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Simultaneous Decentralized Competitive Supply Chain Network Design under Oligopoly Competition

Kaveh Fahimi, Seyed Mohammad Seyedhosseini*, Ahmad Makui

Department of Industrial Engineering, Iran University of Science & Technology, Terhan, Iran

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Abstract

This paper discusses a problem in which n decentralized supply chains enter the market simultaneously with no existing rival chains, shape the supply chains' networks, and set wholesale and retail prices in a noncooperative manner. All the chains produce either identical or highly substitutable products. Customer demand is elastic and price-dependent. A three-step algorithm is proposed to solve this problem. Step one considers the supply chains' potential network structures. Step two is based on a finite-dimensional variational inequality formulation and is solved by a modified projection method to determine equilibrium prices. Step three selects the equilibrium locations to shape the chains' equilibrium network structure with the help of the Wilson algorithm. Finally, this approach is applied to a real-world scenario, and the results are discussed. Moreover, sensitivity analyses are conducted.

Keywords

Competitive decentralized supply chain network design, Nash equilibrium, Simultaneous games, Variational inequality.

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* **Corresponding Author, Email:** seyedhosseini@iust.ac.ir

Introduction

Today's international business and open markets promote developing countries to omit monopoly and enroll in the World Trade Organization (WTO) to achieve benefits from open world trading, so they ratify different foreign investment strategies and policies to observe international investors. In these situations, the investors come across good opportunities to design their networks domestically and obtain intact markets encountered by simultaneous competitions. On the other hand, competition is promoted by firms against firms and supply chains versus supply chains. So, investors have questions such as the following: What is the best network design in this competitive mode? How many market shares can be obtained? What is their equilibrium condition? This paper aims to provide solutions to these questions.

According to the Supply Chain Network Design (SCND) literature many studies on monopoly assumptions (Altiparmak et al., 2006; Badri et al., 2013; Özceylan et al., 2014; Vahdani & Mohamadi, 2015; Yang et al., 2015 b; Ardalan et al., 2016; Keyvanshokooh et al., 2016; Özceylan et al., 2016; Jeihoonian et al., 2017; Varsei & Polyakovskiy, 2017) have been conducted. Several examples of supply chain (SC) competition can be found in maritime shipping, the automotive and retail industries, and online bookstores (see Farahani et al., 2014 for a review on competitive supply chain network design CSCND).

Players and customers are two integral elements in CSCND. Based on players' reactions, a newcomer encounters monopoly competition (i.e., no rival exists, or existing rivals show no reactions to the newcomer), duopoly competition (i.e., just one rival shows reactions to the newcomer), and oligopoly competition (i.e., more than one rival show reactions to the newcomer). Based on players' reactions, three types of competition have been discussed in the literature: Static competition (Berman & Krass, 1998; Aboolian et al., 2007a, 2007b; Revelle et al., 2007), dynamic competition (Sinha & Sarmah, 2010; Friesz et al., 2011; Jain et al., 2014; Chen et al., 2015; Nagurney et al., 2015; Santibanez-Gonzalez & Diabat, 2016; Hjaila et al., 2016 b; Lipan et al., 2017), and competition with foresight (Zhang & Liu, 2013; Yue & You, 2014; Zhu, 2015; Drezner et al., 2015; Yang et al., 2015 a; Hjaila et al., 2016 a; Aydin et al., 2016; Genc & Giovanni, 2017).

Customer behavior and customer demand functions are important factors in CSCND. Customer demand can be elastic or inelastic, and in the case of elastic demand, it can depend on price, service, price and service, or price and distance (Farahani et al., 2014). Customer utility functions are mostly categorized into deterministic, introduced by Hotelling (1929), and random utility, introduced by Huff (1964, 1966) models. Moreover, three types of competition exist in the SC competition literature: Horizontal competition (Nagurney et al., 2002; Cruz, 2008; Zhang & