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Interrelating physical and financial flows in a bi-objective closed-loop supply chain network problem with uncertainty

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Abstract. This paper presents a bi-objective logistic design problem integrating the financial and physical flows of a closed-loop supply chain in which the uncertainty of demand and the return rate are described by a finite set of possible scenarios. The main idea of this paper consists of the joint integration of enterprise finance with the company operations model, where financial aspects are explicitly considered as exogenous variables. The model addresses the company operations decisions as well as the finance decisions. Moreover, the change in equity is considered as objective function along with the profit to evaluate the business aspects. Since the logistic network design is a strategic problem and the change of configuration is not easy in the future, a bi-objective robust optimization with the max-min version is extended to cope with the uncertainty of parameters. In addition, to obtain solutions with a better time, the scenario relaxation algorithm is adapted for the proposed approach. The numerical examples are presented to show the applicability of the model along with a sensitivity analysis on financial parameters. The obtained results illustrate the importance of such modelling systems leading to more overall earnings and expressing further insights on the interactions between operations and finances.

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1. Introduction

Supply Chain Management (SCM) aims to integrate plants with their suppliers, customers and other facilities in network so that they can be managed as a single entity, and to coordinate all input/output flows (of materials, information and funds) so that products are produced and distributed in the right quantities, to the right locations, and at the right time. The recent SCM models in literature, as mentioned by Guillén, Badell, Espuña and Puigjaner [1], are often focused on the physical flows of goods in network including the best location of facilities, the optimum flow of materials/products and optimum value of inventory with respect to the performance measure of cost or profit. However, any SC has in parallel a financial chain, and aspects related to the analysis of corporate financial decisions are not considered within these models. Therefore, these models are no longer adequate and must present an optimized plan along with an optimized budget.

On the other hand, Supply Chain Network Design (SCND) problem is an important one in SCM that involves both strategic and tactical decisions. In general, the SCND problem is concerned with the determination of the optimal number, technology, and configuration of the facilities as well as the quantities

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of purchasing, production, distribution, inventory, and shipments among the established facilities in such a way to optimize both the customer satisfaction and the chain value. The network in a SCND problem consists of two parts: Forward Logistic (FL) and Reverse Logistic (RL). The first only considers the forward facilities (such as supplier, plant, and distribution center), while the latter considers the backward facilities (such as collection center, repair center, and disposal center). Because designing the forward and reverse logistics separately results in sub-optimal designs with respect to objectives of the supply chain, the Closed-Loop Supply Chain (CLSC) network design is critically important and can guarantee the least waste of materials by following the conservation laws during the life cycle of the materials [2].

Hence, this paper presents an integrated design of closed-loop supply chain interrelating physical and financial flows with the uncertainty in demands and return rate. The main idea of this paper is to incorporate the financial issues and a set of budgetary constraints representing balances of cash, debt, securities, payment delays, and discounts in the supply chain planning. In addition, the change in equity is considered as objective function along with the profit to evaluate the SC system. To deal with uncertainty in the parameters, described by a set of possible scenarios, multi-objective robust optimization approach is adapted to solve the proposed model. Besides, to find a solution with a faster computation time, the scenario relaxation algorithm is presented that performs more efficiently compared to the extensive form model. In other words, the main contributions of this paper can be summarized as follows:

- Presenting a novel bi-objective closed-loop supply chain design model integrating the financial flows and the physical flows;
- Achieving the applicability and efficiency of the scenario relaxation algorithm compared to the extensive form model to solve the SCND model that contemplates the uncertainty of the demand and the return rate as a finite number of possible scenarios.

The structure of this paper is as follows. Section 2 reviews the literature of SCND problem with focus on financial issues. A mathematical model for design of closed-loop supply chain under uncertainty with the financial considerations is presented in Section 3. Section 4 addresses multi-objective robust optimization approach and explains the scenario relaxation algorithm to achieve a solution with a faster computation time. Section 5 illustrates the numerical examples and discusses the computational results. Finally, we report the conclusions of this paper in Section 6.

2. Literature review

Regarding SCM models, there have been a considerable number of publications in recent years. The first researches considered linear, single-product, single-period, deterministic problems. Then, complex, non-linear, multi-product, multi-period, stochastic ones as new constraints were appended to the existing models, in order to yield more realistic ones. Two main streams of literature are relevant to our research:

1. The studies considering the financial decisions in SCM;
2. The researches associated with closed-loop supply chain.

In the first stream, incorporation of financial decisions in SCM, both qualitative and quantitative studies can be observed in the literature. Wang, Batta, Bhadury and Rump [3] addressed a facility location problem with budget constraints in which the opening of new facilities and the closing of existing facilities are considered. The objective of the model is to minimize the distance from customer subject to the restriction of investment budget and number of facilities. Badell, Romero, Huertas and Puigjaner [4] presented a Mixed Integer Linear Programming (MILP) model to implement the financial cross functional links with the enterprise value-added chain, where the activities of planning, scheduling, and budgeting are integrated at plant level. The main contribution of this paper is to incorporate the financial issues (i.e. budgeting model) into Advanced Planning and Schedule (APS) enterprise systems. Guillén, Badell and Puigjaner [5] presented a mathematical model that optimizes simultaneously activities of scheduling, production planning, and corporate financial planning in a holistic framework. The objective of this paper is to maximize change in equity instead of maximizing profit.

Puigjaner and Guillén-Gosálbez [6] addressed the supply chain optimization at the operation level in the chemical process industry. An integrated approach was suggested for supply chain management in a multi-agent framework. The paper considers supply chain dynamics, the environmental impacts, the business issues, and key performance indicator in the proposed problem. Hammami, Frein and Hadj-Alouane [7] presented a strategic-tactical model for the design of a supply chain network in the delocalization context. The paper considers the logistic decisions, i.e. location of facilities, technology choice, supplier selection, and product flows among chain, as well as the financial decisions, i.e. transfer pricing and transportation costs allocation. Laínez, Puigjaner and Reklaitis [8] presented a model for supply chain management with focus on the process operations and the Product Development Pipeline Management

(PDPM) problem. The paper addresses the financial and financial engineering considerations with inflow and outflow cash in each period, strategic management of supplier and customer relations by inventory management and option contracts. Protopappa-Sieke and Seifert [9] presented a mathematical model to integrate the operational and financial supply chain management in the inventory control area. The model decides on the optimal purchasing order quantity with respect to the capital constraints and payment delays while performance measurements of the service level, return on investment, profit margin, and inventory level are analysed in the relevant supply chain. Longinidis and Georgiadis [10] proposed a Mixed Integer Linear Programming (MILP) formulation for design of a supply chain network including plants, warehouses, distribution centers, and customers. The paper extends the existing models in the literature by incorporating the financial issues as financial ratios and considering the demand uncertainty. Nickel, Saldanha-da-Gama and Ziegler [11] presented a multi-stage supply chain network design problem in which the decisions of the location of the facilities, the flow of commodities and the investments to be made in alternative activities to those directly related with the supply chain design. The goal was to maximize the total financial benefit and an alternative formulation which is based upon the paths in the scenario tree was also proposed. Longinidis and Georgiadis [12] presented a mathematical model that integrates financial performance and credit solvency modelling with SCN design decisions under economic uncertainty. The multi-objective Mixed Integer Non-Linear Programming (moMINLP) model enchased financial performance through economic value added and credit solvency through a valid credit scoring model.

