A multi-stage stochastic programming model for sustainable closed-loop supply chain network design with financial decisions: A case study of plastic production and recycling supply chain

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Abstract: This paper proposes a multi-objective, multi-stage programming model to design a sustainable closed-loop supply chain network considering financial decisions. A multi-product, sustainable closed-loop plastic supply chain network design problem which encompasses economic, environmental and social objectives is modeled in a mathematical manner. The decisions to be made are concerned with location of facilities; the flow of products, loans to take and investments to make. Uncertainty issue is about demand of customers and investment's rate of return. The decision making model is formulated as a multi-objective, multi-stage mixed integer linear programming problem and is solved by implementing path formulation and augmented ε-constraint methods. Computational analysis, is provided based on the subject company to determine the significance of the proposed model and the efficiency regarding integrating financial decisions with supply chain network design decisions.

Keywords: *supply chain management, Sustainability, Stochastic programming, Supply chain network design, Multi-objective optimization.*

1. Introduction

Due to recent advances made, globalization and unpredictable customer and competitor's behaviors, the field of competition is converted from firm's competition to supply chain's competition. Consequently, supply chain management (SCM) is one of the most sought topics in logistics. Moreover, Supply chain network design (SCND) is a strategic decision contributing to supply chain. Integrating several strategic and tactical decisions like determining the locations, number and capacity of facilities and material flow through the network, make SCND a complex issue in SCM field.

Previously, minimizing total cost or maximizing profit was the main objective of supply chain and pioneering in economical dimension was sufficient to outperform the rivals, while today supply chains are responsible for the environmental and social impacts of their activities. This concern has led to development of a new concept in SCM named the sustainable supply chain management (SSCM), defined as the considering environmental and social impacts of supply chain activities as well as its economic performance in management of material, information and capital flow [1], [2]. With respect to need for sustainability in SCM, some researches propose models regarding SCND

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context. However, the literature on sustainable SCND that covers all three aspects of sustainability (i.e., Economical, Environmental and Social aspects) is scare [3]. Recently, Eskandarpour et al., [4] Reviewed 87 papers that use mathematical models in the field of SCND and include economic factors together with environmental and/or social dimensions. Based on their analysis, in 11% of their reviewed articles all three dimensions of sustainable development in SCND models are concerned.

To avoid sub-optimality that originates from separate modeling of forward and reverse SCNs, some researchers have focused on developing integrated forward and reverse SCND models [5]. Appropriate established close-loop SN (CLSC) can assist firms to decrease the undesired environmental impact of end-of-life (EOL) products and to achieve more economical benefits by recapturing the value of used products and increase their green image in the market. The objective of closed-loop supply chain is closely related to that of SSCM [4]. Accordingly, in the body of SSCND literature, closed-loop SSCND problems have been the major issue among researchers in the recent years [6].

An important challenge associated with SCND problems is to determine the manner of handling the uncertain nature of some future conditions which may influence input parameters of the problem. Uncertainty can be affiliated to economic, legal and political issues, and affects parameters like the level of demand, production cost, supply of raw materials and etc. To cope with this issue in SSCND context; many authors have proposed a number of stochastic programing models.

Recently, a two-stage stochastic programming approach is applied by Giarola et al., [7] and Verma et al., [8] to manage uncertainties in single objective environmental supply chain design. Authors in [9] introduce a robust possibilistic programming (RPP) as a programming approach to cope with uncertain parameters in their bi-objective model, including minimizing the total cost and maximizing SC social responsibility. The computational framework to quantify the influence that uncertainty in the environmental damage could have in the multi-objective optimization of sustainable supply chain is proposed in [10]. A multi-objective (economic and environmental factors) facility location model which investigate the impact of demand and return uncertainties on the SCND by implementing scenario-based stochastic programming is introduces by Amin and Zhang [11]. A stochastic multi-scenario mixed-integer linear program (MILP) where demand uncertainty on the multi-objective optimization of chemical supply chain, Economic and environmental performances are considered in a simultaneous manner is presented by Ruiz-Femenia [12]. The fact that uncertainty and risk should better be considered in sustainable SCND researches is emphasized by Eskandarpour et al., [4].

According to Shapiro [13], strategic level supply chain studies, should make the attempt to incorporate relevant corporate financial decisions in data-driven models. But in the most common approaches in SCND problems only the physical aspect of SC are of concern with a few outlook on financial decisions in the body of literature [14]. Implementing investment decisions and deciding on loans as financial decisions in SCND problem is addressed in [15]. The issue of an optimal financing strategy for supply chain with considering capital constraint is discussed in [16]. Most researchers usually take into account the financial aspect as financial factors [14] and financial flows of SC, while few studies address financial decisions in SCND model as decision variables.

In some cases, it is enough to consider a single-period model to develop an ideal solution for SCND problem. Nevertheless, problems with financial and capital expenditure related decisions should be planned by implementing multi-period planning models [17]. Furthermore, implementing multi-period setting of this model and nature of financial decisions would lead to a multi-stage stochastic programming. Financial decisions involve a sequence of decisions that react to outcomes that evolve over time periods, multi-stage stochastic programming introduce proper strategy to cope with complexity of this issue in SSCND problem [18]. Multi-stage stochastic programming is applied by Nickel et al., [15] to solve SCND problem with financial decisions and uncertainty assumption for demand and interest rate, where uncertainty is presented by a set of scenarios. Despite the importance of integrity between financial and physical aspects in SCND problems, to the best of the authors' knowledge, the financial aspect is completely ignored by researches in the context of sustainable SCND. A list of the above mentioned studies and some other studies in the field of sustainable supply chain is tabulated in Table 1.

To fill the gap of literature on SSCND, a comprehensive multi-stage stochastic mixed-integer linear programming model for a real life multi-period multi-product multi-objective closed-loop SSCND problem with financial decisions and risk consideration subject to investment return rate and demand uncertainty is proposed in this article. This is the first time where in an article financial decisions are applied in SSCND problem. Additionally, this is first time that a SSCND model is developed with all the above mentioned features of multi-objective, multi-product, multi-period, risk measure, uncertainty issue, financial decisions and closed-loop, together with the observance of the all 3 dimensions of sustainable development operating in a simultaneous manner. This proposed model is adopted in designing a real plastic production and recycling supply chain as a case study through which the practical value of this research is proved.

The rest of this paper is organized as follow. The real industrial problem is defined and illustrated in Sec. 2; the problem is formulated as a multi-objective multi-stage stochastic programming model in Sec. 3; the scenario path formulation method is implemented and presented in Sec. 4; the computational analysis of the problem results and the value of considering financial decisions are presented in Sec. 5; the value of multi-stage stochastic problem is measured in Sec. 6; and this article is concluded in Sec. 7.

2. Problem definition

In the last 60 years, plastic has become one of the most practical materials with a wide range of applications. In 2014, around 311 million tons of plastic was produced around the world and 25.8 million tons of post-consumer plastics waste ended up in the waste upstream just in EU, while 30.8% of plastic wastes are still in landfills in EU [33]. Chemically speaking, some reports state that plastic materials take hundreds of years to break down in a landfill. In Iran, 17000 tons of plastics are produced annually, therefore, it can be deduced that managing EOL of different plastic products is a critical and vital issue which can affect all three dimensions of sustainable development.

The logistics network discussed in this article, as illustrated in Figure 1, is formed based on a real Iranian plastic production and recycling supply chain with five echelons of production and recycling center, retailers, customers, collection centers and landfill centers. A new product is produced by recycling EOL products at different production and recycling centers, and then is shipped to retailers based on their demand and availability of the product. Some customers return EOL products to retailers and retailers send it to collection centers, recyclable EOL products are separated and shipped to production and recycling centers and the remained are sent to landfill center. Uncertainty is associated with demand and return rate and multi-period planning horizon is considered. The problem is about finding optimal decision in each period for: location of facilities, production (or collection) technology, investments to make, loans to take and flow of products between facilities.

Each period is divided into two consecutive phases of before and after knowing the demand and return rates of investments [15]. Decisions made on location of facilities, production technology, investment and loans should be made in first phase, and decision regarding flow of product between facilities in the second phase.

