to the transportation between any two points (plant and warehouse, warehouse and distribution center, distribution center and customer, customer and collection center, collection center and plant, collection center and repair center, collection center and disposal center, repair center and distribution center) does not exceed the maximum allowable amount. Constraints (94) and (95) ensure that CO_2 emissions do not exceed the maximum allowable amounts.

3.4. Linearization of the proposed nonlinear formulation

The proposed mathematical formulation includes several terms, formed by multiplication of continuous and binary variables in the first objective function, which makes the model nonlinear. To linearize the expression ($\mathrm{PVLP}_{m}^{[s]}\mathrm{LPW}_{mt}^{[s]}$), two new nonnegative variables $\mathrm{PVLP\_LPW}_{mt}^{[s]}$ and $\mathrm{PVLP\_LPW1}_{mt}^{[s]}$ and constraints (96), (97), (98) and (99) are defined.

$$\mathrm{PVLP\_LPW}_{mt}^{[s]} + \mathrm{PVLP\_LPW1}_{mt}^{[s]} = \mathrm{PVLP}_{1m}^{[s]} \qquad \forall m \in M, \forall t \in T, \forall s \in S \qquad (96)$$

$$\mathrm{PVLP\_LPW}_{mt}^{[s]} \leq \mathrm{LPW}_{mt}^{[s]} * U \qquad \forall m \in M, \forall t \in T, \forall s \in S \qquad (97)$$

$$\mathrm{PVLP\_LPW1}_{mt}^{[s]} \leq (1 - \mathrm{LPW}_{mt}^{[s]}) * U \qquad \forall m \in M, \forall t \in T, \forall s \in S \qquad (98)$$

$$\mathrm{PVLP\_LPW}_{mt}^{[s]}, \mathrm{PVLP\_LPW1}_{mt}^{[s]} \geq 0 \qquad \forall m \in M, \forall t \in T, \forall s \in S \qquad (99)$$

The above constraints indicate that if $\mathrm{LPW}_{\mathrm{mt}}^{[\mathrm{s}]}$ is equal to zero, $\mathrm{PVLP\_LPW}_{\mathrm{mt}}^{[\mathrm{s}]}$ will be zero. On the contrary, if $\mathrm{LPW}_{\mathrm{mt}}^{[\mathrm{s}]}$ is equal to one, $\mathrm{PVLP\_LPW1}_{\mathrm{mt}}^{[\mathrm{s}]}$ will be zero. Considering constraint (96), $\mathrm{PVLP\_LPW}_{\mathrm{mt}}^{[\mathrm{s}]}$ will be an equivalent value for the product of $\mathrm{PVLP}_{1\mathrm{m}}^{[\mathrm{s}]}$ and $\mathrm{LPW}_{\mathrm{mt}}^{[\mathrm{s}]}$.

To linearize the expression ($\mathrm{PVLP}_{2\mathrm{k}}^{[\mathrm{s}]}\mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}$), two new nonnegative variables $\mathrm{PVLP\_LPDC}_{kt}^{[s]}$ and $\mathrm{PVLP\_LPDC1}_{\mathrm{Kt}}^{[\mathrm{s}]}$ are introduced, and constraints (100), (101), (102) and (103) are defined.

$$\mathrm{PVLP\_LPDC}_{\mathrm{kt}}^{[\mathrm{s}]} + \mathrm{PVLP\_LPDC1}_{\mathrm{kt}}^{[\mathrm{s}]} = \mathrm{PVLP}_{2\mathrm{k}}^{[\mathrm{s}]} \qquad \forall \mathrm{k} \in \mathrm{K}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{100}$$

$$\mathrm{PVLP\_LP}DC_{\mathrm{kt}}^{[\mathrm{s}]} \leq \mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]} * \mathrm{U} \qquad \forall \mathrm{k} \in K, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{101}$$

$$\mathrm{PVLP\_LPDC1}_{\mathrm{kt}}^{[\mathrm{s}]} \leq (1 - \mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}) * \mathrm{U} \qquad \forall \mathrm{k} \in \mathrm{K}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{102}$$

$$\mathrm{PVLP\_LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}, \mathrm{PVLP\_LPDC1}_{\mathrm{kt}}^{[\mathrm{s}]} \geq 0 \qquad \forall \mathrm{k} \in \mathrm{K}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{103}$$

These constraints indicate that if $\mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}$ is equal to zero, $\mathrm{PVLP\_LP}DC_{\mathrm{kt}}^{[\mathrm{s}]}$ will be zero. On the contrary, if $\mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}$ is equal to one, $\mathrm{PVLP\_LPDC1}_{\mathrm{kt}}^{[\mathrm{s}]}$ will be zero. Considering constraint (100), $\mathrm{PVLP\_LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}$ will be an equivalent value for the product of $\mathrm{PVLP}_{2\mathrm{k}}^{[\mathrm{s}]}$ and $\mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}$.

To linearize the expression ($\mathrm{PVLP}_{3n}^{[\mathrm{s}]}\mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}$), two new nonnegative variables $\mathrm{PVLP\_LPCC}_{nt}^{[s]}$ and $\mathrm{PVLP\_LPCC1}_{\mathrm{nt}}^{[\mathrm{s}]}$ are introduced, and constraints (104), (105), (106) and (107) are defined.

$$\mathrm{PVLP\_LPCC}_{\mathrm{nt}}^{[\mathrm{s}]} + \mathrm{PVLP\_LPCC1}_{\mathrm{nt}}^{[\mathrm{s}]} = \mathrm{PVLP}_{3\mathrm{n}}^{[\mathrm{s}]} \qquad \forall \mathrm{n} \in \mathrm{N}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{104}$$

$$\mathrm{PVLP\_LP}CC_{\mathrm{nt}}^{[\mathrm{s}]} \leq \mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]} * \mathrm{U} \qquad \forall \mathrm{n} \in N, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{105}$$

$$\mathrm{PVLP\_LPCC1}_{\mathrm{nt}}^{[\mathrm{s}]} \leq (1 - \mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}) * \mathrm{U} \qquad \forall \mathrm{n} \in \mathrm{N}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{106}$$

$$\mathrm{PVLP\_LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}, \mathrm{PVLP\_LPCC1}_{\mathrm{nt}}^{[\mathrm{s}]} \geq 0 \qquad \forall \mathrm{n} \in \mathrm{N}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{107}$$

These constraints indicate that if $\mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}$ is equal to zero, $\mathrm{PVLP\_LP}CC_{\mathrm{nt}}^{[\mathrm{s}]}$ will be zero. On the contrary, if $\mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}$ is equal to one, $\mathrm{PVLP\_LPCC1}_{\mathrm{nt}}^{[\mathrm{s}]}$ will be zero. Considering constraint (104), $\mathrm{PVLP\_LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}$ will be an equivalent value for the product of $\mathrm{PVLP}_{3n}^{[\mathrm{s}]}$ and $\mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}$.

To linearize the expression ($\mathrm{PVLP}_{4r}^{[\mathrm{s}]}\mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}$), two new nonnegative variables $\mathrm{PVLP\_LPRC}_{rt}^{[s]}$ and $\mathrm{PVLP\_LPRC1}_{\mathrm{rt}}^{[\mathrm{s}]}$ are introduced, and constraints (108), (109), (110) and (111) are defined.

$$\mathrm{PVLP\_LPRC}_{\mathrm{rt}}^{[\mathrm{s}]} + \mathrm{PVLP\_LPRC1}_{\mathrm{rt}}^{[\mathrm{s}]} = \mathrm{PVLP}_{4r}^{[\mathrm{s}]} \qquad \forall \mathrm{r} \in \mathrm{R}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{108}$$

$$\mathrm{PVLP\_LP}RC_{\mathrm{rt}}^{[\mathrm{s}]} \leq \mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]} * \mathrm{U} \qquad \forall \mathrm{r} \in R, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{109}$$

$$\mathrm{PVLP\_LPRC1}_{\mathrm{rt}}^{[\mathrm{s}]} \leq (1 - \mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}) * \mathrm{U} \qquad \forall \mathrm{r} \in \mathrm{R}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{110}$$

$$\mathrm{PVLP\_LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}, \mathrm{PVLP\_LPRC1}_{\mathrm{rt}}^{[\mathrm{s}]} \geq 0 \qquad \forall \mathrm{r} \in \mathrm{R}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{111}$$

These constraints indicate that if $\mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}$ is equal to zero, $\mathrm{PVLP\_LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}$ will be zero. On the contrary, if $\mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}$ is equal to one, $\mathrm{PVLP\_LPRC1}_{\mathrm{rt}}^{[\mathrm{s}]}$ will be zero. Considering constraint (108), $\mathrm{PVLP\_LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}$ will be an equivalent value for the product of $\mathrm{PVLP}_{4r}^{[\mathrm{s}]}$ and $\mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}$.

