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A multi-objective, multi-echelon green supply chain network design problem with risk-averse retailers in an uncertain environment

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Abstract. This paper proposes a new multi-objective, multi-echelon supply chain network design problem. The proposed framework is green, in which it tackles the demand uncertainty of a product, environmental uncertainties, and the downstream risk attitude into the problem formulation. In this way, the demand uncertainty is taken into account through the Conditional Value at Risk (CVaR) method which, in turn, relies on the data-driven approach. On the other hand, uncertainty set approach is employed to deal with the environmental uncertainties, i.e. CO_2 emissions. Proposition of such a green supply chain network, based on the aforementioned uncertainties, makes the proposed model realistic, which is what completely missing in the literature. In order to proceed with this model, a robust counterpart of the developed uncertain problem should be formulated. The augmented ε-constraint method is used to transform the developed multi-objective mathematical programming problem into a single-objective one. This may give rise to the global optimal solution through the exact mathematical solution method. Simulation results demonstrate the efficiency of the proposed framework.

1. Introduction

Nowadays, environmental concern is one of the most significant problems, especifically among the Asian countries where the recent expansion of the global economy is considerable [1]. Moreover, establishing a team of companies as a Supply Chain Network (SCN) is important in today's fiercely competitive environment [2]. Thus, forward and backward production-distribution network holistic design in compliance with green principles becomes an important issue [3,4]. Green Supply Chain (GrSC) and its management, called Green Supply Chain Management (GrSCM), has recently become an emerging research area [5].

GrSC significantly reduces the negative impact of environmental concerns which, in turn, enhances the companies' competitiveness [1]. In spite of its importance, there is no exact definition for the GrSC in literature, partly caused by the definition of the SCN and its boundaries [4].

Srivastava [6] demonstrated the efficiency of Mathematical Programming Approach (MPA) to deal with GrSCM. MPA relies on the simultaneous optimization of process operations and environmental concerns. Although there have been a considerable number of research studies on the field of MPA, literature, pertaining to the application of MPA for environmentally conscious SCNs, is limited [5,6]. Moreover,

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modeling of demand and environmental uncertainties in SCN design problem makes crudity of literature more critical [5-7]. Risk, arising from customers' demand uncertainty, increases complexity of modeling in SCN design problem. Styles et al. [8] revealed that customer's attitude is not an effective factor for motivation toward greenness. However, the retailer's strategic position is introduced to be a good greenness driver [8]. Therefore, how to model the uncertainty and how to deal with the risk attitude of a retailer are the important concerns in Green Supply Chain Network Design (GrSCND) problem.

There are many examples of the retailer's risk attitude in real-world GrSCND problems. According to Styles et al. [8] and Choi and Chiu [9], fashion retailers, such as Zara, H&M, Mango, and Top Shot, should be risk-averse in order to obtain better greenness factors. Dwyer [10] highlighted the green agricultural supply chain management in risky environment and lays stress on the importance of policy-makers' risk aversion level. Rezaee et al. [11] successfully examined a GrSCND with stochastic demand in an Australian office furniture production-distribution company.

The retailer's risk aversion level can be modeled using the Conditional Value at Risk (CVaR), introduced by Bertsimas and Brown [12]. The present research employs the CVaR to deal with the uncertainty of the demand occurred in the last tier of SCN. Demand, as one of the main entities in the SCN, is affected by uncertainty in the marketplace [13]. The scenario-based approach is employed in the present paper to deal with the marketplace uncertainty. More like real life, the uncertain parameters related to the CO_2 emissions are also formulated in order to achieve a collaboration between the cost management and GrSCM under uncertain environment. In this way, Carbon pricing has become a common environmental concern in different countries [14]. To the best of our knowledge, there is no similar research to address this collaboration incorporated with the demand, environmental protection costs uncertainty, and risk aversion level of retailers, as Gunasekaran et al. [15] also claimed.

In this paper, a multi-objective mathematical programming is proposed to formulate multi-tiered single product green supply chain network problem. The model successfully addresses the effect of CO_2 emissions in the SCN upstream as well as the demand uncertainty and risk aversion level of the SCN downstream. Here are two main questions:

1. Is there any relation between the retailers' risk attitude and the cost of the designed GrSC?
2. Is there any clear relation between the retailers' risk attitude and the greenness level of the other tiers?

The final objective is to choose one member for each tier of SCN in an optimal robust manner. Therefore, the initial objective function is formulated based on the fixed production, alliance and transportation costs, and environmental protection investment. The variable amount of CO_2 emissions is considered to be the second objective of the model. The latter objective takes 4 levels of facility-dependent environmental investment and relation-dependent CO_2 emissions into account. In what follows, the augmented ε-constraint method (AUGMECON) that is proposed by Mavrotas [16] is employed to transform this multi-objective mathematical programming problem into the single-objective one. The method avoids the production of the weakly Pareto optimal solution. On the other hand, the uncertainty of the demand is formulated through the CVaR concept. A respective transformed convex uncertainty set is established in compliance with the demand uncertainty by scenario-based approach. Furthermore, the uncertainty set approach is employed to deal with uncertain parameters of environmental concerns. Utilizing the simultaneous scenario-based and uncertainty set-based approaches in this paper makes the proposed methodology attractive for GrSCND problem, which is completely missing in literature.