It is assumed that phase one decisions can change from one period to another one. Retailers, customers and landfill center are already fixed and location decisions are about production and recycling centers, and collection centers. In addition, it is assumed that customers pay their debts in the end of time periods, this assumption contributes to better conceive the financial decisions and parameters.

Financial decisions are investment and loan related. Various investment alternatives can be considered for a corporate which is making decision on supply chain network design problem. Investments in stock market, bonds, real state, supply chain tangible assets and supply chain intangible assets are considered as the alternatives in the problem. In addition, deciding how to leverage financial power of a given corporate by taking loan is another strategic financial decision considered in the problem. Diverse loans with different interest rate, payback time and payback policies are among the loan alternatives. ROI is implemented as an index to evaluate financial decisions by [15] who set target for ROI and minimize the downside risk of it. This policy is adopted in this article for evaluation and control of financial performance of the subject. Construction and equipment depreciation rate is another financial parameter influencing ROI. This parameter is not considered in [15] and is not a matter of concern in SSCND literature, nevertheless depreciation rate of facilities is an important parameter that can affect economic performance of supply chain in long term.

Uncertainty is associated with demand and return rate of different investment alternatives. Set of events are considered in assessing the uncertainty of stochastic parameters, where each event consists of demand sub-events and return rate sub-events (defined as an event that just declare one of the stochastic parameters) which are combined in one event and demonstrate both stochastic parameters in a simultaneous manner. For more information about scenario creation, interested readers can refer to [34].

Each time period is divided into two phases where decisions made separately. There exist a problem and an objective function in each phase with the objective of achieving reasonable balance among the three dimensions of sustainability. Decisions on investments, locations and loans should be made in the first phase, and decision on shipment should be made in second phase.

2.1. Environmental impact

To move towards sustainable design in supply chain networks, it is necessary to implement methods and apply tools to measure environmental impact (EI) in different SCND decisions. Each product has different environmental impacts in its various life cycle stages, accordingly, appropriate frameworks should be applied for estimating and assessing the environmental impacts related to the whole life cycle of products. Life cycle assessment (LCA) is a popular component for quantifying and assessing the environmental impact of the product [35]. In order to quantify and assess the EI of products, a LCA-based damage oriented method named Eco-indicator 99 [36] is adopted in this article. User friendly units named Eco-indicators which enable researchers to aggregate and calculate LCA results in an easily understandable manner, is introduced in Eco-indicator 99. This method is of three damage categories of human health, ecosystem quality and resources [37].

2.2. Social impact assessment

Social responsibility is a multidisciplinary and multi-stakeholder phenomenon and its complex nature and extensive scope make its measurement difficult. However, during the past years, many efforts are made to support planning and implementing corporate social responsibility (CSR). A number of standards such as ISO 26000 [38], SA 8000 [39] , AA1000 [40] are developed to provide a comprehensive framework for implementing SR. "International Guidance Standard on Social Responsibility-ISO 26000" [38] is introduced by International Standard Organization (ISO) as an inclusive framework for standard implementation of SR in firms and corporations. ISO 2600 classifies SR issues into seven core subjects: 1) organizational governance, 2) human rights, 3) labor practices, 4) the environment, 5) fair operating practices, 6) consumer issues, 7) community involvement and development.

In this article, SR measures with the following features are selected: 1) relevant to SCND decisions, 2) simply quantified and 3) compatible to social issues of case study's region. Accordingly, first, stakeholder categories of SC are identified. Next, the social impact of supply chain on each stakeholder category is determined based on their social priorities, and finally, some quantitative measures are assigned to each social impact (SI). The information about stakeholders, their concerned social impact and relevant quantitative measures are tabulated in table 2.

2.3. Assumptions, objectives and constraints

Based on the above mentioned problems, this proposed model follows the following assumptions:

- The location decisions can change from one period to another one.
- Retailers, customers and landfill centers are already fixed
- Customers pay their debts at the end of time periods
- meeting customer's whole demand is not necessary
- There is no flow between facilities of the same echelon

Main objectives of this model consist of:

Maximization of total revenue and service level = Revenue of production and recycling centers + Revenue of collection centers + Revenue of other investments - Cost of loans - Risk of falling below the target ROI + Customer service level

Minimization of Env Impact = Environmental impacts of production + Environmental impacts of shipment + Environmental impacts of facility establishment

Maximization of SR = introduced job opportunities + Value of local development - Consumer risk - Damage to worker's health

To accomplish above mentioned objectives, decision makers face the following constraints:

- Flow balance at network facilities
- Meeting capacity
- meeting customer demand by considering service level
- Non-negativity and binary constraints on decision variables
- Considering the budget available at the beginning of each period

3. Model formulation

The indices, parameters and variables applied to formulate concerned sustainable supply chain network design (SSCND) problem are described below.

Indices

i	Index of potential location for production center
j	Index of retailer
k	Index of potential location for collection center
t	Index of periods in the planning horizon, t = {1; 2, . . ., T}
p	Index of products
m	Index of potential investments (indirect in the supply chain and alternative investments)
b	Index of potential loans
q	Index of technology

Technical parameters

K_i^q	Capacity of production center i with technology q
KC_k^q	Capacity of collection center k with technology q
μ_{pi}^{q}	Unit capacity consumption factor of product p by technology q at production center i
ε_{pk}^{q}	Unit capacity consumption factor of product p by technology q at collection center k
ß$_j$	Weight (importance) of retailer j
DF_p	Maximum downfall rate of collected product p during the recycling process (difference between the weight of the collected waste material and recycled product due to washing the pollution and impurity of waste material)
MF_p	Minimum downfall rate of collected product p during the recycling process

Economic (cost and financial) parameters

C_{iq}^{t}	Fixed cost of opening production center i in period t with technology q

Q_{kq}^{t}	Fixed cost of opening collection center k in period t with technology q
V_{ijp}^{t}	Cost for shipping one unit of product p from production center p to retailer j in period t
Vc_{jkp}^{t}	Cost for shipping one unit of wasted product p from retailer j to collection center k in period t
Vr_{kip}^{t}	Cost for shipping one unit of wasted product p from collection center k to production center i in period i
R_{ijp}^{t}	Unitary revenue of product p at production center i, shipped to retailer j in period t (e.g. selling price minus purchasing and operation cost)
Z_{kip}^{t}	Unitary revenue of collected product p wastage at collection center k shipped to production center i in period t (e.g. selling price minus purchasing and collection cost)
η_{b}^{t}	Interest rate of a loan b, payback at the end of period t. This interest rate is always defined for all periods. If no interest rate arises in a period, it is set to zero
ROI	Target ROI
ϕ_{m}^{t}	Rate of return of an investment m, paid at the end of period t
BD^{t}	Exogenous budget available at the beginning of period t
$\hbar_{iq}$	Depreciation rate related to production center i with technology q in each period
γ_{kq}	Depreciation rate related to collection center k with technology q in each period
ς	Weight of the downside risk at objective function

Environmental parameters

en_{p}^{q}	Environmental impact of producing one unit of product p with technology q
em_{ij}^{p}	Environmental impact of shipping one unit of product p from recycling center i to retailer j
ex_{jk}^{p}	Environmental impact of shipping one unit of used product p from retailer j to collection center k
ey_{ki}^{p}	Environmental impact of shipping one unit of collected product p from collection center k to recycling center i
ec_{kp}^{q}	Environmental impact of collecting one unit of wasted product p at collection center k with technology q

es_i^q	Environmental impact associated with establishing recycling center i with technology q
et_k^q	Environmental impact associated with establishing collection center k with technology q

Social Parameters

un_i	Unemployment rate at location i
up_k	Unemployment rate at location$k$
jo_i^q	Number of introduced job opportunities if a recycling center is opened at location i with technology q
jp_k^q	Number of introduced job opportunities if a collection center is opened at location k with technology q
rd_i	$\begin{cases} 1 & importance\ rate\ of\ location\ i, if\ it'sregion\ is\ developed \\ 1.3 & important\ rate\ of\ location\ i, if\ it'sregion\ is\ \ undeveloped \end{cases}$
rv_k	$\begin{cases} 1 & importance\ rate\ of\ location\ k, if\ it'sregion\ is\ developed \\ 1.3 & important\ rate\ of\ location\ k, if\ it'sregion\ is\ \ undeveloped \end{cases}$
lw_i^q	The average number of lost days at each period due to work’s causing damages during the producing at production center i with technology q
lm_k^q	The average number of lost days at each period due to work’s causing damages during the collection at collection center k with technology q
ra_{ij}	The average of annual vehicle accidents occurring on the path recycling center i to retailer j
rt_{jk}	The average of annual vehicle accidents occurring on the path retailer j to collection center k
rc_{ki}	The average of annual vehicle accidents occurring on the path collection center k to recycling center i
fl_p^q	The fraction of potentially harmful products of product p which harm the consumer's, when technology q is applied
ws	The weight given to social impact objective related to worker’s health and safety
wj	The weight given to social impact objective related to employment and delocalization
we	The weight given to social impact objective related to economic development
wc	The weight given to social impact objective related to customer health and safety