In the second stream, network design in closed-loop supply chain, various studies have addressed this problem in literature. Chan, Kumar and Choy [13] presented a facility location-allocation model for collection, reprocessing, and redistribution of carpet to design the location and capacity of a regional recovery center. The model minimized the costs of investment, processing, and transportation. Fleischmann, Beullens, Bloemhof-Ruwaard and Van Wassenhove [2] proposed a SCND model analysing the forward flow together with the return flow. Fleischmann's model was extended by Salema, Barbosa-Povoa and Novais [14] to a multi-product capacitated reverse logistic network with uncertainty in the demands and returns, which was used by an Iberian company. Üster, Easwaran, Akçali and Çetinkaya [15] presented a multi-product close-loop SCND model and considered the production and reproduction separately. They regarded the feature of single sourcing for the customers for a better management of customers. The Benders decomposition method also was used to solve the model.

Ko and Evans [16] developed a dynamic, integrated, closed-loop network operated by the third Party Logistics (3PL) service provider. They applied a Genetic Algorithm (GA) to solve their model. Aras, Aksen and Gönül Tanuğur [17] presented a non-linear recovery logistic network design whose objective is to maximize the total profit. The model decided about the locations of collection centers and suitable price for returned products. Moreover, a Tabu search solution procedure was proposed to find the solution of model. Min and Ko [18] proposed a dynamic design of a reverse SCND problem and presented a GA to solve the problem, including the location and allocation for 3PLs. Salema, Barbosa-Povoa and Novais [19] introduced a multi-product and multi-period model for a supply chain network with reverse flows, where an approach based on graph is applied to model the relevant problem. The model simultaneously integrates the strategic decisions (i.e. network design) and the tactical decisions (i.e. planning of supply chain related to supply, production, storage and distribution).

El-Sayed, Afia and El-Kharbotly [20] proposed a multi-period, multi-echelon, forward-reverse logistics network design model. They considered four layers in the forward direction (i.e. suppliers, plants, distribution centers and customers) and three layers in the return direction (i.e. customers, disassembly and redistribution centers). The objective of their model is to maximize the profit of the supply chain. Pishvaee, Farahani and Dullaert [21] suggested a bi-objective integrated closed-loop supply chain design model in which the costs and the responsiveness of logistic network are considered objectives of model. They developed an efficient multi-objective memetic algorithm by applying three different local searches in order to find the set of non-dominated solutions. Wang and Hsu [22] presented a close-loop SCND model that takes into account the locations of plants, distribution centers, and dismantlers as decision variables. The model used the distribution centers as hybrid processing facilities for both the forward and backward flows. In addition, to solve the proposed model, a revised spanning-tree based GA with determinant encoding representation was introduced. Soleimani, Seyyed-Esfahani and Shirazi [23] proposed a multi-period, multi-product closed-loop supply chain network with stochastic demand and price. A multi criteria scenario based solution approach was then developed to find an optimal solution through some logical scenarios and three comparing criteria. Mean, Standard Deviation (SD), and Coefficient of Variation (CV) were the mentioned criteria for finding the optimal solution. Ramezani, Bashiri and Tavakkoli-Moghaddam [24] introduced a multi-objective stochastic model to design a forward/reverse supply chain network under an uncertain environment. The performance of chain is evaluated through three measures: profit, customer responsiveness, and quality of suppliers (using Six Sigma concept). The Pareto optimal solutions along with the relevant financial risk are computed to illustrate tradeoffs of objectives, and give a proper insight for having a better decision making.

Soleimani, Seyyed-Esfahani and Kannan [25] addressed the design and planning problem of a CLSC in a two-stage stochastic structure. Based on three types of risk measures (i.e. mean absolute deviation, value at risk and conditional value at risk), three types of mean-risk models were developed as objective functions, and decision-making procedures were undertaken based on the expected values and risk adversity criteria. The performances of these developed mean-risk models were evaluated in various aspects. Ramezani, Kimiagari, Karimi and Hejazi [26] addressed the application of fuzzy sets to design a multi-product, multi-period, closed-loop supply chain network in which three objective functions (i.e., maximization of profit, minimization of delivery time, and maximization of quality) are considered. The authors jointly considered fuzzy/flexible constraints for fuzziness, fuzzy coefficients for lack of knowledge, and fuzzy goal of decision maker(s). Longinidis and Georgiadis [27] introduced a Mixed-Integer Non Linear Programming (MINLP) model that integrates sale and leaseback (SLB) technique with SCN design decisions. By exploiting the properties of the MINLP model, it was reformulated into an exact Mixed-Integer Linear Programming (MILP) model that is solved to global optimality. A real case study from a consumer goods company was utilized in order to show model's functionality and to evaluate its adaptability, robustness, and benefit. Ramezani, Kimiagari and Karimi [28] presented a financial approach to model a closed-loop supply chain design with the deterministic parameters in which financial aspects are explicitly considered as exogenous variables. The main contribution of this paper is to incorporate the financial aspects and a set of budgetary constraints in the supply chain planning.

As pointed out by Shapiro [29], Melo, Nickel and Saldanha-da-Gama [30], the financial consideration is one of the most significant issues in SCM. However, as can be concluded from the above-mentioned literature, the studies integrating financial flows with physical product flows in the SCM, especially in the CLSC area, remains scare [31]. A stream of the literature research with a focus on the closed-loop networks was presented in this section. As can be concluded from the above-mentioned literature and also Table 1,

Table 1. Review of the existing studies in closed-loop supply chain network design.

Reference	Logistic network echelons									Model features									Variables					Goals			
										Period		Product		Parameter													
	Supply centers	Manufacturing centers	Distribution centers	Collection centers	Repair centers	Redistribution centers	Remanufacturing centers	Recycling centers	Disposal centers	Single	Multiple	Single	Multiple	Certain	Uncertain	Capacity expansion	Limitation of facilities	Limitation of capacity	Inventory	Transportation value	Demand satisfaction	Facility capacity	Location/allocation	Change in equity	Responsiveness	Environmental impact	Profit/cost
Fleischmann et al. [2]		2[b]	2	2			2			✓		✓		✓						✓	✓		✓				✓
Salema et al. [14]		2	2	2			2			✓			✓		✓			✓		✓	✓		✓				✓
Üster et al. [15]		1	1	2	2					✓			✓	✓						✓			✓				✓
Ko and Evans [16]		1	2		2		1				✓		✓	✓		✓		✓		✓			✓				✓
Min and Ko [18]		1	2		2		1				✓		✓	✓		✓		✓		✓			✓				✓
Salema et al. [19]		1	2			2	1				✓		✓	✓			✓	✓		✓			✓				✓
El-Sayed et al. [20]	2	2	2	2		2	2		2		✓	✓		✓			✓	✓		✓			✓				✓
Pishvaee et al. [21]		2	2	2			2		2	✓		✓		✓				✓		✓		✓	✓				✓
Wang and Hsu [22]	1[a]	2	2	2			2	2		✓		✓		✓				✓		✓			✓				✓
Ramezani et al. [23]	1	2	2	2		2			2	✓			✓		✓			✓		✓		✓	✓		✓		✓
Soleimani et al. [24]	1	1	2	2	2		2	1	1		✓		✓		✓			✓		✓			✓				✓
This paper		1	2	2	2	2	1		1		✓	✓			✓			✓	✓	✓			✓	✓			✓

[a]1: The facility layer is considered.