To linearize the expression ($\mathrm{PMT}_{1\mathrm{m}}^{[\mathrm{s}]}\mathrm{LPW}_{\mathrm{mt}}^{[\mathrm{s}]}$), two new nonnegative variables $\mathrm{PMT\_LPW}_{mt}^{[s]}$ and $\mathrm{PMT\_LPW1}_{\mathrm{mt}}^{[\mathrm{s}]}$ are introduced, and constraints (112), (113), (114) and (115) are defined.

$$\mathrm{PMT\_LPW}_{\mathrm{mt}}^{[\mathrm{s}]} + \mathrm{PMT\_LPW1}_{\mathrm{mt}}^{[\mathrm{s}]} = \mathrm{PMT}_{1\mathrm{m}}^{[\mathrm{s}]} \qquad \forall \mathrm{m} \in \mathrm{M}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \tag{112}$$

$$\mathrm{PMT\_LPW}_{\mathrm{mt}}^{[\mathrm{s}]} \leq \mathrm{LPW}_{\mathrm{mt}}^{[\mathrm{s}]} * \mathrm{U} \qquad \forall \mathrm{m} \in \mathrm{M}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (113)$$

$$\mathrm{PMT\_LPW1}_{\mathrm{mt}}^{[\mathrm{s}]} \leq (1 - \mathrm{LPW}_{\mathrm{mt}}^{[\mathrm{s}]}) * \mathrm{U} \qquad \forall \mathrm{m} \in \mathrm{M}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (114)$$

$$\mathrm{PMT\_LPW}_{\mathrm{mt}}^{[\mathrm{s}]}, \mathrm{PMT\_LPW1}_{\mathrm{mt}}^{[\mathrm{s}]} \geq 0 \qquad \forall \mathrm{m} \in \mathrm{M}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (115)$$

These constraints indicate that if $\mathrm{LPW}_{\mathrm{mt}}^{[\mathrm{s}]}$ is equal to zero, $\mathrm{PMT\_LPW}_{\mathrm{mt}}^{[\mathrm{s}]}$ will be zero. On the contrary, if $\mathrm{LPW}_{\mathrm{mt}}^{[\mathrm{s}]}$ is one, $\mathrm{PMT\_LPW1}_{\mathrm{mt}}^{[\mathrm{s}]}$ will be zero. Considering constraint (112), $\mathrm{PMT\_LPW}_{\mathrm{mt}}^{[\mathrm{s}]}$ will be an equivalent value for the product of $\mathrm{PMT}_{1\mathrm{m}}^{[\mathrm{s}]}$ and $\mathrm{LPW}_{\mathrm{mt}}^{[\mathrm{s}]}$.

To linearize the expression ($\mathrm{PMT}_{2\mathrm{k}}^{[\mathrm{s}]}\mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}$), two new nonnegative variables $\mathrm{PMT\_LPDC}_{kt}^{[s]}$ and $\mathrm{PMT\_LPDC1}_{\mathrm{Kt}}^{[\mathrm{s}]}$ are introduced, and constraints (116), (117), (118) and (119) are defined.

$$\mathrm{PMT\_LPDC}_{\mathrm{kt}}^{[\mathrm{s}]} + \mathrm{PMT\_LPDC1}_{\mathrm{kt}}^{[\mathrm{s}]} = \mathrm{PMT}_{2\mathrm{k}}^{[\mathrm{s}]} \qquad \forall \mathrm{k} \in \mathrm{K}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (116)$$

$$\mathrm{PMT\_LP}DC_{\mathrm{kt}}^{[\mathrm{s}]} \leq \mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]} * \mathrm{U} \qquad \forall \mathrm{k} \in K, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (117)$$

$$\mathrm{PMT\_LPDC1}_{\mathrm{kt}}^{[\mathrm{s}]} \leq (1 - \mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}) * \mathrm{U} \qquad \forall \mathrm{k} \in \mathrm{K}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (118)$$

$$\mathrm{PMT\_LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}, \mathrm{PMT\_LPDC1}_{\mathrm{kt}}^{[\mathrm{s}]} \geq 0 \qquad \forall \mathrm{k} \in \mathrm{K}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (119)$$

These constraints indicate that if $\mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}$ is equal to zero, $\mathrm{PMT\_LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}$ will be zero. On the contrary, if $\mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}$ is equal to one, $\mathrm{PMT\_LPDC1}_{\mathrm{kt}}^{[\mathrm{s}]}$ will be zero. Considering constraint (116), $\mathrm{PMT\_LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}$ will be an equivalent value for the product of $\mathrm{PMT}_{2\mathrm{k}}^{[\mathrm{s}]}$ and $\mathrm{LPDC}_{\mathrm{kt}}^{[\mathrm{s}]}$.

To linearize the expression ($\mathrm{PMT}_{3n}^{[\mathrm{s}]}\mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}$), two new nonnegative variables $\mathrm{PMT\_LPCC}_{nt}^{[s]}$ and $\mathrm{PMT\_LPCC1}_{\mathrm{nt}}^{[\mathrm{s}]}$ are introduced, and constraints (120), (121), (122) and (123) are defined.

$$\mathrm{PMT\_LPCC}_{\mathrm{nt}}^{[\mathrm{s}]} + \mathrm{PMT\_LPCC1}_{\mathrm{nt}}^{[\mathrm{s}]} = \mathrm{PMT}_{3\mathrm{n}}^{[\mathrm{s}]} \qquad \forall \mathrm{n} \in \mathrm{N}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (120)$$

$$\mathrm{PMT\_LPCC}_{\mathrm{nt}}^{[\mathrm{s}]} \leq \mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]} * \mathrm{U} \qquad \forall \mathrm{n} \in N, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (121)$$

$$\mathrm{PMT\_LPCC1}_{\mathrm{nt}}^{[\mathrm{s}]} \leq (1 - \mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}) * \mathrm{U} \qquad \forall \mathrm{n} \in \mathrm{N}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (122)$$

$$\mathrm{PMT\_LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}, \mathrm{PMT\_LPCC1}_{\mathrm{nt}}^{[\mathrm{s}]} \geq 0 \qquad \forall \mathrm{n} \in \mathrm{N}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (123)$$

These constraints indicate that if $\mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}$ is equal to zero, $\mathrm{PMT\_LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}$ will be zero. On the contrary, if $\mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}$ is equal to one, $\mathrm{PMT\_LPCC1}_{\mathrm{nt}}^{[\mathrm{s}]}$ will be zero. Considering constraint (120), $\mathrm{PMT\_LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}$ will be an equivalent value for the product of $\mathrm{PMT}_{3n}^{[\mathrm{s}]}$ and $\mathrm{LPCC}_{\mathrm{nt}}^{[\mathrm{s}]}$.

To linearize the expression ($\mathrm{PMT}_{4\mathrm{r}}^{[\mathrm{s}]}\mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}$), two new nonnegative variables $\mathrm{PMT\_LPRC}_{rt}^{[s]}$ and $\mathrm{PMT\_LPRC1}_{\mathrm{rt}}^{[\mathrm{s}]}$ are introduced, and constraints (124), (125), (126) and (127) are defined.

$$\mathrm{PMT\_LPRC}_{\mathrm{rt}}^{[\mathrm{s}]} + \mathrm{PMT\_LPRC1}_{\mathrm{rt}}^{[\mathrm{s}]} = \mathrm{PMT}_{4r}^{[\mathrm{s}]} \qquad \forall \mathrm{r} \in \mathrm{R}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (124)$$

$$\mathrm{PMT\_LPRC}_{\mathrm{rt}}^{[\mathrm{s}]} \leq \mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]} * \mathrm{U} \qquad \forall \mathrm{r} \in R, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (125)$$

$$\mathrm{PMT\_LPRC1}_{\mathrm{rt}}^{[\mathrm{s}]} \leq (1 - \mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}) * \mathrm{U} \qquad \forall \mathrm{r} \in \mathrm{R}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (126)$$

$$\mathrm{PMT\_LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}, \mathrm{PMT\_LPRC1}_{\mathrm{rt}}^{[\mathrm{s}]} \geq 0 \qquad \forall \mathrm{r} \in \mathrm{R}, \forall \mathrm{t} \in \mathrm{T}, \forall \mathrm{s} \in \mathrm{S} \qquad (127)$$

These constraints indicate that if $\mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}$ is equal to zero, $\mathrm{PMT\_LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}$ will be zero. On the contrary, if $\mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}$ is equal to one, $\mathrm{PMT\_LPRC1}_{\mathrm{rt}}^{[\mathrm{s}]}$ will be zero. Considering constraint (124), $\mathrm{PMT\_LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}$ will be an equivalent value for the product of $\mathrm{PMT}_{4r}^{[\mathrm{s}]}$ and $\mathrm{LPRC}_{\mathrm{rt}}^{[\mathrm{s}]}$.