Stochastic parameters (Technical and Economic)

ω^t	Event in period t
ω^0	Current state of nature
Ω^t	Random variable representing the events that may occur in period t
Ω^0	Normal state in the beginning of the planning horizon
$p\left(\Omega^t = \omega^t\right)$	Probability of event ω^t
$\phi_m^t\left(\Omega^t\right)$	Rate of return of an investment m, paid at the end of period t
$\phi_m^t = \phi_m^t\left(\omega^t\right)$	One realization of $\phi_m^t\left(\Omega^t\right)$
$\mathrm{DP}_{jp}^t\left(\Omega^t\right)$	Demand of product p at retailer j in period t
$\mathrm{DP}_{jp}^t = \mathrm{DP}_{jp}^t\left(\omega^t\right)$	One realization of $\mathrm{DP}_{jp}^t\left(\Omega^t\right)$

Financial decision variables

R_m^t	Amount of money spent in the available investment m in period t
L_b^t	Amount of money obtained from loan b in period t
DR	Downside risk
SL_j	Service level for retailer j

Physical decision variables

$$\mathrm{U}_{iq}^t = \begin{cases} 1 & \text{if productions center } i \text{ with technology q is set operating in period t} \\ 0 & \textit{otherwise} \end{cases}$$

$$\mathrm{UC}_{Kq}^t = \begin{cases} 1 & \text{if collection center k with technology q is set operating in period t} \\ 0 & \textit{otherwise} \end{cases}$$

X_{ijp}^t	Amount of product p shipped from production center i to retailer j in period t
U_{jkp}^t	Amount of returned materials p shipped from retailer j to collection center k in period t
M_{kip}^t	Amount of collected materials of product p shipped from collecting center k to production center i in period t

In order to formulate the multi-stage mixed integer programming model for SSCND problem, firs, each of the periods is divided into two phases and then different problems are introduced for different periods (stages). Accordingly, beginning of each time period is denoted by $t^-$and the end by t^+.

Beginning of period 1

As mentioned in section 2, at the beginning of each time period it is necessary to make decision about facility locations, investments and loans. Problem objectives consist of 1) maximizing expected profit at the end of period one and in period two, 2) minimizing environmental impact of selected facilities at SCN and 3) maximizing social impact of facility decisions.

$$\text{Max } \mathrm{Q}^{-1} = \sum_{\omega^1} \mathrm{P}\left(\Omega^1 = \omega^1\right) * \mathrm{Q}^{+1}\left(\ \mathrm{U}^1.\ \mathrm{UC}^1.\ \mathrm{DP}^1\right) + \sum_{\omega^1} \mathrm{P}\left(\Omega^1 = \omega^1\right) * \mathrm{Q}^{-1}\left(\phi^1.\ \mathrm{R}^1.\ \mathrm{L}^1\right) \tag{1}$$

$$\text{Min } \mathrm{N}^{-1} = \sum_i \sum_q u_{iq}^1 es_i^q + \sum_i \sum_q uc_{kq}^1 et_k^q \tag{2}$$

$$+we\left(\sum_i \sum_q u_{iq}^1 rd_i + \sum_k \sum_q uc_{kq}^1 rv_k\right) - ws\left(\sum_i \sum_q u_{iq}^1 lw_i^q + \sum_k \sum_q uc_{kq}^1 lm_k^q\right) \tag{3}$$

s.t.

$$BD^1 - \sum_i \sum_q C_{iq}^1 U_{iq}^1 - \sum_k \sum_q Q_{kq}^1 UC_{kq}^1 - \sum_m R_M^1 + \sum_b L_b^1 \geq 0 \tag{4}$$

$$U_{iq}^1 . UC_{kq}^1 \in \{0;1\} \quad \forall i.k.q \tag{5}$$

$$rd_i . rv_k \in \{1;1.3\} \quad \forall i.k \tag{6}$$

$$un_i \ .up_k \in [0\ ;1] \quad \forall i.k \tag{7}$$

$$R_M^1 . L_b^1 \geq 0 \quad \forall M.b \tag{8}$$

The expected profit and social impact of decisions are respectively maximized by objective functions (OF) (1) and (3) and the total environmental impact is minimized by OF (2). The budget availability for the first stage of the problem is assessed by Constraint (4). Available budget in addition to the loans cannot be lower than investments and facilities opening cost. enforce binary and non-negativity restrictions on decision variables which should be made at the beginning of first period is enforced by Constraints (5), (7) and (8) respectively, and importance rate of locations is presented by constraint (6).

End of period 1

After making decisions about facility locations, investments and loans in the beginning of the first period, and determining the demand at the end of the period, decisions on shipment of materials among facilities should be made.

$$\text{Max } \mathrm{Q}^{+1} = \sum_i \sum_j \sum_p \sum_k ((R_{ijp}^1 - V_{ijp}^1)X_{ijp}^1 + \left(Z_{kip}^1 - Vr_{kip}^1 - \left(U_{jkp}^1 . Vc_{jkp}^1\right)\right)M_{kip}^1) * (1 + ROI)^{T-1} \tag{9}$$

$$\text{Min N}^{+1} = \sum_{i}\sum_{j}\sum_{q}(en_{p}^{q} + em_{ij}^{p})X_{ijp}^{1} + \sum_{j}\sum_{k}\sum_{p} ex_{jk}^{p} U_{jkp}^{1} \tag{10}$$

$$+\sum_{i}\sum_{k}\sum_{p}(ey_{ki}^{p} + ec_{kp}^{q}) * M_{kip}^{1}$$

(11)

s.t.

$$\sum_{p} \mu_{pi}^{q} * \sum_{j} X_{ijp}^{1} \le K_{i}^{q} * U_{iq}^{1} \quad \forall q.i \tag{12}$$

$$\sum_{p} \varepsilon_{pk}^{q} * \sum_{i} M_{kip}^{1} \le KC_{k}^{q} * UC_{kq}^{1} \quad \forall q.k \tag{13}$$

$$\sum_{i} X_{ijp}^{1} \le DP_{jp}^{1} \quad \forall j.p \tag{14}$$

$$\sum_{k} M_{kip}^{1}\left(1 - MF_{p}\right) \le \sum_{j} X_{ijp}^{1} \le \sum_{k} M_{kip}^{1}\left(1 - DF_{p}\right) \quad \forall i.p \tag{15}$$

$$X_{ijp}^{1}.M_{kip}^{1} \ge 0 \quad \forall i.j.p.k \tag{16}$$

$$MF_{p} \;.DF_{p} \in [0\;;1] \quad \forall p \tag{17}$$

OF (9) maximizes revenue of collection centers and recycling centers in first period and multiple revenue of SCN into the target ROI in order to consider ROI of earned revenue in future periods. The environmental impact is minimized by OF (10) and social impact of shipment decisions is maximized by OF (11). Constraints (12) and (13) are related to capacity constraints of recycling centers and collection centers. Surplus supply to retailers is prevented through constraint (14). The amount of material's flow among collection and recycling centers is balanced through inequality (15) by considering downfall rate of collected materials at recycling centers. Collected plastics downfall weight is the result of wiping impurities during the washing process at recycling centers with an important effect on SC planning of plastic recycling industry. The non-negativity restriction on shipment decision variables is enforced by constraint (16) and the permitted value for downfall rates is indicated by constraint (17).