[b]2: The location decision is made in the facility layer.

few studies have considered the financial aspects in the SCND problems with uncertainty. Moreover, the majority of these studies have considered the financial aspects as general issues and endogenous, whereas this paper considers the financial aspects as exogenous variables with details appeared in the constraints and the objective functions. The novelty of this work lies on the integration of financial issues within a closed loop supply chain network as, to the best of our knowledge, no other study in the field has made this endeavor.

3. Mathematical model

The model proposed in this paper decided about the facility locations, inventory, and the flows among facilities as well as financial issues with respect to uncertainty of the demands and return rate. The general structure of the proposed closed-loop logistic network is illustrated in Figure 1. The purpose is to evaluate a closed-loop logistic system with the criteria of profit and change in equity. The following sets, parameters and variables are used in the formulation:

Indices:

$\mathcal{I}$ Set of plants, $i \in \mathcal{I}$;

$\mathcal{J}$ Set of distribution centers, $j \in \mathcal{J}$;

$\mathcal{E}$ Set of collection centers, $e \in \mathcal{E}$;

$\mathcal{H}$ Set of recovery centers, $h \in \mathcal{H}$;

$\mathcal{K}$ Set of redistribution centers, $k \in \mathcal{K}$;

$\mathcal{F}$ Set of disposal centers, $f \in \mathcal{F}$;

$\mathcal{M}$ Set of first market customer zones, $m \in \mathcal{M}$;

$\mathcal{N}$ Set of second market customer zones, $n \in \mathcal{N}$;

$\mathcal{T}$ Set of time periods, $t \in \mathcal{T}$;

$\mathcal{S}$ Set of scenarios, $s \in \mathcal{S}$.

Parameters:

d^s_{mt} Demand of first customer m in period t under scenario s

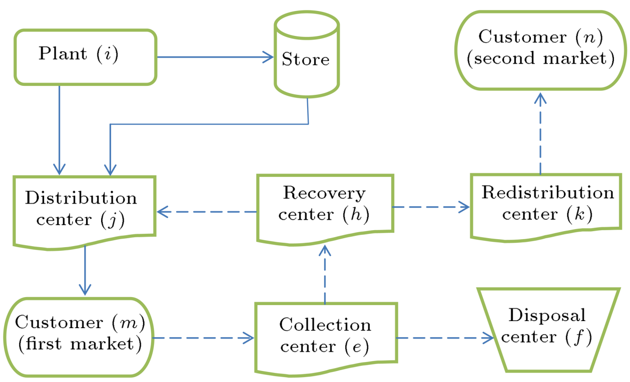

Figure 1. The structure of the proposed supply chain network.

${d'}^s_{nt}$ Demand of second customer n in period t under scenario s;

p_{mt} Price per unit of product for first customer m in period t;

p'_{nt} Price per unit of product for second customer m in period t;

pc_{it} Production cost per unit of product at plant i in period t;

oc_{jt} Operating cost per unit of product at distribution center j in period t;

ic_{et} Inspection and collection cost per unit of product at collection center e in period t;

rc_{ht} Recovery cost per unit of product at recovery center h in period t;

rdc_{kt} Operating cost per unit of product at redistribution k in period t;

dc_{ft} Disposal cost per unit of product at disposal center f in period t;

hc_{it} Holding cost per unit of product at store of plant i in period t;

df_{jt} Fixed cost of establishing distribution center j in period t;

cf_{et} Fixed cost of establishing collection center e in period t;

rf_{ht} Fixed cost of establishing recovery center h in period t;

rdf_{kt} Fixed cost of establishing redistribution k in period t;

cp_{it} Production capacity of plant i in period t;

cs_{it} Store capacity of plant i in period t;

cd_{jt} Processing capacity of distribution center j in period t;

cc_{et} Capacity of collection center e in period t;

cr_{ht} Recovery capacity of recovery center h in period t;

crd_{kt} Redistribution capacity of plant k in period t;

a_{ijt} Transportation cost per unit shipped from plant i to distribution center j in period t;

b_{jmt} Transportation cost per unit shipped from distribution center j to first customer m in period t;

c_{met} Transportation cost per unit shipped from first customer m to collection center e in period t;

d_{eht} Transportation cost per unit shipped from collection center e to recovery center h in period t;

g_{eft} Transportation cost per unit shipped from collection center e to disposal center f in period t;

u_{hjt} Transportation cost per unit shipped from recovery center h to distribution center j in period t;

v_{hkt} Transportation cost per unit shipped from recovery center h to redistribution center k in period t;

o_{knt} Transportation cost per unit shipped from redistribution center k to second customer n in period t;

r_t^s Return ratio of used product in period t under scenario s;

rr_t Recovery ratio of used product in period t;

rs_t Disposal ratio of used product in period t;

rd_t Redistribution ratio of used product for first customer in period t;

re_t Redistribution ratio of used product for second customer in period t

div_t Dividends in period t;

others_t Other net cash obtained in period t;

maxcrd Maximum debt allowed from bank;

mincash Minimum cash imposed from bank;

scu_t Marketable securities of initial portfolio maturing in period t;

ψ The face value of accounts receivable pledged;

$\mu_{tt'}$ Technical coefficient related to investment of marketable securities;

$\lambda_{tt'}$ Technical coefficient related to sale of marketable securities;

$\varphi_{tt'}$ Technical discount coefficient relevant to the payment of production costs executed in period t incurred in period t';

$\chi_{tt'}$ Technical discount coefficient relevant to the payment of handling costs executed in period t incurred in period t';

$\varrho_{tt'}$ Technical discount coefficient relevant to the payment of transportation costs executed in period t incurred in period t'.

Decision variables:

π_{it}^s Quantity of product produced at plant i in period t under scenario s;

α_{ijt}^s Quantity of product shipped from plant i to distribution center j in period t under scenario s;

β_{jmt}^s Quantity of product shipped from distribution center j to first customer m in period t under scenario s;

γ_{met}^s Quantity of returned product shipped from first customer m to collection center e in period t under scenario s;

δ_{eht}^s Quantity of returned product shipped from collection center e to recovery center h in period t under scenario s;

η_{eft}^s Quantity of returned product shipped from collection center e to disposal center f in period t under scenario s;

ρ_{hjt}^s Quantity of returned product shipped from recovery center h to distribution center j in period t under scenario s;

σ_{hkt}^s Quantity of returned product shipped from recovery center h to redistribution center k in period t under scenario s;

τ_{knt}^s Quantity of returned product shipped from redistribution center k to second customer n in period t under scenario s;

θ_{it}^s Quantity of product shipped from plant i to its store in period t under scenario s;

q_{ijt}^s Quantity of product shipped from store of plant i to distribution center j in period t under scenario s;

Inv_{it}^s Residual inventory at store of plant i in period t under scenario s;

$cash_t^s$ Cash in period t under scenario s;

$exncash_t^s$ Exogenous cash in period t under scenario s;

$crdcash_t$ Net cash obtained by money borrowed or repaid to the credit line in period t under scenario s;