$$\mathrm{W_m}, \mathrm{DC_k}, \mathrm{CC_n}, \mathrm{RC_r}, \mathrm{Q_{1ijmt}^{[s]}}, \mathrm{Q_{2imkt}^{[s]}}, \mathrm{Q_{3ikct}^{[s]}}, \mathrm{Q_{4icnt}^{[s]}}, \mathrm{Q_{5inrt}^{[s]}}, \mathrm{Q_{6injt}^{[s]}}, \mathrm{Q_{7inlt}^{[s]}}, \mathrm{Q_{8irkt}^{[s]}}, \mathrm{P_{ijt}^{[s]}}, \mathrm{I_{1ijt}^{[s]}}, \mathrm{I_{2imt}^{[s]}}, \mathrm{I_{3ikt}^{[s]}}, \mathrm{PMT_{1m}^{[s]}}, \mathrm{PMT_{2k}^{[s]}}, \mathrm{PMT_{3n}^{[s]}}, \mathrm{PMT_{4r}^{[s]}}, \mathrm{PVLP_{1m}^{[s]}}, \mathrm{PVLP_{2k}^{[s]}}, \mathrm{PVLP_{3n}^{[s]}}, \mathrm{PVLP_{4r}^{[s]}}) \geq 0 \qquad \forall \mathrm{i, j, m, k, n, r, l, t, s} \tag{128}$$

$$\mathrm{LPW_{mt}^{[s]}}, \mathrm{LPDC_{kt}^{[s]}}, \mathrm{LPCC_{nt}^{[s]}}, \mathrm{LPRC_{rt}^{[s]}}, \mathrm{OPW_{mt}^{[s]}}, \mathrm{OPDC_{kt}^{[s]}}, \mathrm{OPCC_{nt}^{[s]}}, \mathrm{OPRC_{rt}^{[s]}}, \mathrm{PW_m}, \mathrm{PDC_k}, \mathrm{PCC_n}, \mathrm{PRC_r}, \mathrm{PWDC_{mk}}, \mathrm{PDC.\,C_{kc}}, \mathrm{PC.\,CC_{cn}}, \mathrm{PCC.\,RC_{nr}}, \mathrm{PCC.\,P_{nj}}, \mathrm{PCC.\,DPC_{nl}}, \mathrm{PRC.\,DC_{rk}}) \epsilon \{0,1\} \qquad \forall \mathrm{j, m, k, n, r, l, t, s} \tag{129}$$

Constraints (128) and (129) define nonnegative and binary variables. Finally, the linearized version of the first objective function is represented by (130).

$$\mathrm{Obj1}^* = \max \sum_{t=1}^{\frac{EL}{4}} \sum_{S=1}^{2^{\frac{EL}{4}-1}} \Psi_s * \Big[(1-TR)\Big(\sum_i \sum_c PRICE_{ict}^{[s]} DM_{ict}^{[s]} - \sum_i \sum_j C_{ij}^{P} P_{ijt}^{[s]} - \sum_i \sum_j \sum_m C_{ijm}^{TR} Q_{1ijmt}^{[s]} - \sum_i \sum_m \sum_k C_{imk}^{TR} Q_{2imkt}^{[s]} - \sum_i \sum_k \sum_c C_{ikc}^{TR} Q_{3ikct}^{[s]} - \sum_i \sum_c \sum_n C_{icn}^{TR} Q_{4icnt}^{[s]} - \sum_i \sum_n \sum_j C_{inj}^{TR} Q_{6injt}^{[s]} - \sum_i \sum_n \sum_r C_{inr}^{TR} Q_{5inrt}^{[s]} - \sum_i \sum_n \sum_l C_{inl}^{TR} Q_{7inlt}^{[s]} - \sum_i \sum_r \sum_k C_{irk}^{TR} Q_{8irkt}^{[s]} - \sum_i \sum_m C_{im}^{WH} \sum_j Q_{1ijmt}^{[s]} - \sum_i \sum_k C_{ik}^{DH} \sum_m Q_{2imkt}^{[s]} - \sum_i \sum_j C_{ij}^{I} \frac{(I_{1ijt}^{[s]} + I_{1ij,t-1}^{[s]})}{2} - \sum_i \sum_m C_{im}^{I} \frac{(I_{2imt}^{[s]} + I_{2im,t-1}^{[s]})}{2} - \sum_i \sum_k C_{ik}^{I} \frac{(I_{3ikt}^{[s]} + I_{3ik,t-1}^{[s]})}{2} - \sum_i \sum_n C_{in}^{ins} \sum_c Q_{4icnt}^{[s]} - \sum_i \sum_r C_{ir}^{rep} \sum_n Q_{5inrt}^{[s]} - \sum_i \sum_l C_{il}^{dis} \sum_n Q_{7inlt}^{[s]} - \sum_i \sum_j C_{ij}^{rem} \sum_n Q6_{injt}^{[s]} - \sum_m DR_m C_m^{W} OPW_{mt}^{[s]} - \sum_m DR_m PVLP\_LPW_{mt}^{[s]} - \sum_k DR_k C_k^{DC} OPDC_{kt}^{[s]} - \sum_k DR_k PVLP\_LPDC_{kt}^{[s]} - \sum_n DR_n C_n^{CC} OPCC_{nt}^{[s]} - \sum_n DR_n PVLP\_LPCC_{nt}^{[s]} - \sum_r DR_r C_r^{RC} OPRC_{rt}^{[s]} - \sum_r DR_r PVLP\_LPRC_{rt}^{[s]} - \sum_m PMT\_LPW_{mt}^{[s]} - \sum_k PMT\_LPDC_{kt}^{[s]} - \sum_n PMT\_LPCC_{nt}^{[s]} - \sum_r PMT\_LPRC_{rt}^{[s]}\Big) + \sum_m (FV_{mt}^{[s]} - (1 - TP_t DR_m) C_m^{W})(LPW_{mt}^{[s]} - LPW_{m,t-1}^{[s]}) + \sum_k (FV_{kt}^{[s]} - (1 - TP_t DR_k) C_k^{DC})(LPDC_{kt}^{[s]} - LPDC_{k,t-1}^{[s]}) + \sum_n (FV_{nt}^{[s]} - (1 - TP_t DR_n) C_n^{CC})(LPCC_{nt}^{[s]} - LPCC_{n,t-1}^{[s]}) + \sum_r (FV_{rt}^{[s]} - (1 - TP_t DR_r) C_r^{RC})(LPRC_{rt}^{[s]} - LPRC_{r,t-1}^{[s]})\Big] \tag{130}$$

The above linear reformulation results in a MILP model with more constraints and variables, however removes all non-linearities from initial MINLP model. The new MILP model is more tractable and can be solved very effectively to find global optimum even for large-scale instances.

4. Computational results

4.1. Solving the single-objective optimization model

In this section, the proposed model is solved, and computational results are reported and analyzed. In order to demonstrate the impact of SLB, the results are compared with those of the model in which SLB is not considered. Then, a sensitivity analysis of parameters is performed. In this regard, the parameter values are obtained from (Longinidis and Georgiadis, 2014). In this numerical example, eight products are produced by two plants, using four common production resources. These products are delivered to customers by three potential warehouses and four potential distribution centers. In addition, eight customers are considered, and the returned products are collected by three potential collection centers. Then, the repairable products are sent to three potential repair centers. Moreover, defective products are shipped to two destruction centers. The economic life of all potential centers is 16 years. The planning horizon is considered to include four one−year time periods. Table 1 lists the costs directly attributed to the products, including shipping costs between centers, transfer, inventory, production, reproduction, inspection, repair and destruction costs. In addition, Table 1 shows the maximum and minimum production, resource utilization rate and return rate per product. The total available resource is 150,000 units per year.

The probability distributions of parameters related to the price of each product for each customer and the demand of each customer under each scenario are presented in Table 2.

Table 1. The maximum and minimum production, resource utilization rate and return rate per product

	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$	$i = 6$	$i = 7$	$i = 8$
$\mathrm{C}^{\mathrm{TR}}_{\mathrm{ijm}}$	0.62	0.55	0.53	0.55	0.58	0.53	0.58	0.57
$\mathrm{C}^{\mathrm{TR}}_{\mathrm{imk}}$	0.62	0.56	0.56	0.56	0.58	0.56	0.59	0.58
$\mathrm{C}^{\mathrm{TR}}_{\mathrm{ikc}}$	0.77	0.75	0.75	0.75	0.75	0.75	0.75	0.76
$\mathrm{C}^{\mathrm{TR}}_{\mathrm{icn}}$	0.45	0.44	0.43	0.43	0.42	0.47	0.41	0.44
$\mathrm{C}^{\mathrm{TR}}_{\mathrm{inj}}$	0.85	0.84	0.83	0.83	0.82	0.84	0.81	0.89
$\mathrm{C}^{\mathrm{TR}}_{\mathrm{inr}}$	0.64	0.61	0.59	0.6	0.64	0.68	0.59	0.6
$\mathrm{C}^{\mathrm{TR}}_{\mathrm{inl}}$	0.45	0.42	0.43	0.43	0.42	0.43	0.41	0.44
$\mathrm{C}^{\mathrm{TR}}_{\mathrm{irk}}$	0.57	0.55	0.53	0.52	0.57	0.55	0.53	0.52
$\mathrm{C}^{\mathrm{WH}}_{\mathrm{im}}$	0.52	0.53	0.53	0.48	0.37	0.46	0.83	0.77
$\mathrm{C}^{\mathrm{DH}}_{\mathrm{ik}}$	0.59	0.61	0.56	0.66	0.7	0.63	0.6	0.79
$\mathrm{C}^{\mathrm{P}}_{\mathrm{ij}}$	2.88	3.00	3.03	2.68	2.65	2.85	2.68	2.55
$\mathrm{C}^{\mathrm{rem}}_{\mathrm{ij}}$	0.5	0.6	0.61	0.48	0.5	0.54	0.58	0.56
$\mathrm{C}^{\mathrm{rep}}_{\mathrm{ir}}$	0.4	0.45	0.41	0.39	0.41	0.38	0.44	0.42
$\mathrm{C}^{\mathrm{dis}}_{\mathrm{il}}$	0.32	0.33	0.34	0.3	0.35	0.36	0.32	0.31
$\mathrm{C}^{\mathrm{ins}}_{\mathrm{in}}$	0.29	0.3	0.31	0.27	0.29	0.24	0.26	0.3
$\mathrm{C}^{\mathrm{I}}_{\mathrm{ij}}$	0.39	0.26	0.25	0.29	0.29	0.48	0.25	0.2
$\mathrm{C}^{\mathrm{I}}_{\mathrm{im}}$	0.39	0.42	0.33	0.47	0.4	0.45	0.38	0.47
$\mathrm{C}^{\mathrm{I}}_{\mathrm{ik}}$	0.44	0.38	0.41	0.45	0.38	0.37	0.44	0.44
$\mathrm{P}^{\mathrm{max}}_{\mathrm{ijt}}$	2625	2725	2850	2350	2850	2850	2425	2950
$\mathrm{RD}_{\mathrm{it}}$	0.05	0.1	0.05	0.1	0.05	0.1	0.05	0.1
$\mathrm{RM}_{\mathrm{it}}$	0.1	0.05	0.1	0.05	0.1	0.05	0.1	0.05
$\mathrm{RP}_{\mathrm{it}}$	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
$\mathrm{RR}_{\mathrm{it}}$	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
ρ_{ije}	0.019	0.024	0.043	0.054	0.048	0.048	0.035	0.054