Beginning of Period t ϵ {2, ….., T-1}

At the beginning of $t \epsilon \{2. \ldots\ldots T-1\}$. decisions regarding locations, investments and loans should be reconsidered; consequently, the following sub-problem must be solved at the beginning of period $t \epsilon \{2. \ldots. T-1\}$.

$$\text{Max Q}^{-t} = \sum_{\omega^{t}} \text{P}\left(\Omega^{t} = \omega^{t}\right) * \text{Q}^{+t}\left(\text{U}^{t}.\text{UC}^{t}.\text{DP}^{t}\right) + \sum_{\omega^{t}} \text{P}\left(\Omega^{t} = \omega^{t}\right) * \text{Q}^{-(t+1)}\left(\phi^{t}.\text{R}^{t}.\text{L}^{t}\right) \tag{18}$$

$$\text{Min N}^{-t} = \sum_{i}\sum_{q} u_{iq}^{t} es_{i}^{q} + \sum_{i}\sum_{q} uc_{kq}^{t} et_{k}^{q} \tag{19}$$

$$\text{Max S}^{-t} = wj\left(\sum_{i}\sum_{q} u_{iq}^{t}\, jo_{i}^{q} un_{i} + \sum_{k}\sum_{q} uc_{kq}^{t}\, jp_{k}^{q} up_{k}\right)$$

$$+ we\left(\sum_{i}\sum_{q} u_{iq}^{t} rd_{i} + \sum_{k}\sum_{q} uc_{kq}^{t} rv_{k}\right) - ws\left(\sum_{i}\sum_{q} u_{iq}^{t} lw_{i}^{q} + \sum_{k}\sum_{q} uc_{kq}^{t} lm_{k}^{q}\right) \tag{20}$$

s.t.

$$BD^{t} - \sum_{i}\sum_{q} C_{iq}^{t} U_{iq}^{t} - \sum_{k}\sum_{q} Q_{kq}^{t} UC_{kq}^{t} - \sum_{m} R_{M}^{t} + \sum_{b} L_{b}^{t} + \sum_{t=1}^{t-1}\left(\sum_{m} \phi_{m}^{t} . R_{m}^{t} - \sum_{b} \eta_{b}^{t} . L_{b}^{t} \right) \geq 0 \qquad (21)$$

$$U_{iq}^{t} . UC_{kq}^{t} \in \{0;1\} \qquad \forall i.k.q \qquad (22)$$

$$L_{b}^{t} . R_{m}^{t} \geq 0 \qquad \forall b.m.t \qquad (23)$$

The expected profit and social impact of decisions are maximized by OF (18) and (20). OF (19) is applied to minimize the total environmental impact. In constraint (21) revenue of the previous periods is added to available budget and amount of the loans that should be paid back in period t is subtracted from available budget. Non-negative and binary nature of decision variables at the beginning of period t are presented by Constraints (22) and (23), respectively.

End of Period t ϵ {2, ….., T-1}

$$\text{Max Q}^{+t} = \sum_{i}\sum_{j}\sum_{p}\sum_{k} ((R_{ijp}^{t} - V_{ijp}^{t}) X_{ijp}^{t} + \left(Z_{kip}^{t} - Vr_{kip}^{t} - \left(U_{jkp}^{t} . Vc_{jkp}^{t} \right) \right) M_{kip}^{t}) * (1 + ROI)^{T-t} \qquad (24)$$

$$\text{Min N}^{+t} = \sum_{i}\sum_{j}\sum_{q} (en_{p}^{q} + em_{ij}^{p}) X_{ijp}^{t} + \sum_{j}\sum_{k}\sum_{p} ex_{jk}^{p} U_{jkp}^{t} + \sum_{i}\sum_{k}\sum_{p} (ey_{ki}^{p} + ec_{kp}^{q}) * M_{kip}^{t} \qquad (25)$$

$$\text{Max S}^{+t} = -ws \left(\sum_{i}\sum_{j}\sum_{p} X_{ijp}^{t} ra_{ij} + \sum_{j}\sum_{k}\sum_{p} U_{kq}^{t} rt_{jk} + \sum_{i}\sum_{k}\sum_{p} M_{kip}^{t} rc_{ki} \right) - wc \left(\sum_{i}\sum_{j}\sum_{p} X_{ijp}^{t} fl_{p}^{q} \right) \qquad (26)$$

s.t.

$$\sum_{p} \mu_{pi}^{q} * \sum_{j} X_{ijp}^{t} \leq K_{ip}^{q} * U_{iq}^{t} \qquad \forall q.i \qquad (27)$$

$$\sum_{p} \varepsilon_{pk}^{q} * \sum_{i} M_{kip}^{t} \leq KC_{kp}^{q} * UC_{kq}^{t} \qquad \forall q.k \qquad (28)$$

$$\sum_{i} X_{ijp}^{t} \leq DP_{jp}^{t} \qquad \forall j.p \qquad (29)$$

$$\sum_{k} M_{kip}^{t} \left(1 - MF_{p}\right) \leq \sum_{j} X_{ijp}^{t} \leq \sum_{k} M_{kip}^{t} \left(1 - DF_{p}\right) \qquad \forall i.p \qquad (30)$$

$$X_{ijp}^{t} . M_{kip}^{t} \geq 0 \qquad \forall i.j.p.k \qquad (31)$$

OF (24) is applied to maximize revenue of collection centers and recycling centers in period t and multiple revenue of SCN into the target ROI in order to consider ROI of earned revenue in future periods. Environmental impact is minimized by OF (25) and OF (26) is applied to maximize social impact of shipment decisions. Constraints (27) and (28) are related to capacity constraints of recycling centers and collection centers, respectively. Surplus supply to retailers is prevented by constraint (29). The amount of material's flow between collection centers and recycling centers is balanced by inequality (30), by considering downfall rate of collected materials at recycling centers. The non-negativity restrictions on shipment decision variables is are enforced by constraint (31).

Beginning of Period T

The beginning of this period is formulated similar to that of the previous periods:

$$\text{Max } \mathrm{Q}^{-T} = \sum_{\omega^T} \mathrm{P}\left(\Omega^{\mathrm{T}} = \omega^{\mathrm{T}}\right) * \mathrm{Q}^{+\mathrm{T}}\left(\mathrm{U}^{\mathrm{T}}.\,\mathrm{UC}^{\mathrm{T}}.\,\mathrm{DP}^{\mathrm{T}}\right) \tag{32}$$

$$\text{Min } \mathrm{N}^{-T} = \sum_{i}\sum_{q} u_{iq}^{T} es_{i}^{q} + \sum_{i}\sum_{q} uc_{kq}^{T} et_{k}^{q} \tag{33}$$

$$\text{Max } \mathrm{S}^{-T} = wj\,(\sum_{i}\sum_{q} u_{iq}^{T}\, jo_{i}^{q} un_{i} + \sum_{k}\sum_{q} uc_{kq}^{T}\, jp_{k}^{q} up_{k}) \tag{34}$$

$$+we(\sum_{i}\sum_{q} u_{iq}^{T} rd_{i} + \sum_{k}\sum_{q} uc_{kq}^{T} rv_{k}) - ws(\sum_{i}\sum_{q} u_{iq}^{T} lw_{i}^{q} + \sum_{k}\sum_{q} uc_{kq}^{T} lm_{k}^{q})$$

s.t.

$$BD^{T} - \sum_{i}\sum_{q} C_{iq}^{T} U_{iq}^{T} - \sum_{k}\sum_{q} Q_{kq}^{T} UC_{kq}^{T} - \sum_{m} R_{m}^{T} + \sum_{b} L_{b}^{T} + \sum_{t=1}^{T-1}(\sum_{m} \phi_{m}^{T-1} * R_{m}^{t} - \sum_{b} \eta_{b}^{T-1} * L_{b}^{t}) \geq 0 \tag{35}$$

$$U_{iq}^{T}.UC_{kq}^{T} \in \{0;1\} \qquad \forall i.k.q \tag{36}$$

$$L_{b}^{T}.R_{m}^{T} \geq 0 \qquad \forall b.m.t \tag{37}$$

Here, the structure of sub-problems is still the same. The expected profit and social impact of decisions which should be made at the beginning of period T are maximized by OF (32) and (34) respectively and the total environmental impact of these decisions is minimized through OF (33). In constraint (35) the revenue of the previous periods is added to the available budget and the amount of loans that should be paid back in period t is subtracted from available budget. Non-negative and binary nature of decision variables at the beginning of period T are presented by Constraints (36) and (37) respectively.