The main contributions of this paper are threefold as follows:

(a) Formulation of a robust optimization framework for GrSCND in compliance with retailer's risk attitude is the main contribution of the paper;

(b) Integrating environmental uncertain parameters, modeled by uncertainty set approach, with risk management modeled by data-driven (scenario-based) approach, results in a new method to be employed in GrSCND problem;

(c) Tackling the ε-constraint method into the proposed contribution in (b), as another contribution of the present research, significantly enhances the convergence for the exact solution. Such integration of the ε-constraint method with (b) has the advantage of transforming the model to the robust linear single-objective programming problem.

The rest of the paper is organized as follows: The mathematical formulation will be described in Section 2. Model optimization and solution approach will be described in Section 3. Computational results will be summarized in Section 4. Finally, conclusions and future potentials will be presented in Section 5.

2. Literature review

The Supply Chain Network Design (SCND) makes decisions in three levels:

1. Strategic decisions;

2. Tactical decisions;
3. Operational decisions.

The present research is familiar with the second and the third classes. However, it reflects the effect of the Supply Chain (SC) downstream risk aversion level on companies' selection in their downstream by the CVaR method. CVaR is a nice conceptual mathematical approach that is widely applicable in practice [17].

Comprehensive reviews of the GrSCM studies have been widely done by Brandenburg et al. [7], Stefan Schaltegger et al. [14], Gunasekaran et al. [15], Tang and Zhou [18], Benjaafar and Daskin [19], Seuring [20] and Elbounjimi et al. [21]. These researches investigate the concept and associated drawbacks to identify the future trends. In order to prevent redundancy, this section reviews the most recent studies. Coskun et al. [3] designed the Green Supply Chain Network (GrSCN) based on consumers' green expectations throughout the goal programming approach. Huang and Goetschalckx [22] simultaneously considered efficiency and risk in robust SCND problem. Feng et al. [23] developed a closed-loop multi-tiered SCN model with seasonal demand, which is sensitive to price. Gui-tao et al. [24] investigated the two-type suppliers while taking the manufacturers' risk aversion level and customers price rigidities into account. They considered the risk aversion level of the manufacturer in SCND problem regardless of demand uncertainty. The price and service competition in SCND problem, considering the risk attitude parameter, has been previously investigated by Xiao and Yang [25]. Rezaee et al. [11] designed a GrSCN in a carbon trading environment through a two-stage stochastic programming model. They formulated un-robust GrSCND problem without consideration of risk aversion level. Ramezani et al. [26] presented a closed-loop SCND by interrelating physical and financial flows with uncertain demands and return rate. Li et al. [27] investigated un-robust SCND problem with risk-averse retailer and risk-neutral manufacturer. It considers a single-objective dual-channel SC design, regardless of environmental concerns. Jamshidi et al. [28] considered greenness in an un-robust SCND problem without considering risk aversion level. Their use of meta-heuristic method led to near optimal solution. The present research appropriately fulfills the requirements of SCND problem in terms of greenness, robustness, retailers' risk aversion level, and demands uncertainty. Table 1 compares the present approach with the relevant studies in terms of employed features.

Table 1. Summary of some recent related pieces of research.

Article	**Objective function**							**Uncertainty of model**					**Risk**			**Solution approach**
		Cost														
	Greenness	**Fixed linkage/establishment**	**Holding/storage**	**Transportation**	**Fabrication**	**Backorder**	**Shortage cost/penalty**	**Parameters**	**Supply/manufacturer**	**Demand/retailer**	**Scenario based**	**Uncertainty set based**	**Mean standard deviation**	**Risk aversion leve**	**Robustness**	
Coskun et al. [3]	*		*	*	*											Goal programming
Huang and Goetschalckx [22]		*		*	*			*	*	*	*		*		*	Branch and reduce algorithm
Gui-tao et al. [24]		*	*	*			*		*					*		LQP-PC method
Xiao and Yang [25]		*			*					*				*		Backward induction technique
Rezaee et al. [11]	*	*	*	*	*		*	*	*	*	*					GAMS (AMPL solver)
Li et al. [27]										*				*		CVaR approach
Jamshidi et al. [28]	*		*	*		*										Memetic algorithm and Taguchi method
This paper	*	*		*	*	*		*		*	*	*		*	*	Using CVaR to deal with uncertainty and ε-constraint to transform multi-objective to single-objective problem and solve it by CPLEX

3. Problem description

The proposed model considers several candidates to design a multi-echelon green supply chain network considering single product uncertain demand and retailers' risk aversion level. The formulated capacitated optimal GrSCND problem minimizes total network cost. It is through this assumption that each selected enterprise performs only a single operation. The total cost is formulated as a summation of fixed linkage, transportation, fabrication, backorder costs, and environmental protection investment. The relation between SCN and final consumer is permitted only in the last echelon. Hence, the demand uncertainty affects the network directly from this tier.