$scucash_t$ Net cash received or paid in securities transactions in period t under scenario s;

$ppay_{tt'}^s$ Payment for total costs of production executed in period t on accounts payable incurred in period t' under scenario s;

$hpay_{tt'}^s$ Payment for total costs of handling product in facilities executed in period t on accounts payable incurred in period t' under scenario s;

$tpay_{tt'}^s$ Payment for total costs of transportation executed in period t on accounts payable incurred in period t' under scenario s;

rec_t^s Accounts receivable in period t under scenario s;

$plg^s_{tt'}$	Amount of accounts receivable pledged within period t' incurred in period t;
$crdline_t$	Debt in period t under scenario s;
$loan_t$	Amount of cash borrowed to credit line in period t under scenario s;
$repay_t$	Amount of cash repaid to credit line in period t under scenario s;
$iscu_{t't}$	Total cash obtained in period t' by the marketable securities invested in period t under scenario s;
$cscu_{t't}$	Total marketable securities sold in period t maturing in period t' under scenario s;
$pexpns^s_t$	Expense of production in period t under scenario s;
$hexpns^s_t$	Expense of handling product in facilities in period t under scenario s;
$texpns^s_t$	Expense of transportation in period t under scenario s;
$fexpns_t$	Expense of establishing facilities in period t under scenario s;
$iexpns^s_t$	Expense of holding inventory in stores in period t under scenario s;
ΔE^s	Expected change in equity of enterprise;
ΔSA^s	Expected change in short-term asset of enterprise;
ΔLA^s	Expected change in long-term asset of enterprise;
ΔL^s	Expected change in liabilities of enterprise;
profit^s	Expected profit of enterprise.

$$X_j = \begin{cases} 1 & \text{if distribution center } j \text{ is established,} \\ 0 & \text{otherwise;} \end{cases}$$

$$Y_e = \begin{cases} 1 & \text{if collection center } e \text{ is established,} \\ 0 & \text{otherwise;} \end{cases}$$

$$Z_h = \begin{cases} 1 & \text{if recovery center } h \text{ is established,} \\ 0 & \text{otherwise;} \end{cases}$$

$$W_k = \begin{cases} 1 & \text{if redistribution center } k \text{ is established,} \\ 0 & \text{otherwise;} \end{cases}$$

In terms of the above-mentioned notations, the proposed multi-echelon closed-loop logistic network design problem can be categorized according to balance of physical flow, facilities capacity, balance of financial flow, and interrelated relations.

3.1. Balance of physical flows

$$\pi^s_{it} = \sum_j \alpha^s_{ijt} + \theta^s_{it}, \qquad \forall i, t, s, \qquad (1)$$

$$\theta^s_{it} + Inv^s_{i(t-1)} = \sum_j q^s_{ijt} + Inv^s_{it}, \qquad \forall i, t, s, \qquad (2)$$

$$\sum_i \alpha^s_{ijt} + \sum_i q^s_{ijt} + \sum_h \rho^s_{hjt} = \sum_m \beta^s_{jmt}, \qquad \forall j, t, s, \qquad (3)$$

$$\sum_m \beta^s_{jmt} = d^s_{mt}, \qquad \forall m, t, s, \qquad (4)$$

$$\sum_e \gamma^s_{met} = r^s_t d^s_{mt}, \qquad \forall m, t, s, \qquad (5)$$

$$\sum_h \delta^s_{eht} = \sum_m \gamma^s_{met} rr_t, \qquad \forall e, t, s, \qquad (6)$$

$$\sum_m \gamma^s_{met} = \sum_h \delta^s_{eht} + \sum_f \eta^s_{eft}, \qquad \forall e, t, s, \qquad (7)$$

$$\sum_j \rho^s_{hjt} = \sum_e \delta^s_{eht} rd_t, \qquad \forall h, t, s, \qquad (8)$$

$$\sum_e \delta^s_{eht} = \sum_j \rho^s_{hjt} + \sum_k \sigma^s_{hkt}, \qquad \forall h, t, s, \qquad (9)$$

$$\sum_h \sigma^s_{hkt} = \sum_n \tau^s_{knt}, \qquad \forall k, t, s, \qquad (10)$$

$$\sum_k \tau^s_{knt} = {d'}^s_{nt}, \qquad \forall n, t, s, \qquad (11)$$

Constraint (1) shows the production volume for each plant is equal to the sum of the good flow from the plant to all distribution centers and from the plant to its store. Constraint (2) shows, for each plant and in each period, sum of the good flow from the plant to its store and the residual inventory form previous period is equal to the sum of the good flow from the plant store to all distribution centers and the existing residual inventory. Constraint (3) shows, for each distribution center and in each period, sum of the good flow from all plants, plant stores, and recovery centers to the distribution center is equal to the sum of the good flow from the distribution center to all first market customers. Constraint (4) states that the demand of each first market customer must be satisfied in each period. Constraint (5) relates the returned flow to demand of first market customers in each period. Constraints (6) and (7) show the returned flows from collection center to the recovery and disposal centers, respectively. Constraint (8) relates the returned flow from collection center to the returned flow to distribution center in each period. Constraints (9)-(11) conduct the returned flows to the redistribution centers, and second customer zones.

3.2. Facilities capacity

$$\pi_{it}^{s} \leq cp_{it}, \qquad \forall i, t, s, \qquad (12)$$

$$Inv_{it}^{s} \leq cs_{it}, \qquad \forall i, t, s, \qquad (13)$$

$$\sum_{m} \beta_{jmt}^{s} \leq cd_{jt} X_{j}, \qquad \forall j, t, s, \qquad (14)$$

$$\sum_{h} \delta_{eht}^{s} + \sum_{f} \eta_{eft}^{s} \leq cc_{et} Y_{e}, \qquad \forall e, t, s, \qquad (15)$$

$$\sum_{j} \rho_{hjt}^{s} + \sum_{k} \sigma_{hkt}^{s} \leq cr_{ht} Z_{h}, \qquad \forall h, t, s, \qquad (16)$$

$$\sum_{n} \tau_{knt}^{s} \leq crd_{kt} W_{k}, \qquad \forall k, t, s. \qquad (17)$$

Constraint (12) restricts the production value to the capacity of relevant plant. Constraint (13) shows the capacity of plant store in each time period. Constraints (14)-(17) show the capacity of distribution center, collection center, recovery center, and redistribution center, respectively.