End of the Period T

The following problem is formulated for the end of the planning horizon:

$$\begin{aligned} \text{Max } \mathrm{Q}^{+T} = {} & \sum_{i}\sum_{j}\sum_{p}\sum_{k}((R_{ijp}^{T} - V_{ijp}^{T})X_{ijp}^{T} + (Z_{kip}^{T} - Vr_{kip}^{T} - (U_{jkp}^{T} * Vc_{jkp}^{T}))M_{kip}^{T}) \\ & + \sum_{j} \beta_{j} * SL_{j} - \varsigma DR + \\ & \sum_{t=1}^{T}(\sum_{m} \phi_{m}^{T} * R_{m}^{T} - \sum_{b} \eta_{b}^{T} * L_{b}^{T}) - \sum_{i}\sum_{q}(\hbar_{iq}) * U_{iq}^{T} * C_{iq}^{T} - \sum_{k}\sum_{q}(\gamma_{k}^{q}) * UC_{kq}^{T} * Q_{kq}^{T} \end{aligned} \tag{38}$$

$$\text{Min } \mathrm{N}^{+T} = \sum_{i}\sum_{j}\sum_{q}(en_{p}^{q} + em_{ij}^{p})X_{ijp}^{T} + \sum_{j}\sum_{k}\sum_{p} ex_{jk}^{p} U_{jkp}^{T} + \sum_{i}\sum_{k}\sum_{p}(ey_{ki}^{p} + ec_{kp}^{q}) * M_{kip}^{T} \tag{39}$$

$$\text{Max } S^{+T} = -ws\left(\sum_i\sum_j\sum_p X_{ijp}^T ra_{ij} + \sum_j\sum_k\sum_p U_{kq}^T rt_{jk} + \sum_i\sum_k\sum_p M_{kip}^T rc_{ki}\right) \tag{40}$$

$$-wc\left(\sum_i\sum_j\sum_p X_{ijp}^T fl_p^q\right)$$

s.t.

$$\sum_p \mu_{pi}^q * \sum_j X_{ijp}^T \le K_{ip}^q * U_{iq}^T \quad \forall q.i \tag{41}$$

$$\sum_p \varepsilon_{pk}^q * \sum_i M_{kip}^T \le KC_{kp}^q * UC_{kq}^T \quad \forall q.k \tag{42}$$

$$\sum_i X_{ijp}^T \le DP_{jp}^T \quad \forall j.p \tag{43}$$

$$\sum_k M_{kip}^T \left(1-MF_p\right) \le \sum_j X_{ijp}^T \le \sum_k M_{kip}^T \left(1-DF_p\right) \quad \forall i.p \tag{44}$$

$$DR \ge 1 - \frac{\sum_t((\sum_m \phi_m^T.R_m^T - \sum_b \text{ŋ}_b^T.L_b^T) + \sum_i\sum_j\sum_p\sum_p((R_{ijp}^t - V_{ijp}^t) * X_{ijp}^t + \left(Z_{kip}^t - Vr_{kip}^t - \left(U_{jkp}^t.Vc_{jkp}^t\right)\right).M_{kip}^t)) * (1+ROI)^{T-t} - -\sum_i \sum_q (\text{ɧ}_{iq}) * U_{iq}^T * C_{iq}^T - \sum_k \sum_q (\text{ɣ}_{kq}).UC_{kq}^T.Q_{kq}^T}{\sum_t BG^t.\ (1+ROI)^{T-t+1}}$$

(45)

$$\sum_i\sum_t\sum_p X_{ijp}^t \ge SL_j * \sum_t\sum_p DP_{jp}^t \qquad \forall j$$

$$SL_j \in [0;1] \qquad \forall j \tag{47}$$

$$DR \ge 0$$

In OF (38) the following extra terms are considered in comparing with the end of the previous periods. For this purpose, first the depreciation rate of the production and collection centers are subtracted from total revenue, second the service level is maximized, third the downside risk is minimized and forth the total loans payback and total investment revenue are considered. The environmental and social impacts of OFs are similar to that of previous periods. Inequalities (41), (42), (43) and (44) represent the capacity, demand and downfall constraints, respectively. The downside risk of target ROI, which is minimized in OF (38), is calculated through Inequality (45). Finally, the service level for each customer, which is maximized in OF (38) is determined by constraint (46).

4. Solution approach

The above mentioned formulation of SSCND with financial decisions problem explicitly elaborates on the concept and multi-stage structure of the problem. Analyze of interactions among variables prove that the decisions made on locations, investments, loans and shipments interact with each other and affect service level and downside risk at the end of time horizon.

Perceiving of the problem is simplified in the previous section model, while for solving and implementing the problem, a more compact model, compatible with general solver, is needed. The path formulation method for solving their multi-stage SCND problem is introduced by Nickel et all [15], where, the sequence of events are defined as a scenario, then path and sub-paths for each scenario are determined. The following new notations are introduced before presenting path formulation model:

Scenario path formula

$S^t = \Omega^1 \times \Omega^2 \times \ldots\ldots \times \Omega^t$	Set of potential sequence of events until period t
$s^t \in S^t = (\omega^0 \times \omega^1 \times \ldots\ldots \times \omega^t)$	Path of events from root node to one particular node in period t
s^0	Root node
s^T	Path of the events that oriented from root node to a leaf node (A scenario)
$path_{s^t} = \left\{ s^0.\ s^1 \ldots\ldots s^t \right\}$	Set of all sub paths containing parts of path s^t
$P\left(S^t = s^t\right) = \prod_{t=1}^{t} p(\Omega^t = \omega^t)$	Probability that sequence of the events passing through path s^t

Here, the problem is reformulated as follows:

$$
\begin{aligned}
\text{Max Q } = & \sum_{t} \sum_{s^t \in S^t} P(S^t = s^t) * [\sum_{i} \sum_{j} \sum_{p} \sum_{k} ((R^t_{ijp} - V^t_{ijp}) X^t_{ijp}(s^t)) + \\
& (Z^t_{kip} - Vr^t_{kip} - (U^t_{jkp}(s^t) * Vc^t_{jkp})) * M^t_{kip}(s^t))] + \\
& \sum_{s^T \in S^T} P(S^T = s^T) * [\sum_{j} \beta_j * SL_j(s^T) - \varsigma * DR(s^T) \\
& + \sum_{t} \sum_{s^{t-1} \in path_{s^T}} (\sum_{m} \phi^t_m(s^T) * R^t_m(s^{t-1}) - \sum_{b} \eta^t_b(s^T) * L^t_b(s^{t-1})) - \sum_{i} \sum_{q} (\hbar_{iq}) * U^T_{iq}(s^{t-1}) * C^T_{iq} \\
& - \sum_{k} \sum_{q} (\gamma_{kq}) * UC^T_{kq}(s^{t-1}) * Q^T_{kq}]
\end{aligned}
\qquad (49)
$$

$$
\begin{aligned}
\text{Min N } = & \sum_{t} \sum_{s^t \in S^t} P(S^t = s^t) * [\sum_{q} \sum_{p} \sum_{i} \sum_{j} (en^q_p - em^p_{ij}) X^t_{ijp}(s^t) + \\
& \sum_{j} \sum_{k} \sum_{p} en^p_{jk} * U^t_{jkp}(s^t) + \sum_{q} \sum_{p} \sum_{k} \sum_{i} (ey^p_{ki} + ec^q_{kp}) * M^t_{kip}(s^t)] + \\
& \sum_{t} \sum_{s^t \in S^t} P(S^t = s^t) * [\sum_{i} \sum_{q} U^T_{iq} * es^q_i + \sum_{k} \sum_{q} UC^T_{kq} * et^q_k]
\end{aligned}
\qquad (50)
$$

$$\begin{aligned}\text{Max S } &= \sum_t \sum_{s^t \in S^t} P(S^t = s^t) * [-ws(\sum_i \sum_j \sum_p X^{\,t}_{ijp}(s^t) * ra_{ij} + \\ &\sum_j \sum_k \sum_p U^{\,t}_{jkp}(s^t) * rt_{jk} + \sum_k \sum_i \sum_p M^{\,t}_{kip}(s^t) * rc_{ki}) - wc(\sum_i \sum_j \sum_p \sum_q X^{\,t}_{ijp}(s^t) * fl^{\,q}_{p})] \\ &+ \sum_t \sum_{s^t \in S^t} P(S^t = s^t) * [wj(\sum_i \sum_q U^{\,t}_{iq}(s^{t-1}) * jo^q_i * un_i + \sum_k \sum_q UC^{\,t}_{kq}(s^{t-1}) * jp^q_k * up_k) \\ &+ we(\sum_i \sum_q U^{\,t}_{iq}(s^{t-1}) * rd_i + \sum_k \sum_q UC^{\,t}_{kq}(s^{t-1}) * rv_{\,k}) - \\ &ws(\sum_i \sum_q U^{\,t}_{iq}(s^{t-1}) * lw^{\,q}_{i} + \sum_k \sum_q UC^{\,t}_{kq}(s^{t-1}) * lm^q_k)]\end{aligned} \tag{51}$$

s.t.