Table 2. Fair value, implied interest rate, lessee's incremental borrowing rate and capacities

$FV^{[s]}_{mt}$	[36000,49000]	$\mathrm{C}^{\mathrm{w}}_{\mathrm{m}}$	[37000,43000]
$FV^{[s]}_{kt}$	[35000,49000]	$\mathrm{C}^{\mathrm{DC}}_{\mathrm{k}}$	[37000,45000]
$FV^{[s]}_{nt}$	[35000,42000]	$\mathrm{C}^{\mathrm{CC}}_{\mathrm{n}}$	[29000,32000]
$FV^{[s]}_{rt}$	[35000,40000]	$\mathrm{C}^{\mathrm{RC}}_{\mathrm{r}}$	[28000,29000]
$LIBR^{[s]}_{\mathrm{mt}}$	[0.05,0.08]	$\mathrm{W}^{\mathrm{max}}_{\mathrm{m}}$	[16000,20000]
$LIBR^{[s]}_{\mathrm{kt}}$	[0.05,0.08]	$\mathrm{W}^{\mathrm{min}}_{\mathrm{m}}$	[1900,2500]
$LIBR^{[s]}_{\mathrm{nt}}$	[0.05,0.07]	$\mathrm{DC}^{\mathrm{max}}_{\mathrm{k}}$	[20000,27000]
$LIBR^{[s]}_{\mathrm{rt}}$	[0.04,0.07]	$\mathrm{DC}^{\mathrm{min}}_{\mathrm{k}}$	[1100,1900]
$IRIL^{[s]}_{\mathrm{mt}}$	[0.05,0.07]	$\mathrm{CC}^{\mathrm{max}}_{\mathrm{n}}$	[15000,20000]
$IRIL^{[s]}_{\mathrm{kt}}$	[0.05,0.08]	$\mathrm{CC}^{\mathrm{min}}_{\mathrm{n}}$	[900,1100]
$IRIL^{[s]}_{\mathrm{nt}}$	[0.05,0.07]	$\mathrm{RC}^{\mathrm{max}}_{\mathrm{r}}$	[12000,13000]
$IRIL^{[s]}_{\mathrm{rt}}$	[0.05,0.07]	$\mathrm{RC}^{\mathrm{min}}_{\mathrm{r}}$	[900,1100]

The coefficients of the capacity of warehouses are 0.01 and the confidence coefficients for the plants, warehouses and distribution centers are 0.1, 0.05 and 0.01, respectively. The minimum and maximum amounts of product transferred between two points are 100 and 1000. The scenario tree structure is presented in Figure 2. The probability of each scenario is 0.0625. The depreciation of firm's fixed assets is calculated according to the straight-line method. In addition, the tax rate is considered to be 0.3. Table 3 shows the uniform distributions by which parameters related to the price of each product for each customer and the demand of each customer under each scenario are generated.

Table 3. Uniform distributions to generate price and demand parameters

$\mathrm{PRICE}_{ict}^{[s]}$	[7,12]	$\mathrm{DM}_{ict}^{[s]}$	[300,500]

The parameters related to the amount of CO_2 released per product in transfer between two points, production, reproduction, repair and disposal phases are given in Table 4.

Table 4. Amount of carbon dioxide released per product

M_{ijm}	[0.01,0.05]	M_{inj}	[0.03,0.08]
M_{imk}	[0.01,0.05]	M_{inl}	[0.02,0.05]
M_{ikc}	[0.01,0.05]	M_{irk}	[0.01,0.05]
M_{icn}	[0.05,0.1]	M_{ij}	[0.03,0.07]
M_{inr}	[0.04,0.07]	M_{ij}^{rem}	[0.03,0.09]

In this section, a single-objective optimization model aiming to optimize the first objective function (Equation 130) subject to the set of predefined constraints is solved, and the obtained results are compared with a similar model without SLB. The optimization models were run on a 2.20 GHz Intel Core i7-4720HQ CPU system using GAMS software. As Table 5 shows, the optimization model including SLB outperforms the model without SLB.

Table 5. Objective function values for both models, with and without SLB

Optimal objective (with SLB)	253518.658
Optimal objective (without SLB)	197726.875

Figure 3 shows the cost breakdown for the optimal solution of the single-objective optimization model based on all scenarios.

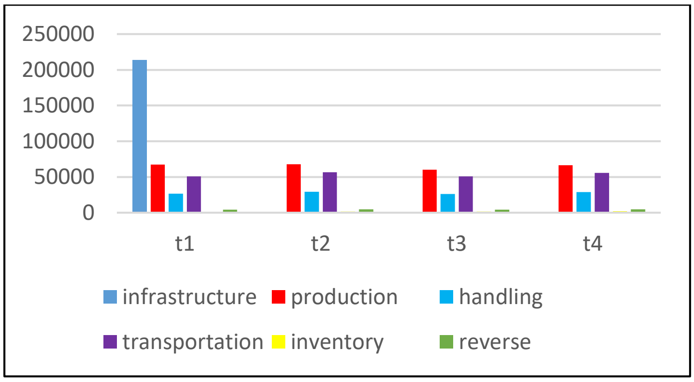

Figure 3. Cost breakdown for the optimal solution of the single-objective optimization model

4.2. Solving the bi-objective optimization model

There are two sort of approaches for solving multi-objective mathematical models, namely exact and approximate methods. Heuristics and metaheuristics are of popular approximate methods especially when the models are Np-hard (Cheraghalipour et al., 2018). Common multi-objective methods (except Pareto-based methods) can be sorted in four classes as follows (Pasandideh et al., 2015).

1) Methods that operate without any preliminary information from the decision maker (DM), like the LP metrics,
2) Methods that operate with preliminary information from the DM, like goal programming,
3) Methods that operate with information from the DM to be used, like the satisfactory goals method,
4) Methods that operate with information from the DM after solving the problem, like the minimum deviation method.

Because there is no need for preliminary information from the DM and easy generalization, two methods of class (1) are applied to solve the proposed bi-objective optimization model, namely LP-metric and max-min methods. Then, in order to compare the performances of these two methods, the hypothesis of equality of means is tested. Also, to select the best between these two methods, Technique for Order Preference by similarity to Ideal Solution (TOPSIS) and Simple Additive Weighting (SAW) methods are used. The explanation of the mentioned methods is provided in the following sub-sections.

4.2.1. LP-metric method

The purpose of LP-metric method is to provide the solution that minimizes the difference between the values of objective functions and their ideal values. To provide ideal solutions, single-objective optimization problems are solved for each objective function separately. The objective function of the LP-metric method, which should be optimized subject to all constraints of the model is $\mathrm{Min}\ \mathrm{D} = (\sum_{j=1}^{p}(\frac{f_j^* - f_j}{f_j^*})^r)^{\frac{1}{r}}$ (Najafzad et al. 2019, Nemati-Lafmejani and Davari-Ardakani, 2021). In this paper, the value of r is set to 1.

4.2.2. Max-Min method

The purpose of the Max-Min method is to maximize the minimum values calculated by dividing all objective functions by their corresponding ideal solutions. The objective function of the Max-Min method, which should be optimized subject to all constraints of the model, is $\mathrm{Max}(\mathrm{Min}\left(\frac{f_1}{f_1^*}, \frac{f_2}{f_2^*}, \dots, \frac{f_j}{f_j^*}\right))$ (Heidari-Fathian and Davari-Ardakani, 2020).

In order to assess the performance of the proposed bi-objective optimization model, 30 different-sized test problems are generated, and solved using both LP-metric and Max-Min methods. Then, the performance of the solution methods are compared with respect to both objective function values and CPU time. Table 6 shows the dimensions of all 30 test problems.