4. Model formulation

The following notations are described for the model development:

4.1. Sets and index

$a \in A = \{1, 2, \cdots, \varphi\}$	Set of operations (tiers) used in product manufacturing
$i \in I$	Set of candidate companies available for use by the chain in tier a
$j \in J$	Set of candidate companies available for use by the chain in tier $a+1$
$v \in V = \{0, 1, \cdots, V\}$	Set of environmental protection level

4.2. Parameters

N_a	Number of pre-qualified candidates in tier a
$fc_{i(a)j(a+1)}$	Fixed cost of setting up an alliance between candidate i in tier a and candidate j in tier $a+1$
$fe_{i(a)v}$	Fixed environmental protection investment at candidate i in tier a according to environmental protection level v
$tc_{i(a)j(a+1)}$	Transportation unit cost from candidate i in tier a to candidate j in tier $a+1$
$pc_{i(a)}$	Unit processing cost at candidate i in tier a
$\theta_{i(\varphi)}$	Production capacity available at candidate i in tier φ
$q_{i(a)}$	The environmental protection level of candidate i in tier a
s^-	The under-achievement of the goal
m	A very large number
β	Fill rate provided to the customer
ϕ	Unit penalty cost, assigned to control the CO_2 emissions level deviation in all the SCN
α	Risk aversion level of the retailer
$g_{i(\varphi)}$	Backorder unit cost at candidate i in tier φ
ε	Adequately small number as a penalty for the s^-
Ψ	The adjustable control parameter for the size of the uncertainty set

4.3. Uncertain parameters

$\tilde{d}$	Uncertain amount of demand
$\tilde{h}_{i(a)v}$	Uncertain per-unit environmental influence in facility i in tier a according to environmental protection level v
$\tilde{e}_{i(a)j(a+1)}$	Uncertain amount of CO_2 emissions for the arc $i(a)j(a+1)$ that is established between candidate i in tier a and candidate j in tier $a+1$
$\tilde{\Lambda}$	Uncertain amount of total CO_2 emissions level in all the SCN

4.4. Decision variables

$x_{i(a)j(a+1)}$	Amount of product shipped from candidate i in tier a to candidate j in tier $a+1$
$t_{i(\varphi)}$	Amount of product shipped to the customer from candidate i in tier φ
$b_{i(\varphi)}$	Amount of backorder at candidate i in tier φ
$z_{i(a)}$	Amount of product manufactured at candidate i in tier a

$$y_{i(a)j(a+1)} = \begin{cases} 1 & \text{If candidate } i \text{ in tier } a \text{ and candidate } j \text{ in tier } a+1 \text{ are connected} \\ 0 & \text{Otherwise} \end{cases}$$

$$w_{i(a)} = \begin{cases} 1 & \text{If candidate } i \text{ in tier } a \text{ is included in the chain} \\ 0 & \text{Otherwise} \end{cases}$$

$$q_{i(a)v} = \begin{cases} 1 & \text{If the environmental protection } v \text{ is selected} \\ 0 & \text{Otherwise} \end{cases}$$

4.5. Mathematical model presentation

The multi-objective mixed integer linear programming formulation of the model is described through Eqs. (1)

to (22):

$$\zeta = \min \left\{ \begin{array}{l} \sum_{a=1}^{\varphi} \sum_{j=1}^{N_{a+1}} \sum_{i=1}^{N_a} fc_{i(a)j(a+1)} y_{i(a)j(a+1)} \\ + \sum_{a=1}^{\varphi} \sum_{i=1}^{N_a} pc_{i(a)} z_{i(a)} \\ + \sum_{a=1}^{\varphi} \sum_{j=1}^{N_{a+1}} \sum_{i=1}^{N_a} tc_{i(a)j(a+1)} x_{i(a)j(a+1)} \\ + \sum_{i=1}^{N_\varphi} g_{i(\varphi)} b_{i(\varphi)} \\ + \sum_{a=1}^{\varphi-1} \sum_{i=1}^{N_a} \sum_{v=0}^{V} fe_{i(a)v} q_{i(a)v} \end{array} \right\}, \tag{1}$$

$$\zeta' = \min \left\{ \sum_{a=1}^{\varphi-1} \sum_{i=1}^{N_a} z_{i(a)} \sum_{v=0}^{V} \tilde{h}_{i(a)v} + \sum_{a=1}^{\varphi-1} \sum_{i=1}^{N_a} \sum_{j=1}^{N_{a+1}} \tilde{e}_{i(a)j(a+1)} x_{i(a)j(a+1)} \right\}. \tag{2}$$