$$BD^1 - \sum_i \sum_q C^1_{iq} U^1_{iq}\left(s^0\right) - \sum_k \sum_q Q^1_{kq} UC^1_{kq}\left(s^0\right) - \sum_m R^1_M\left(s^0\right) + \sum_b L^1_b\left(s^0\right) \geq 0 \tag{52}$$

$$\begin{aligned}&BD^t - \sum_i \sum_q C^t_{iq} U^t_{iq}\left(s^{t-1}\right) - \sum_k \sum_q Q^t_{kq} UC^t_{kq}\left(s^{t-1}\right) - \sum_m R^t_M\left(s^{t-1}\right) + \sum_b L^t_b\left(s^{t-1}\right) \\ &+ \sum_{t=1}^{t-1}(\sum_m \phi^t_m * R^t_m(s^{t-1}) - \sum_b \eta^t_b * L^t_b(s^{t-1})) \geq 0\end{aligned} \tag{53}$$

$$\sum_p \mu^q_{pi} * \sum_i X^{\,t}_{ijp}\left(s^t\right) \leq K^q_i * U^t_{iq}\left(s^{t-1}\right) \qquad \forall q.j \tag{54}$$

$$\sum_p \varepsilon^q_{pk} * \sum_i M^{\,t}_{kip}\left(s^t\right) \leq KC^q_k * UC^t_{kq}\left(s^{t-1}\right) \quad \forall q.k \tag{55}$$

$$\sum_i X^{\,t}_{ijp}\left(s^t\right) \leq DP^t_{jp}\left(s^t\right) \quad \forall j.p \tag{56}$$

$$\sum_k M^{\,t}_{kip}\left(1 - MF_p\right) \leq \sum_j X^{\,t}_{ijp} \leq \sum_k M^{\,t}_{kip}\left(1 - DF_p\right) \quad \forall i.p \tag{57}$$

$$DR \geq 1 - \frac{\sum_{s^T} \sum_t((\sum_m \phi^T_m\left(s^T\right) * R^T_m\left(s^{t-1}\right) - \sum_b \eta^T_b\left(s^T\right) * L^T_b\left(s^{t-1}\right)) + \sum_i \sum_j \sum_p \sum_p(\left(R^t_{ijp} - V^t_{ijp}\right) * X^t_{ijp}\left(s^t\right) + \left(Z^t_{kip} - Vr^t_{kip} - \left(U^t_{jkp}.Vc^t_{jkp}\right)\right) * M^t_{kip}(s^t))).\left(1 + ROI\right)^{T-t} - \sum_i \sum_q(\text{ɧ}_{iq}) * U^T_{iq}\left(s^{t-1}\right) * C^T_{iq} - \sum_k \sum_q(\gamma_{kq}) * UC^T_{kq}\left(s^{t-1}\right) * Q^T_{kq}}{\sum_t BG^t * (1 + ROI)^{T-t+1}} \tag{58}$$

$$\sum_i \sum_t \sum_p X^{\,t}_{ijp}\left(s^t\right) \geq SL_j * \sum_t \sum_p DP^t_{jp}\left(s^t\right) \qquad \forall j.s^t \tag{59}$$

$$U^1_{iq} \ .UC^1_{kq} \in \left\{0;1\right\} \tag{60}$$

$$X^{\,t}_{ijp}\left(s^t\right).M^{\,t}_{kip}\left(s^t\right).DP^t_{jp}\left(s^t\right).R^t_m\left(s^{t-1}\right).L^t_b\left(s^{t-1}\right).DR\left(s^T\right) \geq 0 \qquad \forall i.j.p.k.m.b \tag{61}$$

$$SL_j\left(s^T\right) \in \left[0;1\right] \qquad \forall j \tag{62}$$

The concept of the above path formulation model is completely based on the multi-period, multi-product CL_SSCND problem explained in Sec. 3, where every combination of events is considered as a scenario. Here, every scenario consists of different consequences of events (path). Probability of each scenario path is calculated by multiplying probability of path's event by them. Finally, here the OFs are computed based on probability of scenarios (equations 46, 47 and 48). An example scenario tree with 3 periods and 2 possible events in each period is depicted by figure 2. Specified lines with red color, demonstrate a scenario which encompasses event 2 in period 1, event 1 in period 2 and event 1 in period 3.

The SSCND problem is multi-objective in nature. To solve multi-objective programming (MOP) models, there exist many methods. In this article, ε-constraint method is adopted to deal with MO nature of SSCND problem. Several versions of ε-constraint method are proposed in the body of literature. Here, the augmented ε-constraint (AUGMECON) method proposed by Mavrotas [41] is adopted. In comparison with other ε-constraint method versions, AUGMECON is 1) able to guarantee efficiency of obtained solution, 2) calculate range of the objective functions over the efficient set and 3) acceptable solution time in the cases with several objectives [41].

In order to solve the problem with above mentioned method, firstly, economical OF presented in OF (49), is considered as a main objective and OFs (50) and (51) are expressed in the form of inequality constraints. Then, environmental OF is optimized by adding Economical OF=Q* as an equality constraint and OF (51) as an inequality constraint. Subsequently, the social OF is optimized by considering Economical OF=Q* and Environmental OF=N* as constraints. Consequently, payoff matrix of the problem is employed as a tool for calculating ranges of objective functions. In next step, economic OF is taken as the one to optimized, and ranges of environmental and social OFs are separated into same intervals. Based on defined intervals, constraints related to environmental and social OFs are taken into account for defining some sub-problems. Therefore, the Pareto set is obtained by solving each sub-problem. In order to avoid inefficiency of ε-constraint method, slack variable technique is deployed based on augmented ε-constraint method [41]. Finally, decision maker selected most desired solution among all derived non dominated solutions.

5. Implementation and evaluation

The validity of developed model and the functionality of the solution method are assessed through the data of considered case study. The subject firm here has 20 customers and 10 candidate locations are considered for production centers and collection centers. This firm can produce two products with two different technologies that each technology has different depreciation rate. The firm has 6 investment alternatives with different rate of return and different variances. Beside the available exogenous budget, the firm's manager has opportunity to give 5 different loans with different payback time and payback types.

The proposed model is coded and solved through IBM ILOG CPLEX 12.1. A time limit of 3600 seconds is considered in this process. The results are tabulated in Table 3.

In order to evaluate effectiveness of considering financial decisions in SSCND problem, the proposed model is solved without considering financial decisions. The results of problem solved without taking financial decisions are tabulated in Table 4.

Comparing the content of table 3 and 4 confirm that by solving the model with financial decisions, both the customer service level and OF value increase, indicating that financial leveraging with loans and considering other investment alternatives beside the investments in SCN, can improve the physical and financial performance of SCN. Considering financial decision in studied firm increased service level by 6/531% and OF value by 12/56%. The comparisons between service level amount of financial and non-financial models are expressed in Figure 3.

Above mentioned results are achieved by considering the 5 loan's alternatives, that can be added to the available budget of investors. A sensitivity analysis is run on number of available loans. Decreasing the number of available loans, reduce the financial leveraging power of investors. The fact that more financial leverage increases the economic value of this model is expressed in Figure 4.

By taking advantage of the available loans, investors can increase number of facilities, consequently raise the amount of production and sale. In this proposed model, the advantage of taking loans is improving the economic value of model, as far as the profit generated from sale raise, and is sufficient to pay back the loans and their interest. The fact that considering all 5 available loans have improved the economical OF by 5.26% and the whole system service level by 4% is tabulated in Table 5.