3.3. Balance of financial flows

$$\begin{aligned} \text{cash}_{t}^{s} =& \text{cash}_{t-1}^{s} + \text{exncash}_{t}^{s} + \text{crdcash}_{t} \\ &+ \text{scucash}_{t} - fexpns_{t} - \sum_{t' \leq t} ppay_{tt'}^{s} \\ &- \sum_{t' \leq t} hpay_{tt'}^{s} - \sum_{t' \leq t} tpay_{tt'}^{s} - div_{t} \\ &+ \text{others}_{t}, \qquad \forall t, s, \qquad (18) \end{aligned}$$

$$\begin{aligned} \text{exncash}_{t}^{s} =& rec_{t-t_{del}}^{s} - \sum_{t-t_{del} \leq t' < t} plg_{t-t_{del}t'}^{s} \\ &+ \sum_{t-t_{del} < t' \leq t} plg_{t't}^{s}.\psi, \qquad \forall t, s, \qquad (19) \end{aligned}$$

$$\sum_{t \leq t' < t+t_{del}} plg_{tt'}^{s} \leq rec_{t}^{s}, \qquad \forall t, s, \qquad (20)$$

$$\begin{aligned} crdLine_{t} =& crdline_{t-1} + loan_{t} - repay_{t} \\ &+ \text{ir}.crdline_{t-1}, \qquad \forall t, \qquad (21) \end{aligned}$$

$$crdcash_{t} = loan_{t} - repay_{t}, \qquad \forall t, \qquad (22)$$

$$crdline_{t} \leq maxcrd, \qquad \forall t, \qquad (23)$$

$$cash_{t} \geq mincash, \qquad \forall t, \qquad (24)$$

$$\begin{aligned} scucash_{t} =& scu_{t} - \sum_{t'>t} iscu_{t't} + \sum_{t'>t} cscu_{t't} \\ &+ \sum_{t'<t} iscu_{tt'}.(1+\mu_{tt'}) \\ &- \sum_{t'<t} cscu_{tt'}.(1+\lambda_{tt'}), \qquad \forall t, \qquad (25) \end{aligned}$$

$$\begin{aligned} \sum_{t'<t} cscu_{tt'}.(1+\lambda_{tt'}) \leq& scu_{t} \\ &+ \sum_{t'<t} iscu_{tt'}.(1+\mu_{tt'}), \qquad \forall t, \qquad (26) \end{aligned}$$

$$\sum_{t' \geq t} \varphi_{t't}.ppay_{t't}^{s} \leq pexpns_{t}^{s}, \qquad \forall t, \qquad (27)$$

$$\sum_{t' \geq t} \chi_{t't}.hpay_{t't}^{s} \leq hexpns_{t}^{s}, \qquad \forall t, \qquad (28)$$

$$\sum_{t' \geq t} \varsigma_{t't}.tpay_{t't}^{s} \leq texpns_{t}^{s}, \qquad \forall t. \qquad (29)$$

Constraint (18) states that the cash in each period is computed based on the cash in previous period, exogenous cash derived from the sales of products, and the pledging of accounts receivables, net cash obtained by money borrowed or repaid to the credit line, net cash received or paid in securities transactions, payment for costs related to facilities, dividends, and net cash resulted from any other source. Constraint (19) shows that the exogenous cash in each period is equal to the sum of the accounts receivable belonged to period of $t - t_{del}$ matured in period t, minus total amount of the accounts receivable pledged within period $t - t_{del}$ to $t-1$ belonged to periods $t - t_{del}$, plus the cash derived from pledging of accounts receivable belonged to periods $t - t_{del} + 1$ to t matured in period t. Constraint (20) states that the total amount of accounts receivable belonged to periods t pledged within period t to $t + t_{del} - 1$ cannot exceed the amount of accounts receivable in period t.

Constraint (21) states that the total debt in each period is a function of the debt in the previous period, cash borrowed to credit line, cash repaid to credit line, and the interest costs, where Net cash obtained by money borrowed or repaid to the credit line is defined as Constraint (22). In addition to pledging, loan borrowed from bank is another financing source, obtained at the beginning of period with annual interest rate (ir) under an agreement with the bank. In this case, the bank imposes firm to have minimum cash, usually as percentage of the amount borrowed, and also restricts firm to an open line of credit. Constraints (23) and (24) show the minimum cash and the maximum credit agreed with the bank.

Constraint (25) shows that, in each period, the cash relevant to the securities transactions is computed as sum of the cash derived from the marketable securities of initial portfolio, minus the cash invested as the marketable securities in the current period, plus the cash resulted from the sale of the marketable securities in the current period, plus total cash obtained in the current period by the marketable securities invested in previous periods with regard to technical coefficient of investment ($\mu_{tt'}$), and minus total marketable securities sold in previous periods maturing in the current period with regard to technical coefficient of sale ($\lambda_{tt'}$). Constraint (26) states that, in each period, total marketable securities sold in previous periods, maturing in the current period, cannot exceed the sum of the cash derived in the current period from the marketable securities of initial portfolio and total cash obtained in the current period by the marketable securities invested in previous periods. Finally, constraints (27)-(29) show the payments associated with production, handling, and transportation with regard to the relevant expenses.

3.4. Interrelated relations

$$pexpns_t^s = \sum_i \pi_{it}^s.pc_{it}, \qquad \forall t, s, \qquad (30)$$

$$hexpns_t^s = \sum_j \sum_m \beta_{jmt}^s.oc_{jt} + \sum_m \sum_e \gamma_{met}^s.ic_{et} + \sum_e \sum_h \delta_{eht}^s.rc_{ht} + \sum_h \sum_k \sigma_{hkt}^s.rdc_{kt} + \sum_e \sum_f \eta_{eft}^s.dc_{ft}, \qquad \forall t, s, \qquad (31)$$

$$texpns_t^s = \sum_i \sum_j (\alpha_{ijt}^s + q_{ijt}^s).a_{ijt} + \sum_i \theta_{it}^s.a'_{it} + \sum_j \sum_m \beta_{jmt}^s.b_{jmt} + \sum_m \sum_e \gamma_{met}^s.c_{met} + \sum_e \sum_h \delta_{eht}^s.d_{eht} + \sum_e \sum_f \eta_{eft}^s.g_{eft} + \sum_h \sum_j \rho_{hjt}^s.u_{hjt} + \sum_h \sum_k \sigma_{hkt}^s.v_{hkt} + \sum_k \sum_n \tau_{knt}^s.o_{knt}, \qquad \forall t, s, \qquad (32)$$

$$fexpns_t = \sum_j X_j.df_{jt} + \sum_e Y_e.cf_{et} + \sum_h Z_h.rf_{ht} + \sum_k W_k.rdf_{kt}, \qquad \forall t, \qquad (33)$$

$$iexpns_t^s = \sum_i Inv_{it}^s.hc_{it}, \qquad \forall t, s, \qquad (34)$$

$$rec_t^s = \sum_j \sum_m p_{mt}.\beta_{jmt}^s + \sum_k \sum_n p'_{nt}..\tau_{knt}^s, \qquad \forall t, s, \qquad (35)$$

$$\Delta SA^s = cash_T^s + \sum_{T-t<t_{del}} rec_t^s - \sum_{t,t'|T-t\leq t_{del} \wedge t'>T-t_{del}} plg_{tt'}^s + \sum_i Inv_{iT}^s.pc_{iT} - \text{cash}_{t_0}^s - rec_{t_0}^s - \sum_i Inv_{it_0}^s.pc_{it_0}, \qquad (36)$$

$$\Delta LA^s = \sum_t fexpns_t - fexpns_{t_0}, \qquad (37)$$

$$\Delta L^s = crdline_T + \sum_t pexpns_t^s + \sum_t hexpns_t^s + \sum_t texpns_t^s - \sum_{tt'} \varphi_{tt'}.ppay_{tt'}^s - \sum_{tt'} \chi_{tt'}.hpay_{tt'}^s - \sum_{tt'} \varsigma_{tt'}.tpay_{tt'}^s - crdline_{t_0}. \qquad (38)$$

To determine the outflows of cash required to compute the profit and the equity, the expense of production, handling, transportation, establishing facilities, and holding inventory are defined as Constraints (30)-(34), respectively. Constraint (35) shows that, in each period, the accounts receivable is defined as the sale of final products to the customers in the same period. The change in short-term assets is equal to the difference between the short-term assets (including the cash available, accounts receivable, and inventory) at the end of first period and last period presented as Constraint (36). In this equation, the inventory value is computed based on the Generally Accepted Accounting Principles (GAAP) of historic cost, i.e. the lowest price that is production price. Constraint (37) shows the change in long-term assets as sum of expenses of establishing facilities at the end of last period minus the expenses of establishing facilities at the end of the first period. Constraint (38) states that the change in liabilities is equal to the difference between the short-term and long-term liabilities at the end of the first period and the last period including the debts and accounts payable related to the production, handing, and transportation.