Subject to:

$$\sum_{v=0}^{V} q_{i(a)v} \leq 1, \quad i = 1,\cdots,N_a, \quad a = 1,\cdots,\varphi-1, \tag{3}$$

$$\sum_{i=1}^{N_a} w_{i(a)} = 1, \quad a = 1,2\cdots,\varphi, \tag{4}$$

$$y_{i(a)j(a+1)} \leq w_{i(a)}, \quad \forall (i,j) \in A, \quad a = 1,2,\cdots,\varphi, \tag{5}$$

$$y_{i(a)j(a+1)} \leq w_{j(a+1)}, \quad \forall (i,j) \in A, \quad a = 1,2,\cdots,\varphi, \tag{6}$$

$$y_{i(a)j(a+1)} \geq w_{i(a)} + w_{j(a+1)} - 1, \quad \forall (i,j) \in A, \quad a = 1,2,\cdots,\varphi, \tag{7}$$

$$w_{i(a)} = \sum_{v=1}^{V} q_{i(a)v}, \quad i = 1,\cdots N_a, \quad a = 1,2,\cdots,\varphi, \tag{8}$$

$$z_{i(a)} \leq \theta_{i(a)} \times w_{i(a)}, \quad i = 1,2,\cdots,N_a, \quad a = 1,2,\cdots,\varphi, \tag{9}$$

$$\sum_{j=1}^{N_{a+1}} x_{i(a)j(a+1)} \leq m \times w_{i(a)}, \quad i = 1,2,\cdots,N_a, \quad a = 1,2,\cdots,\varphi, \tag{10}$$

$$\sum_{i=1}^{N_a} x_{i(a)j(a+1)} \leq m \times w_{j(a+1)}, \quad j = 1,2,\cdots,N_{a+1}, \quad a = 1,2,\cdots,\varphi, \tag{11}$$

$$\sum_{j=1}^{N_{a+1}} x_{i(a)j(a+1)} - z_{i(a)} = 0, \quad i = 1,2,\cdots,N_a, \quad a = 1,2,\cdots,\varphi, \tag{12}$$

$$t_{i(\varphi)} - z_{i(\varphi)} = 0, \quad i = 1,2,\cdots,N, \tag{13}$$

$$z_{i(a)} \geq \beta \tilde{d}w_{i(a)}, \quad i = 1,2,\cdots,N_\varphi, \quad a = 1,2,\cdots,\varphi, \tag{14}$$

$$b_{i(\varphi)} = \tilde{d}w_{i(\varphi)} - t_{i(\varphi)}, \quad i = 1,2,\cdots,N_\varphi, \tag{15}$$

$$q_{i(a)v} \in \{0,1\}, \quad i = 1,\cdots,N_a, \quad a = 1,2,\cdots,\varphi, \quad v = 0,1,\cdots,V, \tag{16}$$

$$t_{i(\varphi)} \geq 0, \quad i = 1,2,\cdots,N_a, \tag{17}$$

$$b_{i(\varphi)} \geq 0, \quad i = 1,2,\cdots,N_a, \tag{18}$$

$$z_{i(a)} \geq 0, \quad i = 1,2,\cdots,N_a, \quad a = 1,2,\cdots,\varphi, \tag{19}$$

$$x_{i(a)j(a+1)} \geq 0, \quad \forall (i,j) \in A, \quad a = 1,2,\cdots,\varphi, \tag{20}$$

$$y_{i(a)j(a+1)} \in \{0,1\}, \quad \forall (i,j) \in A, \quad a = 1,2,\cdots,\varphi, \tag{21}$$

$$w_{i(a)} \in \{0,1\}, \quad i = 1,\cdots,N_a, \quad a = 1,2,\cdots,\varphi. \tag{22}$$

Eq. (1) represents the total cost of the network, including installing alliances, fabrication, transportation and backorder costs, and the total environmental protection investment in compliance with CO_2 emissions. Eq. (2) measures the total amount of the CO_2 emissions in the SCN, that is, integrating facility-dependent and linkage-dependent CO_2 emissions into related deviational variables. The logical limitation that imposes the final optimal SCN to select only one-environmental level for any selected candidate is defined by the Constraint (3). According to Constraints (4)-(7), the final network contains only one enterprise from any tier. The impediment that enforces the assigned environmental level to be chosen only from the opening candidate arises from Constraint (8). The amount of production in each enterprise is confined to the predefined capacity by Constraint (9). Constraints (10) and (11) enforce the products to be performed only through the final designed enterprises, while Constraints (12) and (13) are the flow balancing constraints. The fill rate is assigned by Constraint (14), while constraint (15) reveals that the calculated demand by Constraint (14) should be met or backordered. Finally, the type of variables is defined by constraints (16)-(22).