In general, the above mentioned tables and figures approve effectiveness of considering financial decisions in SSCND problem. Considering other investment alternatives in addition to SSCN investments, provide an overall view to investors and expand their choices. Moreover, possibility of financial leveraging by getting loans empowers the firms with respect to their financial status. As a result, investors become enable to increase profitability of their decisions regarding SSCND problem.

6. The relevance of applying a stochastic approach

When uncertainty is considered in an optimization model, the important issue is to assess its advantage in comparison with deterministic methods. Relative value of multi-stage stochastic approach (RVMSA) is a value that measures this relevance. RVMSA examines the importance of achieving perfect information on stochastic parameters [42], the approach of RVMSA is to measure the distance between stochastic and deterministic problem's value and divide the yield distance into deterministic problem's value. The product of this division examines the effectiveness of applying multi-stage stochastic approach.

In order to compute RVMSA, the value of deterministic problem should be computed, which is obtained through substituting all random variables with their expected values [15]. To accomplishing this, $\phi_m^t(s^T)$ is substituted with $E[\phi_m^t(s^T)]$ and $\mathrm{DP}_{jp}^t(s^T)$ is substituted with $E\left[\mathrm{DP}_{jp}^t(s^T)\right]$.

To analyze the performance of this multi-stage stochastic approach in the context of the introduced problem here, the deterministic problem value (Q^{DET}) is computed for the subject firm. Here, the RVMSA is measured as follows:

$$RVMSA = \frac{Q^{STO} - Q^{DET}}{Q^{DET}} = \frac{465868 - 441163}{441163} = 0.056$$

The result of RVMSA measurement indicates that solving this problem through this multi-stage stochastic approach can improve supply chain performance at problem time horizon by 5.6% in OF value, and approve effectiveness of implementing multi-stage stochastic approach in SSCND problem with financial decisions.

7. Conclusions

In this article, integration of physical and financial decisions in SSCND problem with uncertainty issue is facilitated by implementing a multi-stage stochastic approach. The main objectives of this proposed multi-objective model consist of: 1) maximizing total revenue, maximizing service level to customers and minimizing deviation from target ROI, 2) minimizing environmental impact and 3) maximizing social benefits. In addition to general decisions made on location and allocation, financial decisions are of concern. The issue of uncertainty is on demand and investment rate of return, in order to cope with this issue, a mixed-integer multi-stage stochastic programming formulation is implemented. The applicability of this model is tested in the case study consisting of a real plastic recycling company located in Iran. ε-constraint and path-formulation methods are adopted for handling multi-objectiveness and stochastic nature of the problem. Computational results indicate that considering the financial decisions improve service level and OF value. Moreover, sensitivity analysis run on loan consideration proves the benefits of considering loan alternatives in such problems. Loan consideration assists managers to leverage their financial power. Furthermore, RVMSA index is applied to assess the value of implementing multi-stage stochastic approach, where the results indicate that stochastic approach is outperforming the deterministic approach.

The results of this article can be applied in other industries of closed-loop SC structure such as petrochemical, electrical, etc. The proposed model can be extended for future studies by making improvement in its different aspects. For example, future researches could be aimed for implementing other policies for coping with uncertainty and analyzing performance of different policies. Also, it is necessary to evaluate value of stochastic approach at social and environmental OFs.

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Tables and figures

Table 1: Sustainable supply chain network design futures in the body of literature

Article	dimensions	Uncertainty issue	Uncertainty consideration policy	Multi-period	Multi-product	Multi-objective	Financial decisions	Closed-loop	Financial Risk measure	Depreciation rate
Pishvaee et al., [3]	Eco-Env-Soc	•	Possibilistic programming			•		•		
Babazadeh et al., [19]	Eco-Env	•	Possibilistic programming	•	•	•				
Pishvaee et al., [9]	Eco-Soc	•	Robust possibilistic programming			•				
Giarola et al., [7]	Eco-Env	•	Two-stage stochastic programming	•	•					
Verma et al., [8]	Eco-Env	•	Two-stage stochastic programming							
Grossman [10]	Eco-Env	•	Bi-criterion Stochastic non-convex MINLP	•	•	•				
Amin and Zhang [11]	Eco-Env	•	Scenario-based stochastic programming		•	•		•		
Ruiz-femenia et al., [12]	Eco-Env	•	Stochastic multi-scenario MILP	•	•	•				
Balaman and Selim [20]	Eco-Env	•	Fuzzy goal programming (FGP)	•	•	•				
Pishvaee and Razmi [21]	Eco-Env	•	Pssibilistic programming			•		•		
Pishvaee et al., [22]	Eco-Env	•	Credibility-based fuzzy mathematical programming			•				
Saffar et al., [23]	Eco-Env	•	Auxiliary crisp	•	•	•		•		
Saffar et al., [24]	Eco-Env	•	Auxiliary crisp	•	•	•		•		
Guillen at al., [25]	Eco-Env	•	Bi-criterion MINLP	•	•	•				
Mohammadi et al., [26]	Eco-Env	•	Mixed possibilistic-stochastic programming			•				
Zhalechian et al., [27]	Eco-Env-Soc	•	Stochastic-possibilistic programming and modified game theory	•	•	•		•		
Shaw et al., [28]	Eco-Env	•	Bender decomposition and chance constrait programming							
Mohseni and Pishvaee [29]	Eco-Env	•	Robust optimization	•						
Mohammed et al., [30]	Eco-Env	•	Robust optimization	•	•			•		
MA et al., [31]	Eco-Env	•	Robust optimization		•	•		•		
Golpira et al., [32]	Eco-Env	•	Conditional Value at Risk (CVaR)			•				

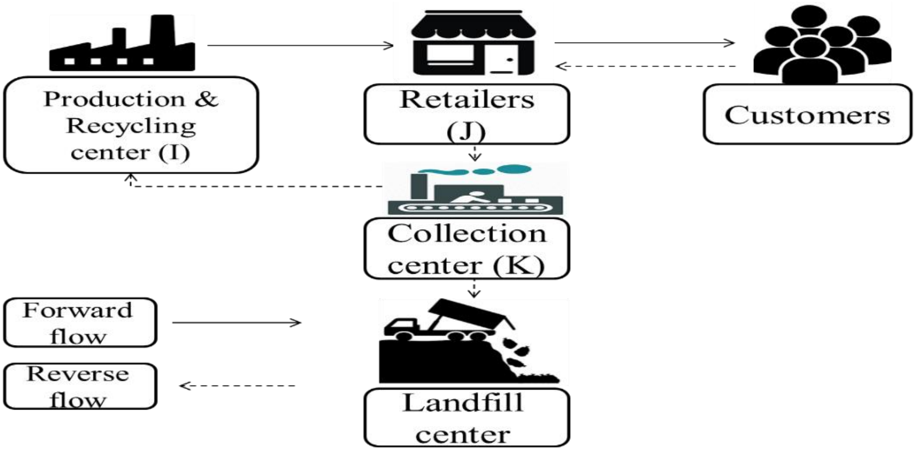

Figure 1: The underlying structure of the concerned supply chain network

Table 2: Stakeholders, their concerned social impact and relevant quantitative measures

Stakeholder	**Concerned social impact**	**Relevant quantitative measure(s)**
Workers (production and collection workers in addition to transportation workers)	Health and safety	The average number of lost days caused from work's damages - average of annual road accident at the roads
Local inhabitants	Delocalization- Unemployment	Number of created job opportunities – importance rate of region based on development unemployment rate
Consumers	Health and safety	The fraction of potentially harmful products
Governments	Delocalization- Unemployment – economic development	Number of created job opportunities – importance rate of region based on development - unemployment rate