3.5. Objective functions

$$
\begin{aligned}
profit^s = & \sum_j \sum_m \sum_t p_{mt} \cdot \beta^s_{jmt} + \sum_k \sum_n \sum_t p'_{nt} \cdot \cdot \tau^s_{knt} \\
& - \sum_t pexpns^s_t - \sum_t hexpns^s_t \\
& - \sum_t texpns^s_t - \sum_t iexpns^s_t \\
& - fexpns_t, \qquad \forall s, \qquad (39)
\end{aligned}
$$

$$\Delta E^s = \Delta SA^s + \Delta LA^s - \Delta L^s, \qquad \forall s. \qquad (40)$$

The first objective is the profit that is equal to the total income associated with the sales of products in customer zones minus the total cost associated with the expenses of production, processing, inventory, and transportation expressed by Eq. (39). Traditionally, the decisions related to design/planning and financial issues are measured in isolated environments. The more common objectives traditionally used in the literature is maximization of the profit or minimization of the cost. However, the financial community has been for years making decisions taking into account other criteria, such as market to book value, liquidity ratios, capital structure ratios, return on equity, sales margin, turnover ratios, stock security ratios, etc. Nevertheless, second objective function considers the direct enhancement of the shareholder's value as the change in equity expressed by Eq. (40).

4. Multi-objective robust optimization

Robust optimization approaches include the min-max and min-max regret versions defined by Kouvelis and Yu [32]. Let S be a finite set of scenarios and x denote the feasible solution of a given problem. For a minimization problem, $Z_s(x)$ and Z^*_s denote the objective and the optimal objective of problem under scenario s (where $s \in S$), respectively. The goal of the min-max version is to find a solution with the best worst case value across all possible scenarios, which can be stated by:

$$\min_{x \in X} \max_{s \in S} Z_s(x).$$

In the min-max regret version, the regret value of each scenario is defined by the difference between the objective value of the feasible solution (i.e., $Z_s(x)$) and the optimal objective value (i.e., Z^*_s). This difference can be defined by the absolute regret or relative regret. The goal of the min-max regret and the min-max relative regret is to find a robust solution minimizing its maximum regret and its maximum relative regret, respectively, which can be formulated by:

$$\min_{x \in X} \max_{s \in S} Z_s(x) - Z^*_s,$$

$$\min_{x \in X} \max_{s \in S} \frac{Z_s(x) - Z^*_s}{Z^*_s}.$$

Indeed, the corresponding max-min and min-max regret version can be defined for maximization problems.

Aissi, Bazgan and Vanderpooten [33] addressed the min-max regret and min-max relative regret approaches and presented a comprehensive discussion of the incentives for developing these approaches and diverse aspects of employing robust optimization in practice. Chan, Kumar and Choy [13], Ben-Tal and Nemirovski [34] were engaged in robust optimization, by allowing the data to be ellipsoids, and proposed efficient algorithms to solve convex optimization problems under data ambiguity. Gümüs and Güneri [35], Bertsimas and Sim [36] presented an approach for discrete optimization and network flow problems that provides the degree of conservatism of the solution to be handled. They demonstrated that the robust equivalent of an NP-hard α-approximable 0-1 discrete optimization problem stays α-approximable.

In addition, some approaches have been proposed to reduce the number of scenarios. Lee, Chiu, Yeh and Huang [37] proposed an α-reliable min-max regret model to find a solution minimizing the problem with regard to a selected subset of scenarios whose occurrence probability is greater than the user-specified value α. Moussawi-Haidar and Jaber [38] suggested another approach, called lexicographic α-robustness, which considers all scenarios in the lexicographic order from the worst to the best, instead of considering the worst case scenario. This approach incorporates a tolerance threshold, α, so not to differentiate among solutions with similar values. Assavapokee, Realff, Ammons and Hong [39] presented a scenario relaxation algorithm for the min-max regret version and the min-max relative regret version. The algorithm iteratively solves and updates a series of relaxed sub-problems so that both the feasibility and optimality conditions of the problem are satisfied.

The proposed model in this study assumes that the demand and the return rate are uncertain, introduced by a finite set of possible scenarios with unknown joint probability distribution. To obtain a Pareto solution of the proposed model, we use the ϵ-constraint method presented by Wang, Fu, Lee and Zeng [40]. This method is one of the multi-objective techniques with priori articulation of DM's preference information and is a one-stage technique with computationally fast time. The method is based on optimization of one objective function and considering the other objectives as constraint with allowable worst bound. Then, the bound is consecutively modified to generate the other Pareto-optimal solutions. Corresponding to the ϵ-constraint method, the robust multi-objective closed-loop SCND problem with the best worst case value across all possible scenarios is formulated as follows:

$$\min \quad \zeta$$
$$\text{s.t.} \quad \left.\begin{array}{l} f_1^s(V,Q_s) \geq \zeta \\ f_2^s(V,Q_s) \geq g_2 \\ \text{Eqs. (1)-(38)} \end{array}\right\} \quad \forall s \in S, \tag{41}$$

where f_s^1 is the first objective function under scenario s; g_2 is the desired worst of second objective function; V is the set of first-stage variables; and Q_s is the set of second-stage variables, where, decision variables have to be taken before the realization of the uncertainty and the second-stage variables will be made after the uncertain parameters have been revealed.

Unfortunately, the size of the model presented in Relation (41), referred as the extensive form model under deviation robust definition, can become unmanageably large when a large number of scenarios are considered. The implementation of this model requires a vigorous computational time to obtain a robust solution with a large number of scenarios. For this reason, we use the scenario relaxation algorithm to obtain a solution with a better time. In the algorithm, the optimal first objective function of each scenario is necessarily resulted by solving the following model.

$$f_s^{1*} = \begin{cases} \max \quad f_1^s(V,Q_s) \\ \text{s.t.} \\ \qquad f_2^s(V,Q_s) \geq g_2 \\ \qquad \text{Eqs. (1)-(38)} \end{cases} \tag{42}$$

The main idea of the scenario relaxation algorithm is that in a problem with a large number of possible scenarios only a small subset of scenarios actually is employed to find an optimal solution. Initially, the algorithm solves the problem for a subset of scenarios (sub-problems) and then sequentially searches to examine all possible scenarios. The algorithm adds those scenarios that disturb the optimality and/or feasibility conditions to the sub-problem. It is showed that the algorithm stops at an optimal robust solution (if one exists) in a finite number of iterations. The overall procedure of the scenario relaxation algorithm for the max-min version can be summarized as follows.