5. Solution method

Dealing with the formulated large multi-objective mathematical mixed 0-1 linear programming is in contrast to the straightforward methods of single objective. This may be caused by debility to achieve an optimal solution for all the objectives simultaneously. In this paper, CVaR is incorporated with AUGMECON to assure the convergence with the most preferred solution in a quantitative way.

In the AUGMECON, one of the objective functions is held to be optimized, and the others are considered to be constraints. In the present research, Eq. (1) is the main objective and Eq. (2) is considered to be the constraint. The constraint tackled the "$\tilde{\Lambda}$", as uncertain goal value is assigned by the retailer into the problem formulation. Therefore, one could re-write Eq. (2), i.e. constraint as:

$$\sum_{a=1}^{\varphi-1}\sum_{i=1}^{N_a} z_{i(a)}\sum_{v=0}^{V}\tilde{h}_{i(a)v} + \sum_{a=1}^{\varphi-1}\sum_{i=1}^{N_a}\sum_{j=1}^{N_{a+1}} \tilde{e}_{i(a)j(a+1)}x_{i(a)j(a+1)} \tilde{\leq} \tilde{\Lambda}. \tag{23}$$

In this constraint, "$\tilde{\leq}$" means that the inequality is not fulfilled completely.

By assigning an appropriate slack variable, i.e. s^-, to Eq. (23), Eqs. (1) and (2) could be re-written as:

$$\zeta = \min\left\{\begin{array}{l} \sum_{a=1}^{\varphi}\sum_{j=1}^{N_{a+1}}\sum_{i=1}^{N_a} fc_{i(a)j(a+1)}y_{i(a)j(a+1)} \\ +\sum_{a=1}^{\varphi}\sum_{i=1}^{N_a} pc_{i(a)}z_{i(a)} \\ +\sum_{a=1}^{\varphi}\sum_{j=1}^{N_{a+1}}\sum_{i=1}^{N_a} tc_{i(a)j(a+1)}x_{i(a)j(a+1)} \\ +\sum_{i=1}^{N_\varphi} g_{i(\varphi)}b_{i(\varphi)} \\ +\sum_{a=1}^{\varphi-1}\sum_{i=1}^{N_a}\sum_{v=0}^{V} fe_{i(a)v}q_{i(a)v} + (\varepsilon\times s^-/r) \end{array}\right\}, \tag{24}$$

subject to:

$$\sum_{a=1}^{\varphi-1}\sum_{i=1}^{N_a} z_{i(a)}\sum_{v=0}^{V}\tilde{h}_{i(a)v} + \sum_{a=1}^{\varphi-1}\sum_{i=1}^{N_a}\sum_{j=1}^{N_{a+1}} \tilde{e}_{i(a)j(a+1)}x_{i(a)j(a+1)} - \tilde{\Lambda} + \varepsilon^- = 0, \tag{25}$$

where r is explicitly employed to avoid any scaling problem. The value of r could be calculated based on payoff table. The payoff table is configured based on optimal value of each individual objective function [16].

In order to deal with Eq. (25), a box uncertainty set is utilized to reformulate a robust counterpart of the corresponding constraint, which, in turn, prevents the problem from being non-linear [29]. Reformulation of the above constraint is done by:

$$\begin{aligned} &\sum_{a=1}^{\varphi-1}\sum_{i=1}^{N_a} z_{i(a)}\sum_{v=1}^{V}\bar{h}_{i(a)v} \\ &\quad + \sum_{a=1}^{\varphi-1}\sum_{i=1}^{N_a}\sum_{j=1}^{N_{a+1}} \bar{e}_{i(a)j(a+1)}x_{i(a)j(a+1)} - \bar{\Lambda}x_0 \\ &\quad + \Psi\left[\sum_{a=1}^{\varphi-1}\sum_{i=1}^{N_a} z_{i(a)}\sum_{v=1}^{V}\hat{h}_{i(a)v}\right. \\ &\quad \left. + \sum_{a=1}^{\varphi-1}\sum_{i=1}^{N_a}\sum_{j=1}^{N_{a+1}} \hat{e}_{i(a)j(a+1)}x_{i(a)j(a+1)} - \hat{\Lambda}x_0\right] \\ &\quad + \varepsilon^- = 0, \end{aligned} \tag{26}$$

in which:

$$\tilde{h}_{j(a)v} = \bar{h}_{j(a)v} + \hat{h}_{j(a)v}\xi_{j(a)v},$$

$$\tilde{e}_{i(a)j(a+1)} = \bar{e}_{i(a)j(a+1)} + \hat{e}_{i(a)j(a+1)}\xi_{i(a)j(a+1)},$$

$$\tilde{\Lambda} = \bar{\Lambda} + \hat{\Lambda}\xi,$$

where $\bar{h}$, $\bar{e}$, $\bar{\Lambda}$ and $\hat{h}$, $\hat{e}$, $\hat{\Lambda}$ are the mean and half-length values of $\tilde{h}$, $\tilde{e}$, $\tilde{\Lambda}$, respectively. Here, it should be noted that $U_\infty = \{\xi \mid \|x\|_\infty \leq \Psi\}$ defines the box uncertainty set. The term x_0 in Eq. (26) is defined as a variable to deal with the right-hand side of Eq. (23). The value of this variable is set to one [12].