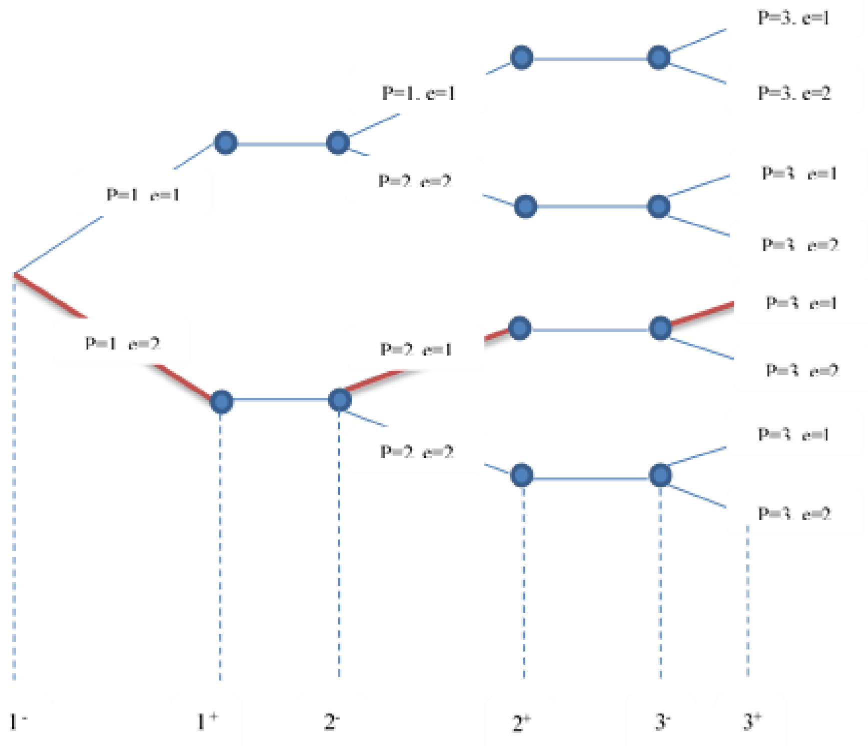

Figure2: An example scenario tree

Table 3: Result of problem solved with financial decisions

Number and region of customer	Service level of customer during the whole time horizon	Weighted average of whole system service level	Economical OF value at the end of last period	Downside risk related to OF's value
1=Isfahan	0.87	0.7487	465868	0.15
2=Isfahan	0.89			
3=Isfahan	0.70			
4=Isfahan	0.66			
5=Isfahan	1.00			
6=Isfahan	0.70			
7=Isfahan	1.00			
8=Tehran	1.00			
9=Hormozgan	0.10			
10=Azerbaijan	0.50			
11=Isfahan	0.65			
12=Tehran	1.00			
13=Isfahan	0.90			
14=Isfahan	0.70			
15=Markazi	0.63			
16=Khoozestan	0.90			
17=Isfahan	0.76			
18=Fars	0.50			
19=Khorasan	0.60			
20=Yazd	0.63			

Table 4: Result of problem solved without financial decisions

Number and region of customer	Service level of customer during the whole time horizon	Weighted average of whole system service level	Economical OF value at the end of last period	Downside risk related to OF's value
1=Isfahan	0.70	0.7028	413879	0.12
2=Isfahan	0.75			
3=Isfahan	0.63			
4=Isfahan	0.63			
5=Isfahan	0.95			
6=Isfahan	0.70			
7=Isfahan	0.97			
8=Tehran	0.99			
9=Hormozgan	0.09			
10=Azerbaijan	0.50			
11=Isfahan	0.60			
12=Tehran	1.00			
13=Isfahan	0.89			
14=Isfahan	0.65			
15=Markazi	0.59			
16=Khoozestan	0.85			
17=Isfahan	0.70			
18=Fars	0.45			
19=Khorasan	0.58			
20=Yazd	0.59			

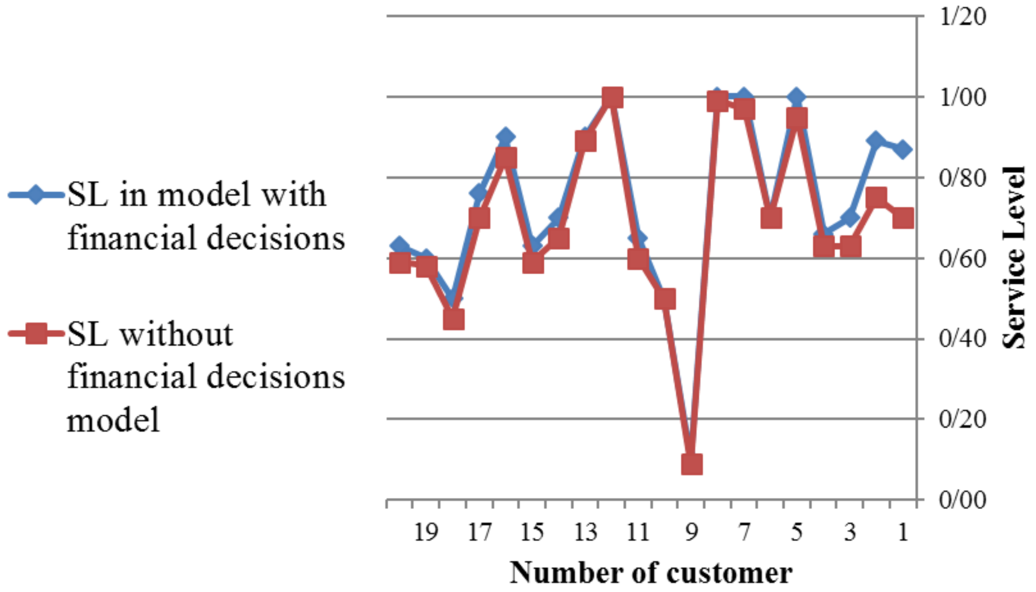

Figure 3: Comparison between SL in models with financial decisions and without financial decisions

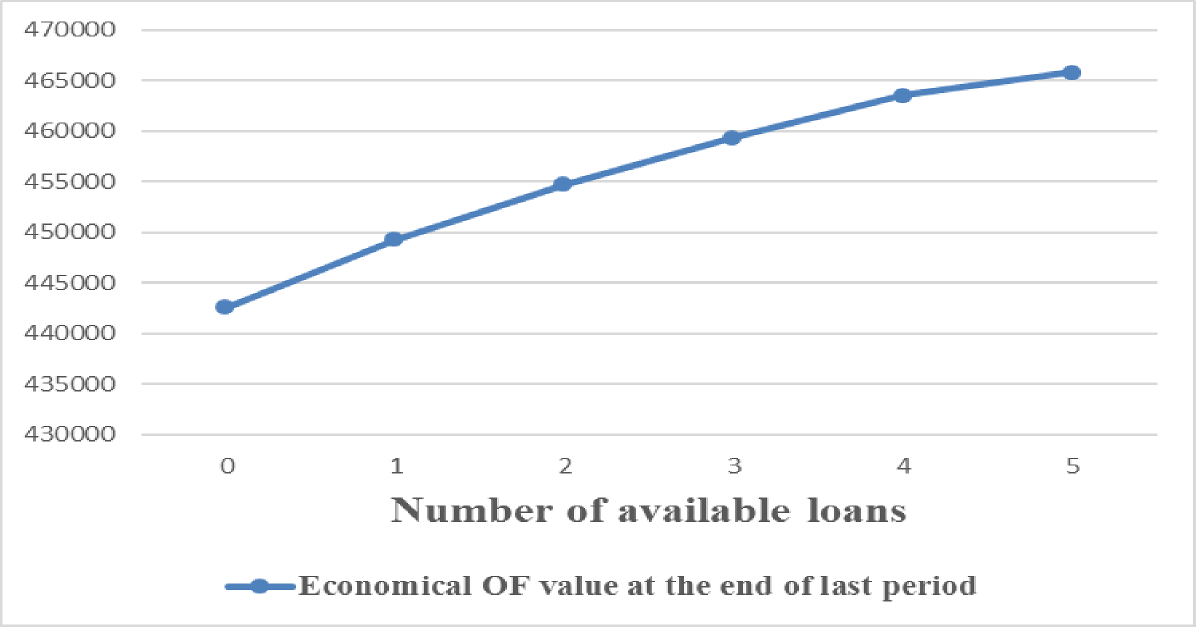

Figure 4: Effect of available loans on economical OF

Table 5: Sensitivity analysis on number of available loans

Number of available loans	Weighted average of whole system service level	Economical OF value at the end of last period
0	0.7197	442575
1	0.7285	449315
2	0.7359	454773
3	0.7419	459367
4	0.7464	463539
5	0.7487	465868