Table 6. Dimensions of all 30 test problems

Test Problem No.	Plant	Warehouse	Distribution Center	Customer	Collection center	Repair center	Disposal center
1	2	2	3	3	2	2	2
2	2	2	3	5	2	2	2
3	2	3	3	5	2	2	2
4	2	3	3	5	2	2	2
5	2	3	4	4	3	3	2
6	2	3	4	8	3	3	2
7	2	3	4	4	4	4	3
8	2	3	5	8	4	4	3
9	2	3	5	7	3	2	2
10	2	4	5	9	3	3	3
11	2	4	6	8	4	4	3
12	3	3	5	8	3	3	2
13	3	4	5	8	3	3	2
14	3	4	4	6	4	4	3
15	3	5	5	10	5	5	2
16	3	5	6	10	6	5	2
17	3	5	5	12	5	5	3
18	3	6	6	9	6	5	3
19	3	5	6	8	6	5	3
20	3	4	4	10	3	3	3
21	3	5	6	12	6	5	3
22	4	6	6	9	5	5	3
23	4	5	6	9	6	6	3
24	4	5	7	10	6	5	3
25	4	6	6	10	6	5	3
26	4	5	5	10	5	5	3
27	4	5	5	12	5	5	3
28	4	5	5	15	5	5	3
29	5	5	5	12	5	5	3
30	5	5	6	15	5	5	3

Figure 4 shows the values of the first objective function obtained by using LP-metric and Max-Min methods. The mean values for the LP-metric and Max-Min methods are 272610 and 268218, with 90953 and 96441standard deviations, respectively.

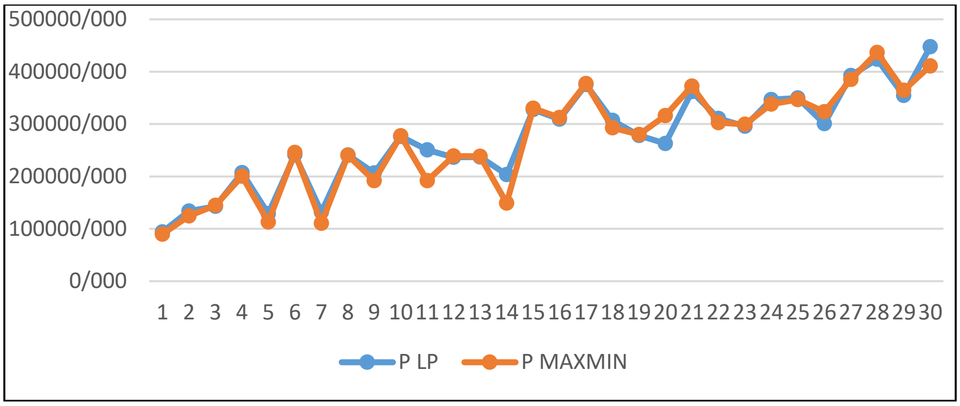

Figure 4. Values of the first objective function for test problems using LP-metric and Max-Min methods

Figure 5 shows the values of the second objective function obtained by LP-metric and Max-Min methods. The mean values for the LP-metric and Max-Min methods are 18409 and 18340, with 6101 and 6076 standard deviations, respectively.

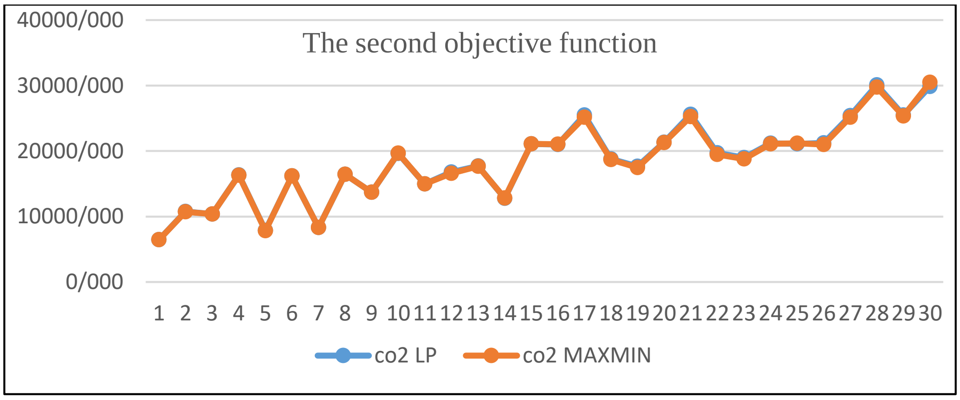

Figure 5. Values of the second objective function for test problems using LP-metric and Max-Min methods

Figure 6 shows the CPU times obtained by solving test problems. The mean values of CPU times for the LP-metric and Max-Min methods are 956 and 1489, and their standard deviations are 168 and 312, respectively.

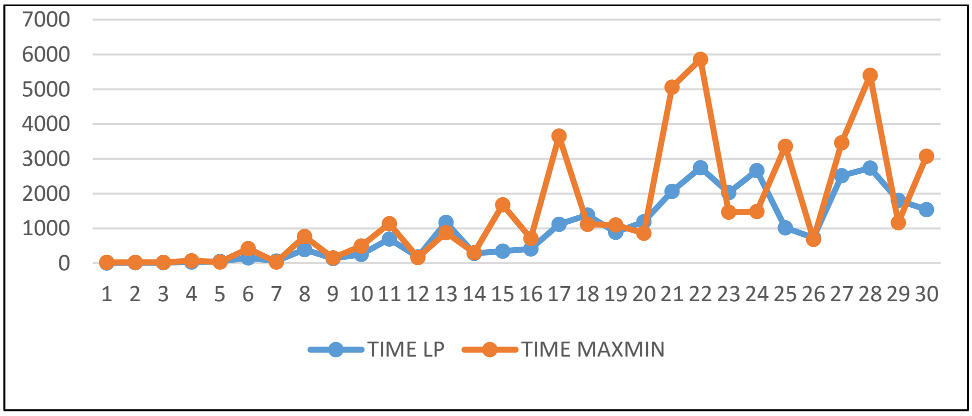

Figure 6. CPU times obtained by solving all test problems using LP-metric and Max-Min methods

In order to statistically compare the performance of both solution methods for solving all 30 randomly generated test problems, the mean values obtained by both solution methods are used. Testing the hypothesis of equality of means is an appropriate method to compare the results of both methods. As shown by expression (131), the null hypothesis states the equality of the mean values obtained by both LP-metric and Max-Min methods, while the alternative one states that they are not equal.

$$\begin{cases} H_0: \mu_{\text{LP-metric}} = \mu_{\text{Max-Min}} \\ H_1: \mu_{\text{LP-metric}} \neq \mu_{\text{Max-Min}} \end{cases} \quad \forall \text{Obj}_1, \text{Obj}_2, \text{CPU time} \tag{131}$$

The hypothesis testing was performed with 95% confidence level using Minitab16 software. Table 7 summarizes the results for performed hypothesis tests. Accordingly, the null hypothesis regarding the value of the first objective function is not rejected. This means that with a 95% confidence level, there is no significant difference between the mean values of the first objective function in both solution methods. In addition, the null hypotheses regarding the value of the second objective function and CPU time are rejected. In other words, with a 95% confidence level, there is significant difference between the mean values of the second objective function in both solution methods. This is also the case for CPU time.

Table 7. Results of hypothesis tests to compare both solution methods

Method	The first objective		The second objective		CPU time	
	mean	standard deviation	mean	standard deviation	mean	standard deviation
LP-metric	272610	90953	18409	6101	956	168
Max-Min	268218	96441	18340	6076	1489	312
p-value	0.255		0.044		0.015	
95% CI for µ_difference	(-3336, 12121)		(1.9, 137.2)		(-956, -111)	
Result	Not reject		Reject		Reject	

After performing a statistical comparison between LP-metric and Max-Min methods, TOPSIS and SAW, as two prominent multi-attribute decision making methods, are used to assess the performance of these solution methods.

In general, TOPSIS defines two positive ideal (ideal) and negative ideal (anti-ideal) solutions which have the best and worst possible performances with respect to all evaluation criteria. The superior option is one that has the shortest distance from the ideal solution and at the same time the farthest distance from the negative ideal solution. In other words, in ranking the alternatives by TOPSIS method, those options that have the most similarity with the ideal solution get a higher rank. The steps of TOPSIS method are shown by expressions (132)-(138).

Step 1: Construct the decision matrix X with m alternatives and n evaluation criteria.

$$\mathrm{X} = [\mathrm{x_{ij}}] \qquad \mathrm{i} = 1, \dots, \mathrm{m} \quad \mathrm{j} = 1, \dots, \mathrm{n} \tag{132}$$

Step 2: Construct the weighted normalized decision matrix V.

$$\mathrm{V} = [\mathrm{v_{ij}}] \qquad \mathrm{i} = 1, \dots, \mathrm{m} \quad \mathrm{j} = 1, \dots, \mathrm{n}$$

$$\mathrm{v_{ij}} = \frac{\mathrm{w_j x_{ij}}}{\sqrt{\sum_{\mathrm{i}=1}^{\mathrm{m}} \mathrm{x_{ij}^2}}} \tag{133}$$

where, w_j is the standard weight of the j^{th} criterion, and $\sum_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{w_j} = 1$.