The scenario-based CVaR is employed to reformulate the demand uncertainty based on the retailers' risk aversion level $(1-\alpha)$. This means:

$$\mathrm{CVaR}_{1-\alpha} = \frac{1}{s_{1-\alpha}}\sum_{s=1}^{\lfloor s_{1-\alpha}\rfloor} d_{(s)} - \left(\frac{s_{1-\alpha} - \lfloor s_{1-\alpha}\rfloor}{\lfloor s_{1-\alpha}\rfloor}\right) d_{(\lceil s_{1-\alpha}\rceil)}, \tag{27}$$

where s_v is the number of scenarios remaining after trimming to the level $\alpha(s_\alpha = \lfloor S.(1-\alpha)+\alpha\rfloor\alpha \approx S.(1-\alpha))$. $d_{(S_\alpha)}$ is the S_αth best amount of demands regarding the objective function of the problem. So, a reformulation of Constraints (14) and (15) is as follows:

$$z_{i(\varphi)} \geq \beta \left(\frac{1}{s_{1-\alpha}} \sum_{s=1}^{\lfloor s_{1-\alpha} \rfloor} d_{(s)} - \left(\frac{s_{1-\alpha} - \lfloor s_{1-\alpha} \rfloor}{\lfloor s_{1-\alpha} \rfloor} \right) d_{(\lceil s_{1-\alpha} \rceil)} \right) .w_{i(\varphi)},$$

$$i = 1, 2, \cdots, N_{\varphi}, \tag{28}$$

$$b_{i(\varphi)} + t_{i(\varphi)} = \left(\frac{1}{s_{1-\alpha}} \sum_{s=1}^{\lfloor s_{1-\alpha} \rfloor} d_{(s)} - \left(\frac{s_{1-\alpha} - \lfloor s_{1-\alpha} \rfloor}{\lfloor s_{1-\alpha} \rfloor} \right) d_{(\lceil s_{1-\alpha} \rceil)} \right) .w_{i(\varphi)},$$

$$i = 1, 2, \cdots, N_{\varphi}. \tag{29}$$

6. Computational results and sensitivity analysis

The computational results are provided in this section to demonstrate practical usefulness of the proposed model.

The network with 4 echelons, 3 potential enterprises in each echelon, and 4 environmental investment levels is illustrated in Figure 1. Each node of echelon i ($i = 1, 2, 3$), could be tied to a node of echelon j ($j = i + 1$). This gives rise to $12^3 \times 3 = 5184$ feasible routes altogether. Table 2 provides the numerical data for the studied example. "Unif" in Table 2 stands for uniform distribution. The demand and corresponding probability are assumed to have a uniform distribution. It is obvious that the sum of all demands probabilities should be equal to 1. The defined problem can be solved by CPLEX 11.0 on a PC that has a 2.20 GHz Intel(R) Core(TM)2 Duo CPU and 3.0 G RAM.

In the studied problem, the alliance-related CO_2 emissions, the amount of CO_2 emissions, and the per-unit environmental influence are uncertain parameters. The additional information about these parameters is as follows:

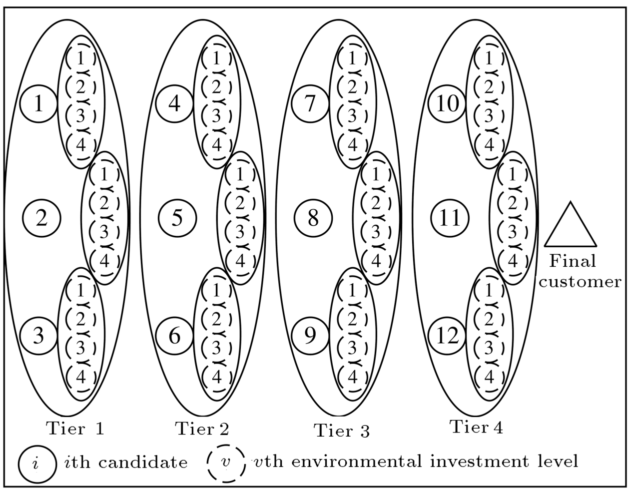

Figure 1. Four-echelon SCN for the numerical example.

Table 2. Data used in the problem.