Step 0: Select a subset $\bar{S} \subset S$, set $LB = -\infty$ and $UB = 0$, determine a predetermined small nonnegative value ε, and then proceed to Step 1. Here subset $\bar{S}$ randomly is selected and its cardinality is two. Moreover, value of ε is equal to zero.

Step 1: Solve the relaxed model considering only the scenario set $\bar{S}$ instead of S. If the relaxed model is infeasible, the algorithm is ended (i.e., no robust solution exists). Otherwise, set $UB = \zeta^*$ (i.e., the optimal value of the relaxed model) and fix the first-stage variables in the current solution form of the relaxed model. If $LB - UB \geq \varepsilon$, the resulting robust solution is globally ε-optimal robust solution, and algorithm is ended. Otherwise, proceed to Step 2.

Step 2: Solve the general model for each scenarios $S \backslash \bar{S}$. Let $S_1 \subset \backslash \bar{S}$ such that the model is infeasible and let $S_2 \subset S \backslash (\bar{S} \cup S_1$ such that $f_s^{1*}(V,Q_s) \leq \zeta^*$.

Step 3: If $S_1 \neq \emptyset$ proceed to Step 4. Otherwise, update the lower bound of algorithm as follows.

$$LB \leftarrow \max(LB, \min_{s \in S}(f_s^{1*}(V,Q_s))).$$

If $LB - UB \geq \varepsilon$, the resulting robust solution is globally ε-optimal robust solution and algorithm is ended. Otherwise, proceed to Step 5.

Step 4: Choose a subset $S_1' \subset S_1$, add to scenario set $\bar{S}$, and then proceed to Step 1. Here, we randomly select subset S_1' with cardinality 2 as algorithm confronts the scenarios in which model is infeasible.

Step 5: Choose a subset $S_2' \subset S_2$, add to scenario set $\bar{S}$, and then proceed to Step 1. Here, we select subset S_2' with cardinality 1 as value of $f_s^{1*}(V,Q_s)$ is minimum, although it can be randomly selected.

5. Computational results

To demonstrate the verification and practicality, we consider several test problems to analyse the proposed supply chain system. The sizes of these test problems are illustrated in Table 2. The proposed closed-loop supply chain involves two echelons in forward direction related to the plants, distribution centers, and first customers as well as four echelons in backward direction related to the collection centers, recovery centers, redistribution centers, disposal centers, and second customers. The plants are responsible for producing the

Table 2. Size of test problems.

Problem code	$\lvert\mathcal{I}\rvert$	$\lvert\mathcal{J}\rvert$	$\lvert\mathcal{E}\rvert$	$\lvert\mathcal{H}\rvert$	$\lvert\mathcal{K}\rvert$	$\lvert\mathcal{F}\rvert$	$\lvert\mathcal{M}\rvert$	$\lvert\mathcal{N}\rvert$	$\lvert\mathcal{T}\rvert$
2-3-3-3-2-2-5-3-5	2	3	3	3	2	2	5	3	5
3-5-4-4-3-2-10-5-5	3	5	4	4	3	2	10	5	5
4-6-4-4-3-3-15-8-5	4	6	4	4	3	3	15	8	5
5-7-4-4-3-3-20-5-10	5	7	4	4	3	3	20	5	10
7-10-6-5-4-3-25-8-10	7	10	6	5	4	3	25	8	10
8-12-7-6-6-4-30-10-10	8	12	7	6	6	4	30	10	10

new product to first customer shipped via distribution centers. In backward direction, the returned products from customers are shipped to collection centers to inspect. If the returned product is recoverable, it is shipped to the recovery center; otherwise, it is shipped to the disposal center. After shipping the recoverable products to recovery centers, depending on the quality of the recovered products, they are shipped to distribution or redistribution centers.

Table 3 illustrates the parameters used in the test problems. The initial cash is equal to 300000, where the minimum cash in each period is equal to 120000. Moreover, an open line of credit with a maximum debt of 100000 is allowed in each period. Table 4 shows the initial portfolio of marketable securities investment. The price of the inventories at the end of the time period is the lowest price, i.e. the production price. The products sold in each period are paid with a delay of 2 time periods and the account receivables are pledged at 80% of their value. Moreover, liabilities borrowed due to the costs of production, processing in facilities must be repaid within 3 time period (2%: 1 time period, net-3 time periods), where technical coefficients ($\varphi_{tt'}$, $\chi_{tt'}$ and $\varrho_{tt'}$) introduce the relevant term. Thus, the discount can be obtained if the payments are executed timely, otherwise the discount cannot be acquired. The payments related to the transportation services cannot be stretched, and must be executed within the same period of time. Associated with technical coefficients and with transactions of marketable securities, a 2.8% annual interest for purchases and a 3.5% one for sales are assumed. Outflows withdrawn from the company, as dividends at the end of the time horizon, as well as outflows due to payrolls, tax, wages, rents, changes in fixed assets, and the repayment of the long-term debt during the whole time horizon are also considered. It is assumed that each uncertain parameter can varies from 80% to 120% of the values in the deterministic model that is defined by a finite number of possible scenarios. The number of possible scenarios also varies from 20 to 150 scenarios in each test problem. The test problems were coded using GAMS and CPLEX solver with $\varepsilon = 0$ on a computer with an Intel core2 Duo 2.00 GHz processor and 2.00 GB of RAM.

Table 3. Values of parameters used in the test problems.

Parameter	Value
d	Uniform (400, 650)
d'	Uniform (170, 260)
p	Uniform (230, 320)
p'	Uniform (140, 210)
pc	Uniform (25, 35)
oc	Uniform (10, 15)
ic	Uniform (3, 7)
rc	Uniform (8, 16)
rdc	Uniform (9, 15)
dc	Uniform (4, 9)
hc	Uniform (4, 9)
df	Uniform (30,000, 45,000)
cf	Uniform (10,000, 15,000)
rf	Uniform (15,000, 20,000)
rdf	Uniform (12,000, 16,000)
cp	Uniform (750, 900)
cs	Uniform (150, 250)
cd	Uniform (550, 750)
cc	Uniform (450, 600)
cr	Uniform (250, 350)
crd	Uniform (200, 300)
a, b, c, d, g, u, v, o	Uniform (2, 9)
r	Uniform (0.35, 0.55)
rr	Uniform (0.6, 0.9)
rs	1-rr
rd	Uniform (0.5, 0.65)
re	1-rd

To evaluate the proposed model, first, we consider the test problem 1 with Gap 0. Figure 2 shows trade-off between the profit and the change in equity as a Pareto curve, while the number of scenarios is equal to 20. As can be seen in Figure 2, the profit decreases with increase of the change in equity. In addition, a sensitivity analysis of demand is shown in Figure 2, where with increase of demand, both, the change in equity and the profit increase, as well as with decrease of demand, the objectives decrease. This Pareto curve helps the decision maker(s) for a better

Table 4. Marketable securities of initial portfolio.