Step 3: Determine the positive ideal (A^+) and the negative ideal (A^-) solutions.

$$\mathrm{A}^+ = \{(\max \mathrm{v_{ij}} | \mathrm{j} \in \mathrm{J}^+), (\min \mathrm{v_{ij}} | \mathrm{j} \in \mathrm{J}^-) | \mathrm{i} = 1, \dots, \mathrm{m}\} = \{\mathrm{v_1^+}, \mathrm{v_2^+}, \dots, \mathrm{v_n^+}\} \tag{134}$$

$$\mathrm{A}^- = \{(\min \mathrm{v_{ij}} | \mathrm{j} \in \mathrm{J}^+), (\max \mathrm{v_{ij}} | \mathrm{j} \in \mathrm{J}^-) | \mathrm{i} = 1, \dots, \mathrm{m}\} = \{\mathrm{v_1^-}, \mathrm{v_2^-}, \dots, \mathrm{v_n^-}\} \tag{135}$$

Step 4: Calculate the distance between all alternatives and each positive and negative ideal solutions.

$$\mathrm{d_i^+} = \sqrt{\sum_{\mathrm{j}=1}^{\mathrm{n}} (\mathrm{v_{ij}} - \mathrm{v_i^+})^2} \qquad \mathrm{i} = 1, \dots, \mathrm{m} \tag{136}$$

$$\mathrm{d_i^-} = \sqrt{\sum_{\mathrm{j}=1}^{\mathrm{n}} (\mathrm{v_{ij}} - \mathrm{v_i^-})^2} \qquad \mathrm{i} = 1, \dots, \mathrm{m} \tag{137}$$

Step 5: Determine the relative closeness of each alternative to the ideal solution, and rank alternatives in a descending order.

$$\mathrm{CI_i^*} = \frac{\mathrm{d_i^-}}{\mathrm{d_i^-} + \mathrm{d_i^+}} \tag{138}$$

Tables 8-12 show a summary of numerical results obtained in each step of TOPSIS method to rank LP-metric and Max-Min methods.

Table 8. The constructed decision matrix (Step 1)

Method	The average of the first objective function (+)	The average of the second objective function (-)	Average CPU time (-)
LP-metric	272610.003	18409.061	955.833
Max-Min	268217.697	18339.506	1489.067

Table 9. The weighted normalized decision matrix (Step 2)

Method	The average of the first objective function (+)	The average of the second objective function (-)	Average CPU time (-)
LP-metric	0.7128260	0.7084439	0.5401881
Max-Min	0.7013409	0.7057672	0.8415443

Table 10. Positive and negative ideal solutions (Step 3)

	The average of the first objective function (+)	The average of the second objective function (-)	Average CPU time (-)
A^+	0.7128260	0.7057672	0.5401881
A^-	0.7013409	0.7084439	0.8415443

Table 11. Distance between each alternative and both positive and negative ideal solutions (Step 4)

d_1^+	0.0026767	d_2^+	0.3015750
d_1^-	0.3015750	d_2^-	0.0026767

Table 12. Relative closeness values and final ranking of alternatives based on TOPSIS method (Step 5)

Method	CI_i^*	Rank
LP-metric	0.9912024	1
Max-Min	0.0087976	2

In addition, SAW, as another prominent multi-attribute decision making method, is used to assess the performance of both solution methods. The steps of SAW method are shown by expressions (139)-(144).

Step 1: Construct the decision matrix X with m alternatives and n evaluation criteria.

$$X = [x_{ij}] \qquad i = 1, \dots, m \quad j = 1, \dots, n \tag{139}$$

Step 2: Normalize the decision matrix X to construct the normalized decision matrix R.

$$R = [r_{ij}] \qquad i = 1, \dots, m \quad j = 1, \dots, n \tag{140}$$

For any benefit criterion (e.g., the first objective function), the elements of R are calculated.

$$r_{ij} = \frac{x_{ij}}{x_j^{max}} \tag{141}$$

For any cost criterion (e.g., the second objective function and CPU time), the elements of R are calculated.

$$r_{ij} = \frac{x_j^{min}}{x_{ij}} \tag{142}$$

Step 3: Construct the weighted normalized decision matrix V.

$$V = [v_{ij}] \qquad i = 1, \dots, m \quad j = 1, \dots, n$$

$$v_{ij} = w_j \times r_{ij} \tag{143}$$

In this problem, the values of the weights of each of the 3 criteria are equal to 1/3.

Step 4: Calculate the score of each alternative, and rank them based on the calculated scores.

$$A^* = \{A_i | \max_i \sum_{j=1}^{n} v_{ij}\} \tag{144}$$

Tables 13-16 show a summary of numerical results obtained in each step of SAW method to rank LP-metric and Max-Min methods.

Table 13. The constructed decision matrix (Step 1)

Method	The average of the first objective function (+)	The average of the second objective function (-)	Average CPU time (-)
LP-metric	272610.003	18409.061	955.833
Max-Min	268217.697	18339.506	1489.067

Table 14. The normalized decision matrix (Step 2)

Method	The average of the first objective function (+)	The average of the second objective function (-)	Average CPU time (-)
LP-metric	1.000	0.996	1.000
Max-Min	0.984	1.000	0.642

Table 15. The weighted normalized decision matrix (Step 3)

Method	The average of the first objective function	The average of the second objective function	Average CPU time
LP-metric	0.333	0.332	0.333
Max-Min	0.328	0.333	0.214

Table 16. The final scores of alternatives (Step 4)

Method	A_i	Rank
LP-metric	0.998	1
Max-Min	0.874	2

Results of both TOPSIS and SAW methods confirm that the LP-metric method outperforms the Max-Min method in solving the proposed bi-objective optimization model.

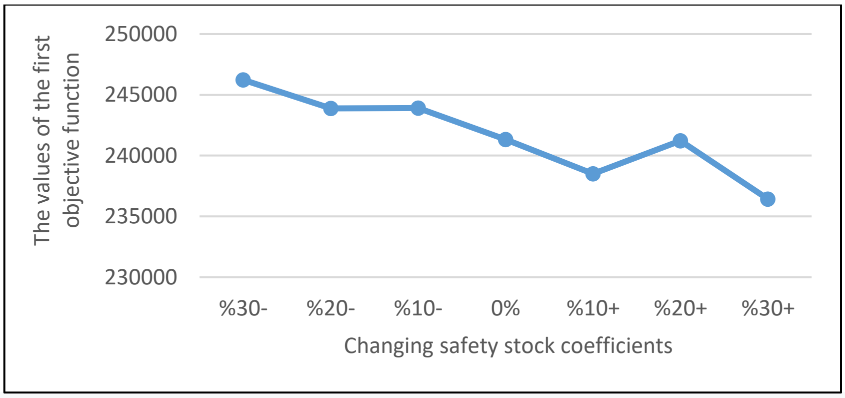

Figure 7. The values of the first objective function with respect to changing safety stock coefficients

4.3. Sensitivity analysis

In this section, sensitivity analysis is used to evaluate the effects of parameters' changes on the values of objective functions. First, the changes in parameters related to the safety stock coefficient for the plants, warehouses and distribution centers are studied. Figure (7) and Figure (8) show the results of the sensitivity analysis performed on the parameters related to safety stock coefficients.

According to Figure 7, safety stock coefficients and profit have an indirect relationship, i.e., if the coefficients increase, the profit decreases. However, the profit is unsensitive to the change of the coefficients' between -10% and -20%. This indicates that reducing coefficients more than 20% leads to more drastic increase in profit.

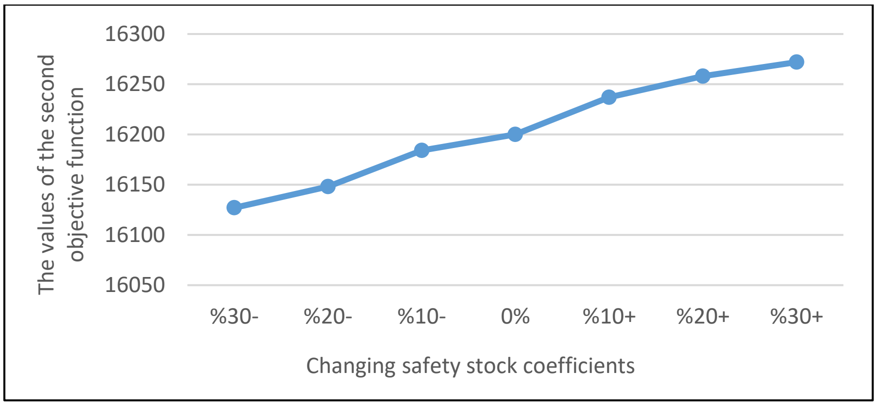

Figure 8. The values of the second objective function with respect to changing safety stock coefficients

Figure 8 illustrates a direct relationship between safety stock coefficients and CO_2 emissions, however increment beyond 10% shows less sensitivity of CO_2 emission to the coefficients.

Afterward, sensitivity analysis is performed to evaluate the effect of changing the fair value parameters for each potential center. Table 17 shows the results related to this analysis.

Table 17. The values of first objective function with respect to changing fair value parameters for potential centers

Objective values by changing $\mathrm{FV}_{\mathrm{rt}}^{[s]}$	Objective values by changing $\mathrm{FV}_{\mathrm{nt}}^{[s]}$	Objective values by changing $\mathrm{FV}_{\mathrm{kt}}^{[s]}$	Objective values by changing $\mathrm{FV}_{\mathrm{mt}}^{[s]}$	
224870.085	222443.083	219010.101	208916.962	-40%
224870.085	222443.083	219010.101	207691.389	-30%
224870.085	222443.083	219010.101	207886.758	-20%
224870.085	206849.955	220171.894	218831.029	-10%
224870.085	224870.085	224870.085	224870.085	0%
224870.085	230081.653	229444.766	234186.793	10%
224870.085	236763.257	241161.511	241503.705	20%
224870.085	244467.319	254824.37	254104.184	30%
224870.085	252232.185	268486.251	256525.912	40%

As can be seen from Table 17, profit is not sensitive to $\mathrm{FV}_{\mathrm{rt}}^{[s]}$ (repair centers) and does not change as this parameter varies. Also, for values under -20% the profit shows no sensitivity to $\mathrm{FV}_{\mathrm{nt}}^{[s]}$ (collection center) and $\mathrm{FV}_{\mathrm{kt}}^{[s]}$ (distribution center). For other values, there is a direct relationship between these two parameters and profit. A direct relationship also exists between profit and $\mathrm{FV}_{\mathrm{mt}}^{[s]}$ (warehouse).