Data type	Range
Demand	Unif (50, 800)
Transportation unit cost	Unif (10, 15)
Fixed alliance cost	Unif (1000, 5000)
Production unit cost	Unif (20, 60)
Fixed environmental protection investment	Unif (100, 300)
Backorder unit cost	Unif (10, 15)

$$\hat{h}_{j(a)v} = 0.2\bar{h}_{j(a)v}, \qquad \bar{h}_{j(a)1} = 60,$$

$$\bar{h}_{j(a)2} = 30, \qquad \bar{h}_{j(a)3} = 15,$$

$$\bar{h}_{j(a)4} = 7.5, \qquad \hat{e}_{i(a)j(a+1)} = 0.2\bar{e}_{i(a)j(a+1)},$$

$$\bar{e}_{i(a)j(a+1)} = 20, \qquad \hat{\Lambda} = 0.2\bar{\Lambda},$$

$$\bar{\Lambda} = 20000.$$

The simulation results are illustrated in Table 3. As expected, the level of retailer's risk aversion level has a significant impact on the designed network configuration. The analysis begins with $\alpha = 0.01$ and continues by increasing it according to the first column of Table 3. It is obvious from Table 3 that by decreasing the level of risk aversion level, the expected cost decreases.

Figure 2 reveals that the relationship between the total cost of the designed GrSCN and the retailers' risk attitude is linear with R^2 equal to 0.9889. Figure 3 illustrates the four designed networks with respect to the parameter $1 - \alpha$. The preference of these chains, with respect to the increasing level of $1 - \alpha$,

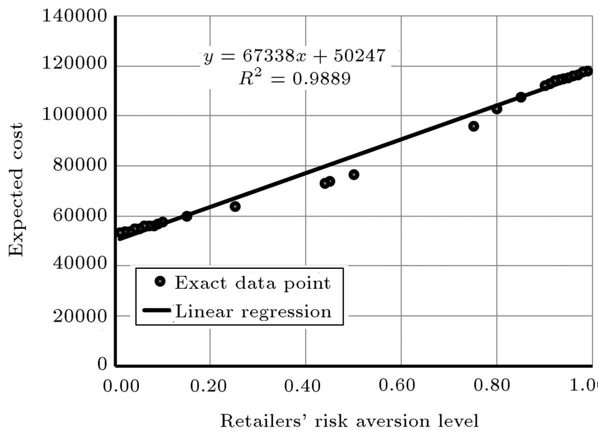

Figure 2. Trend-line for total cost with respect to retailers risk averseness.

Table 3. Results of computational study.

Retailers' risk attitude	Expected cost	Located facilities (environmental level)	Chain preference
$1-\alpha=0.99$	118141.07	2(4)-6(1)-8(1)-11	100%
$1-\alpha=0.98$	117598.49	2(4)-6(1)-8(1)-11	100%
$1-\alpha=0.97$	116734.54	2(4)-6(1)-8(1)-11	100%
$1-\alpha=0.96$	116348.22	2(4)-6(1)-8(1)-11	100%
$1-\alpha=0.95$	115578.46	2(4)-6(1)-8(1)-11	099%
		2(4)-6(1)-7(1)-12	001%
$1-\alpha=0.94$	115057.42	2(4)-6(1)-8(1)-11	098%
		2(4)-6(1)-7(1)-12	002%
$1-\alpha=0.93$	114535.65	2(4)-6(1)-8(1)-11	097%
		2(4)-6(1)-7(1)-12	003%
$1-\alpha=0.92$	114121.37	2(4)-6(1)-8(1)-11	095%
		2(4)-6(1)-7(1)-12	005%
$1-\alpha=0.91$	113230.88	2(4)-6(1)-8(1)-11	092%
		2(4)-6(1)-7(1)-12	008%
$1-\alpha=0.90$	112432.27	2(4)-6(1)-8(1)-11	084%
		2(4)-6(1)-7(1)-12	016%
$1-\alpha=0.85$	107581.03	2(4)-6(1)-8(1)-11	063%
		2(4)-6(1)-7(1)-12	037%
$1-\alpha=0.80$	103026.57	2(4)-6(1)-8(1)-11	008%
		2(4)-6(1)-7(1)-12	085%
		2(4)-4(1)-7(1)-10	007%
$1-\alpha=0.75$	96095.34	2(4)-6(1)-7(1)-12	055%
		2(4)-4(1)-7(1)-10	030%
		2(4)-4(1)-7(1)-12	013%
		2(4)-4(1)-9(1)-12	002%
$1-\alpha=0.50$	76493.37	2(4)-4(1)-9(1)-12	095%
		2(4)-4(1)-7(1)-10	005%
$1-\alpha=0.45$	73913.59	2(4)-4(1)-9(1)-12	098%
		2(4)-4(1)-7(1)-10	002%
$1-\alpha=0.44$	73250.10	2(4)-4(1)-9(1)-12	100%
$1-\alpha=0.25$	63952.03	2(4)-4(1)-9(1)-12	100%
$1-\alpha=0.15$	59885.20	2(4)-4(1)-9(1)-12	100%
$1-\alpha=0.10$	57869.71	2(4)-4(1)-9(1)-12	100%
$1-\alpha=0.09$	57001.85	2(4)-4(1)-9(1)-12	100%
$1-\alpha=0.08$	56148.71	2(4)-4(1)-9(1)-12	100%
$1-\alpha=0.07$	56112.45	2(4)-4(1)-9(1)-12	100%
$1-\alpha=0.06$	56037.42	2(4)-4(1)-9(1)-12	100%
$1-\alpha=0.05$	55037.83	2(4)-4(1)-9(1)-12	100%
$1-\alpha=0.04$	55053.93	2(4)-4(1)-9(1)-12	100%
$1-\alpha=0.03$	53979.97	2(4)-4(1)-9(1)-12	100%
$1-\alpha=0.02$	53778.21	2(4)-4(1)-9(1)-12	100%
$1-\alpha=0.01$	53444.14	2(4)-4(1)-9(1)-12	100%