	Time periods									
	***t*1**	***t*2**	***t*3**	***t*4**	***t*5**	***t*6**	***t*7**	***t*8**	***t*9**	***t*10**
Initial portfolio	40000	30000	21000	15000	12000	25000	20000	35000	8000	27000

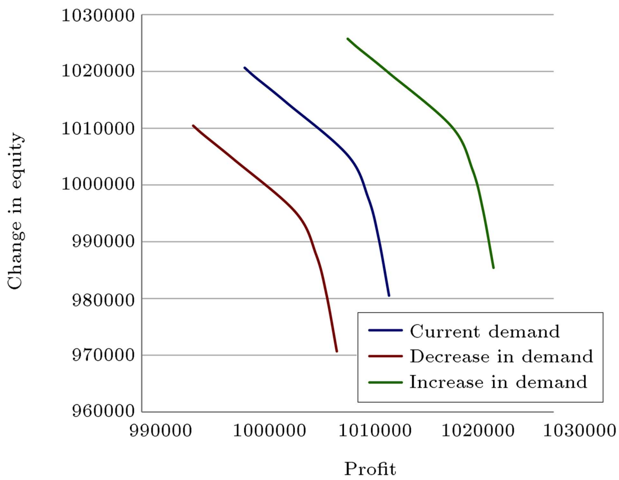

Figure 2. Change in equity versus profit.

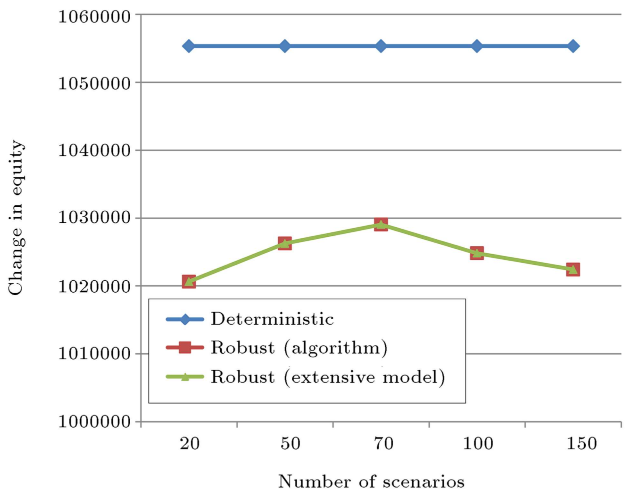

Figure 3. Change in equity for the different modes.

analysis. Moreover, Figure 3 shows the behavior of objective function of the change in equity under the different scenarios. The value of change in equity for the robust mode computed by both the extensive model and the scenario relaxation algorithm is less than the deterministic mode; this is reasonable because the robust approach optimizes the worst-case scenario. As can be seen in Figure 3, the values of the change in equity for the extensive model and the scenario relaxation algorithm is the same. It is proved that the scenario relaxation algorithm produces an optimal solution, of course with a better time.

On the other hand, to illustrate the applicability of the scenario relaxation algorithm, six test problems with various scenarios are evaluated only by the change in equity; the relevant results are reported in Table 4. If the extensive model does not obtain a solution within 1 hour, the computational time is reported as "> 1 hr" in this table. As can be observed, the number of constraints and variables of test problems increase with increment in the number of scenarios. As the results show, the scenario relaxation algorithm dominates the extensive model in all test problems with respect to the computational time; especially this superiority is more significant when the scale of test problems and the number of scenarios are increased. Table 5 also shows the number of scenarios actually used by the scenario relaxation algorithm (i.e., $|\bar{S}|$) to find an optimal solution. Increase (or decrease) in number of these scenarios proportionally increases (or decreases) the computational time of the scenario relaxation algorithm. For example, in test problem 3, the computational time of algorithm, for instance with 70 scenario, is greater compared, for instance, with 100 scenario; this is because the number of scenarios employed by the algorithm for instance with 70 scenario, is more compared for instance with 100 scenario. According to the previous discussion, the results are consistent and obviously show the benefit of using the scenario relaxation algorithm over the extensive model. These results, which are good improvements, convince the decision makers to employ the scenario relaxation algorithm.

6. Conclusion

This paper has presented a model integrating the financial flows with the physical flows in the design of a closed-loop supply chain in which the effective measure based on an economic performance indicator (i.e. the change in equity) in addition to the commonly used profit is regarded. The model also has considered the uncertainty in demand and return rate through scenario, which assign the occurring possibilities on each scenario. This approach enables the supply chain managers to forecast their demands and return rate as well as to modify their wrong forecasts. To cope with the uncertainty, the robust optimization was employed in the proposed model. Moreover, to find a robust solution with better time, the scenario relaxation algorithm was extended to a max-min version and for multiple objectives. The results showed a successful design of the proposed closed-loop logistic network as well as an obvious performance of the scenario relaxation algorithm on the given problems.

Table 5. Computational results for test problems.

Problem code	$\|S\|$	$\|\bar{S}\|$	Computational time (s)		Gap	Variables	Constraints
			The extensive form model	The algorithm			
2-3-3-3-2-2-5-3-5	20	4	22	13	0.00	10,367	6,239
	50	6	76	45	0.00	25,817	15,539
	70	5	134	54	0.00	36,117	21,739
	100	7	252	81	0.00	51,567	31,039
	150	5	495	73	0.00	77,317	46,539
3-5-4-4-3-2-10-5-5	20	3	28	17	0.00	21,872	8,939
	50	4	219	59	0.00	54,572	22,289
	70	4	333	77	0.00	76,372	31,189
	100	5	801	105	0.00	109,072	44,539
	150	4	1097	158	0.00	163,572	66,789
4-6-4-4-3-3-15-8-5	20	4	109	36	0.00	31,673	10,839
	50	3	466	44	0.00	79,073	27,039
	70	4	904	94	0.00	110,673	37,839
	100	3	1112	76	0.00	158,073	54,039
	150	4	2077	172	0.00	237,073	81,039
5-7-4-4-3-3-20-5-10	20	3	159	42	0.00	82,779	24,179
	50	4	601	87	0.00	206,679	60,329
	70	4	1103	128	0.00	289,279	84,429
	100	5	>1 hr	167	0.00	413,179	120,579
	150	3	>1 hr	198	0.00	619,679	180,829
7-10-6-5-4-3-25-8-10	20	4	606	179	0.01	147,386	31,779
	50	5	>1 hr	452	0.01	368,186	79,329
	70	5	>1 hr	557	0.01	515,386	111,029
	100	3	>1 hr	201	0.01	736,186	158,579
	150	4	>1 hr	372	0.01	1,104,186	237,829
8-12-7-6-6-4-30-10-10	20	3	591	124	0.01	209,992	37,779
	50	5	>1 hr	405	0.01	524,692	94,329
	70	4	>1 hr	571	0.01	734,492	132,029
	100	5	>1 hr	719	0.01	1,049,192	188,579
	150	4	>1 hr	651	0.01	1,573,692	282,829

As a result, incorporating the financial flow helps DM(s) to take holistic decisions in order to guarantee new funds from shareholders and financial institutions that will permit the continuously financing of company's operations. Moreover, related to performance measures, a decision making process, that does not consider both these measures, may result in configuration which performs well only one of the objectives, but performs poorly the other objectives. Hence, the trade-off between these measures, as a Pareto curve, is a useful tool for the supply chain managers to make a proper decision. Finally, it should be pointed out that incorporating other issues related to the product portfolio theory, game theory, future contracts, and sell techniques in model can be considered as future research.

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