Other parameters to be considered are those related to the interest rate implicit in the lease and lessee's incremental borrowing rate. In this regard, all parameters related to the interest rate implicit in the lease are changed simultaneously. The related results are presented in Table 18.

Table 18. The impact of changing parameters related to interest rate implicit in the lease and lessee's incremental borrowing rate on the first objective function

Objective values by changing $\mathrm{LIBR}_{\mathrm{nt}}^{[s]}$،$\mathrm{LIBR}_{\mathrm{kt}}^{[s]}$،$\mathrm{LIBR}_{\mathrm{mt}}^{[s]}$, $\mathrm{LIBR}_{rt}^{[s]}$	Objective values by changing $\mathrm{IRIL}_{\mathrm{nt}}^{[s]}$،$\mathrm{IRIL}_{\mathrm{kt}}^{[s]}$،$\mathrm{IRIL}_{\mathrm{mt}}^{[s]}$, $\mathrm{IRIL}_{rt}^{[s]}$	
197726.875	280897.659	-40%
206565.044	269517.733	-30%
217326.723	268113.689	-20%
228621.128	266034.455	-10%
253518.658	253518.658	0%
264966.923	227971.863	10%
265374.261	221474.429	20%
266495.467	215937.365	30%
266874.325	203088.552	40%

As shown by Table 18, by increasing the lessee's incremental borrowing rate, the value of the first objective function increases, while by increasing the interest rate implicit in the lease, the value of the first objective function decreases. Figure 9 and Figure 10 present schematic representations for better understanding of the above-mentioned analysis.

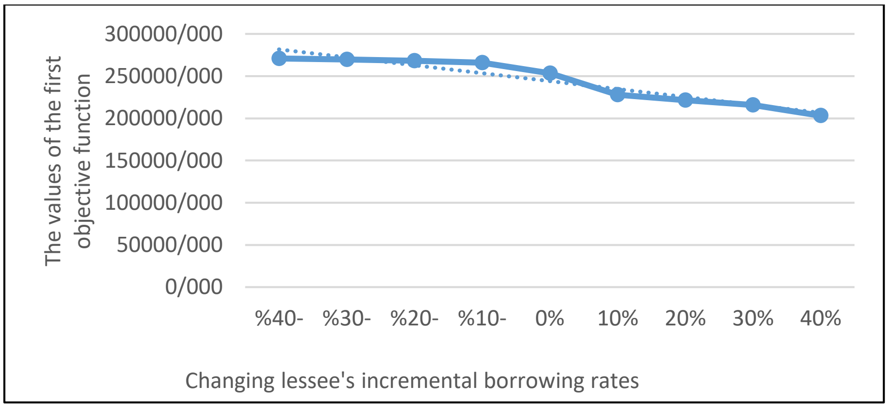

Figure 9. The values of the first objective function with respect to changing lessee's incremental borrowing rates

Based on Figure 9, an indirect relationship can be seen between profit and lessee's incremental borrowing rates. However, profit do not show significant sensitivity for values less than -10%, but more sensitivity can be seen for lessee's incremental borrowing rates in the range of -10% to +10%.

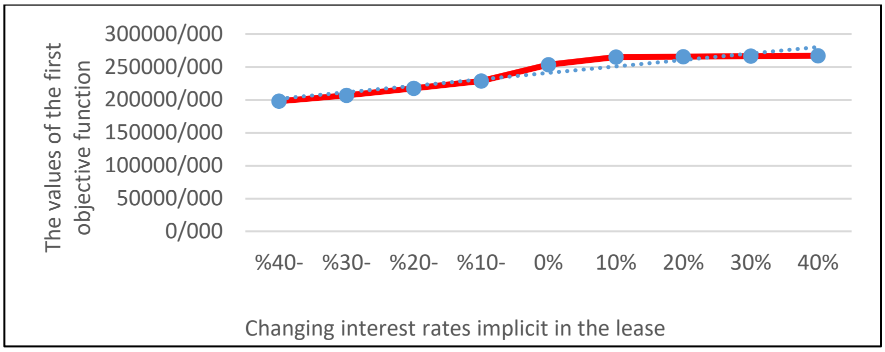

Figure 10. The values of the first objective function with respect to changing interest rates implicit in the lease

According to Figure 10, the direct relationship between profit and interest rates, shows an opposite sensitivity in comparison to lessee's incremental borrowing rates. That means profit has no significant sensitivity to interest rates beyond 10% increment.

Regarding the outputs, several managerial insights can be inferred.

1. Decision makers can use the proposed model to do trade-offs between profitability and CO_2 emissions in presence of SLB possibility.
2. Taking the advantage of SLB makes more profit for the supply chain.
3. Lp-metric method provides better solutions for the proposed supply chain.
4. Decision makers may relive decrease in profit, resulting from reduction of interest rates, by seeking for lower lessee's incremental borrowing rates.
5. Increment of interest rates or decrement of lessee's incremental borrowing rates cannot influence profitability anymore beyond specified values.
6. Decision maker may not worry about fair values of repair centers, because the profitability shows no sensitivity to their values.

5. Conclusion

This paper proposed a scenario-based bi-objective stochastic optimization model to cope with the closed-loop supply chain (CLSC) network design problem considering Sale and LeaseBack (SLB) transactions and environmental issues. The main motivations to deal with such a problem are threefold. First, governments have found the importance of issues such as environmental protection and less use of raw materials. Hence, they emphasize on recycling the products so that they can be restored to manufacturing after recovery. For this reason, the backward logistics and CLSC issues have been considered, and the designed model is concerned with End-of-Life product return and reuse. Second, many companies are faced with liquidity problems, and for various reasons they are incapable of borrowing. In such situations, selling the fixed assets and leasing them back is an effective solution. Numerical results of the proposed model showed that the inclusion of SLB transaction increases the financial benefits of the network. Third, according to the global warming and other environmental issues, considering CO_2 emissions indicator is a matter of crucial importance.

To assess the performance of the proposed model, 30 different-sized test problems were generated, and solved by two prominent multi-objective decision making techniques, namely LP-metric and Max-Min methods. Then, TOPSIS and SAW methods were used to assess the performance of solution methods, and showed that LP-metric method outperforms the Max-Min method in solving the proposed bi-objective optimization model.

Finally, sensitivity analysis on the main parameters of the proposed model, namely safety stock coefficients, fair value parameters for potential centers, interest rate implicit in the lease and lessee's incremental borrowing rate, was performed. Sensitivity analysis results showed that by increasing the lessee's incremental borrowing rate, the value of the first objective function increases, while by increasing the interest rate implicit in the lease, the value of the first objective function decreases. So, decision makers may relive decrease in profit, resulting from reduction of interest rates, by seeking for lower lessee's incremental borrowing rates. Moreover, increment of interest rates or decrement of lessee's incremental borrowing rates cannot influence profitability anymore beyond specified values. Another interesting finding indicates that decision maker may not worry about fair values of repair centers, because the profitability is not sensitive to their values.

As a limitation, the proposed model considers two stages for the proposed multi period problem. However, in reality and especially for long term, multi-stage consideration may be more realistic because it provides more adjustability over specified milestones. On the other hand, measuring accurate value or distribution function for many parameters may be difficult or impossible in unstable circumstances. So, incorporating fuzzy numbers can be advantageous.

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Appendix: Parameters

Cost Parameters	
C_m^w	Fixed cost of establishing a warehouse at location m
C_k^{DC}	Fixed cost of establishing a distribution center at location k
C_n^{CC}	Fixed cost of establishing a collection center at location n
C_r^{RC}	Fixed cost of establishing a repair center at location r
C_{ijm}^{TR}	Unit transportation cost of product i from plant j to warehouse m
C_{imk}^{TR}	Unit transportation cost of product i from warehouse m to distribution center k
C_{ikc}^{TR}	Unit transportation cost of product i from distribution center k to customer c
C_{icn}^{TR}	Unit transportation cost of returned product i from customer c to collection center n
C_{inj}^{TR}	Unit transportation cost of returned product i from collection center n to plant j
C_{inr}^{TR}	Unit transportation cost of returned product i from collection center n to repair center r
C_{inl}^{TR}	Unit transportation cost of returned product i from collection center n to disposal center l
C_{irk}^{TR}	Unit transportation cost of returned product i from repair center r to distribution center k
C_{ik}^{DH}	Unit transfer cost of product i in distribution center k
C_{im}^{WH}	Unit transfer cost of product i at warehouse m
C_{ij}^{P}	Unit production cost for product i at plant j
C_{ij}^{rem}	Unit reproducing cost for product i at plant j
C_{ir}^{rep}	Unit repair cost of product i at repair center r