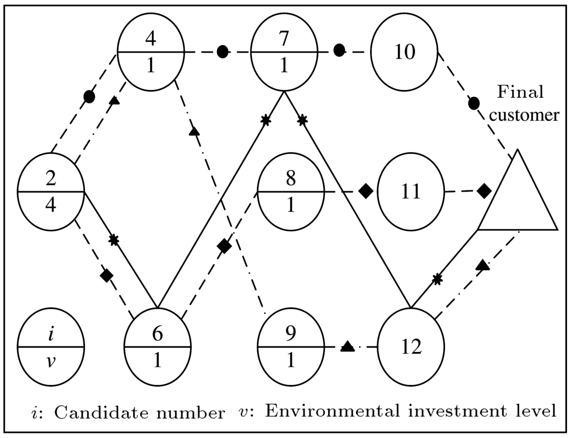

Figure 3. Designed SC structure.

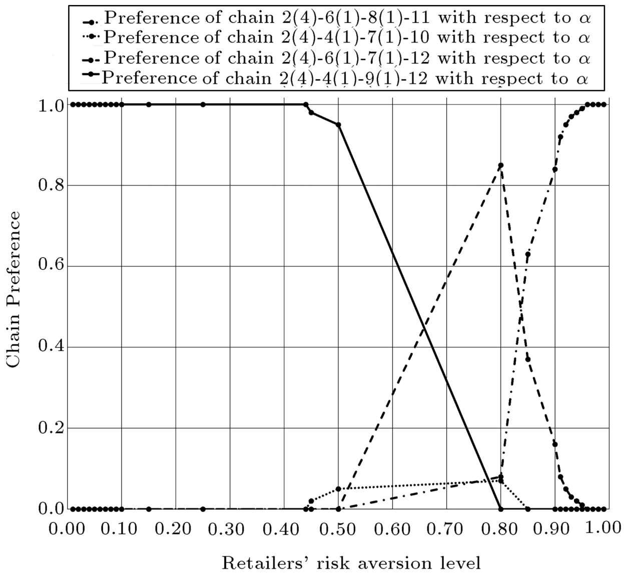

Figure 4. Designed chain performance with respect to $1-\alpha$.

is graphically shown in Figure 4. It could be clearly seen from Table 2 and Figure 4 that with respect to the expected cost with the large levels of $1-\alpha$, chain 2(4)-6(1)-8(1)-11 is optimal. By decreasing the level of $1-\alpha$, this chain is substituted by the chain 2(4)-4(1)-9(1)-12 as the competitive alternative. It is obvious that by decreasing the level of $1-\alpha$, the retailer is changed from node 12, i.e. conservative retailer, to node 11, i.e. non-conservative retailer.

7. Conclusion

This paper formulates a new multi-tiered single product green supply chain network design problem. The multi-objective mathematical programming concept is used to address the retailers' attitude in the last tier. The model investigates the effect of CO_2 emissions on the SCN upstream and the demand uncertainty of the SCN downstream. The preference of the model is its capability to consider uncertainty not only in demand, but also in environmental investment parameters, in addition to the risk attitude of the retailer. We found the following:

1. The level of retailer's risk aversion has a significant impact on the GrSCN configuration;
2. It is clear from the results that there is a linear relationship between the retailers risk aversion level and the final cost of the designed GrSCN;
3. Using the robust counterpart of the first three tiers to deal with environmental uncertainties makes the environmental parameters robust with respect to the retailers attitude;
4. It is acceptable to utilize the simultaneous scenario-based and the uncertainty set approaches to deal with uncertain data.

Simulation results for a defined network reveal the efficiency of the proposed model and solution methodology. It is shown that the main competition is made by the chains 2(4)-6(1)-8(1)-11 and 2(4)-4(1)-9(1)-12 with respect to the decreasing level of $1-\alpha$.

The present research comes with limitations that make some directions for further studies. Future research can consider consumers' green expectations, in addition to the retailers' risk averseness. Also, one can use the transportation modes, in addition to the other parameters. Finally, other directions for future research may be obtained by considering the other sources of the risk (e.g., supply, exchange rate, and tax).

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