$\mathrm{C}_{\mathrm{il}}^{\mathrm{dis}}$	Unit disposal cost of product i at disposal center l
$\mathrm{C}_{\mathrm{in}}^{\mathrm{ins}}$	Unit inspection and collection cost of product i at collection center n
$\mathrm{C}_{\mathrm{ij}}^{\mathrm{I}}$	Unit inventory cost of product i at plant j
$\mathrm{C}_{\mathrm{im}}^{\mathrm{I}}$	Unit inventory cost of product i at warehouse m
$\mathrm{C}_{\mathrm{ik}}^{\mathrm{I}}$	Unit inventory cost of product i at distribution center k
Capacity Parameters	
$\mathrm{P}_{\mathrm{ijt}}^{\max}$	Maximum production capacity of plant j for product i during period t
$\mathrm{P}_{\mathrm{ijt}}^{\min}$	Minimum production capacity of plant j for product i during period t
$\mathrm{W}_{\mathrm{m}}^{\max}$	Maximum capacity of warehouse m
$\mathrm{W}_{\mathrm{m}}^{\min}$	Minimum capacity of warehouse m
$\mathrm{DC}_{\mathrm{k}}^{\max}$	Maximum capacity of distribution center k
$\mathrm{DC}_{\mathrm{k}}^{\min}$	Minimum capacity of distribution center k
$\mathrm{CC}_{\mathrm{n}}^{\max}$	Maximum capacity of collection center n
$\mathrm{CC}_{\mathrm{n}}^{\min}$	Minimum capacity of collection center n
$\mathrm{RC}_{\mathrm{r}}^{\max}$	Maximum capacity of repair center r
$\mathrm{RC}_{\mathrm{r}}^{\min}$	Minimum capacity of repair center r
Depreciation rate parameters	
DR_{m}	Depreciation rate of warehouse m
DR_{k}	Depreciation rate of distribution center k
DR_{n}	Depreciation rate of collection center n
DR_{r}	Depreciation rate of repair center r
Sale and Leaseback parameters	
$\mathrm{FV}_{\mathrm{mt}}^{[\mathrm{s}]}$	Fair value of warehouse m at the end of time period t under scenario s
$\mathrm{FV}_{\mathrm{kt}}^{[\mathrm{s}]}$	Fair value of distribution center k at the end of time period t under scenario s
$\mathrm{FV}_{\mathrm{nt}}^{[\mathrm{s}]}$	Fair value of collection center n at the end of time period t under scenario s
$\mathrm{FV}_{\mathrm{rt}}^{[\mathrm{s}]}$	Fair value of repair center r at the end of time period t under scenario s
$\mathrm{IRIL}_{\mathrm{mt}}^{[\mathrm{s}]}$	Interest rate implicit in the lease for warehouse m at the end of time period t under scenario
$\mathrm{IRIL}_{\mathrm{kt}}^{[\mathrm{s}]}$	Interest rate implicit in the lease for distribution center k at the end of time period t under
$\mathrm{IRIL}_{\mathrm{nt}}^{[\mathrm{s}]}$	Interest rate implicit in the lease for collection center n at the end of time period t under
$\mathrm{IRIL}_{\mathrm{rt}}^{[\mathrm{s}]}$	Interest rate implicit in the lease for repair center r at the end of time period t under scenario
$\mathrm{LIBR}_{\mathrm{mt}}^{[\mathrm{s}]}$	Lessee's incremental borrowing rate for warehouse m at the end of time period t under
$\mathrm{LIBR}_{\mathrm{kt}}^{[\mathrm{s}]}$	Lessee's incremental borrowing rate for distribution center k at the end of time period t under scenario s
$\mathrm{LIBR}_{\mathrm{nt}}^{[\mathrm{s}]}$	Lessee's incremental borrowing rate for collection center n at the end of time period t under scenario s
$\mathrm{LIBR}_{\mathrm{rt}}^{[\mathrm{s}]}$	Lessee's incremental borrowing rate for repair center r at the end of time period t under
CO_2 emission parameters	
$\mathrm{M}_{\mathrm{ijm}}$	The amount of CO_2 released from the vehicle per unit of product i transferred from plant j to warehouse m
$\mathrm{M}_{\mathrm{imk}}$	The amount of CO_2 released from the vehicle per unit of product i transferred from warehouse m to distribution center k
$\mathrm{M}_{\mathrm{ikc}}$	The amount of CO_2 released from the vehicle per unit of product i transferred from distribution center k to customer c
$\mathrm{M}_{\mathrm{icn}}$	The amount of CO_2 released from the vehicle per unit of product i transferred from customer c to the collection center n
$\mathrm{M}_{\mathrm{inj}}$	The amount of CO_2 released from the vehicle per unit of product i transferred from collection center n to plant j
$\mathrm{M}_{\mathrm{inr}}$	The amount of CO_2 released from the vehicle per unit of product i transferred from collection center n to repair center r
$\mathrm{M}_{\mathrm{inl}}$	The amount of CO_2 released from the vehicle per unit of product i transferred from collection center n to disposal center l
$\mathrm{M}_{\mathrm{irk}}$	The amount of CO_2 released from the vehicle per unit of product i transferred from repair center r distribution center k

M_{ij}	The amount of CO_2released due to the production of each unit of product i in the plant j
$\mathrm{M}_{\mathrm{ij}}^{\mathrm{rem}}$	The amount of CO_2 released due to the reproduction of each unit of product i in the plant j
$\mathrm{M}_{\mathrm{MAX}}$	Maximum allowable amount of CO_2 emissions
Other parameters	
$\mathrm{Q}_{\mathrm{ijm}}^{\mathrm{max}}$	Maximum quantity of product i that can be transferred from plant j to warehouse m
$\mathrm{Q}_{\mathrm{ijm}}^{\mathrm{min}}$	Minimum quantity of product i that can be transferred from plant j to warehouse m
$\mathrm{Q}_{\mathrm{imk}}^{\mathrm{max}}$	Maximum quantity of product i that can be transferred from warehouse m to distribution
$\mathrm{Q}_{\mathrm{imk}}^{\mathrm{min}}$	Minimum quantity of product i that can be transferred from warehouse m to distribution
$\mathrm{Q}_{\mathrm{ikc}}^{\mathrm{max}}$	Maximum quantity of product i that can be transferred from distribution center k to
$\mathrm{Q}_{\mathrm{ikc}}^{\mathrm{min}}$	Minimum quantity of product i that can be transferred from distribution center k to
$\mathrm{Q}_{\mathrm{icn}}^{\mathrm{max}}$	Maximum quantity of product i that can be transferred from customer c to collection center
$\mathrm{Q}_{\mathrm{icn}}^{\mathrm{min}}$	Minimum quantity of product i that can be transferred from customer c to collection center
$\mathrm{Q}_{\mathrm{inr}}^{\mathrm{max}}$	Maximum quantity of product i that can be transferred from collection center n to repair
$\mathrm{Q}_{\mathrm{inr}}^{\mathrm{min}}$	Minimum quantity of product i that can be transferred from collection center n to repair
$\mathrm{Q}_{\mathrm{inj}}^{\mathrm{max}}$	Maximum quantity of product i that can be transferred from collection center n to plant j
$\mathrm{Q}_{\mathrm{inj}}^{\mathrm{min}}$	Minimum quantity of product i that can be transferred from collection center n to plant j
$\mathrm{Q}_{\mathrm{inl}}^{\mathrm{max}}$	Maximum quantity of product i f that can be transferred from collection center n to disposal
$\mathrm{Q}_{\mathrm{inl}}^{\mathrm{min}}$	Minimum quantity of product i that can be transferred from collection center n to disposal
$\mathrm{Q}_{\mathrm{irk}}^{\mathrm{max}}$	Maximum quantity of product i that can be transferred from repair center r to distribution
$\mathrm{Q}_{\mathrm{irk}}^{\mathrm{min}}$	Minimum quantity of product i that can be transferred from repair center r to distribution
R_{je}	Total rate of availability of resource e at plant j (hours/year)
$RM_{it}^{[s]}$	Reproduction ratio of product i in time period t under scenario s
$RP_{it}^{[s]}$	Repair ratio of product i in time period t under scenario s
$RR_{it}^{[s]}$	Return ratio of product i from customer c in time period t under scenario s
TP_{t}	Cumulative time period index
TR	Tax rate
$\mathrm{I}_{\mathrm{iit}}^{[\mathrm{s}],\mathrm{min}}$	Minimum inventory of product i held in plant j at the end of time period t under scenario s
$\mathrm{I}_{\mathrm{imt}}^{[\mathrm{s}],\mathrm{min}}$	Minimum inventory of product i held in warehouse m at the end of time period t under
$\mathrm{I}_{\mathrm{ikt}}^{[\mathrm{s}],\mathrm{min}}$	Minimum inventory of product i held in distribution center k at the end of time period t under scenario s
γ_{ik}	Coefficient relating capacity of distribution center k to inventory of product i held
γ_{im}	Coefficient relating capacity of warehouse m to inventory of product i held
δ_{ij}	Safety stock coefficient for product i held in plant j
δ_{im}	Safety stock coefficient for product i held in warehouse m
δ_{ik}	Safety stock coefficient for product i held in distribution center k
ρ_{ije}	Coefficient of utilization rate of resource e in plant j to produce product i
Ψ_{s}	Probability of occurring scenario s during the lifetime of the network
$\mathrm{PRICE}_{\mathrm{ict}}^{[\mathrm{s}]}$	Price of product i for customer c in time period t under scenario s
$\mathrm{DM}_{\mathrm{ict}}^{[\mathrm{s}]}$	Demand of product i for customer c in time period t under scenario s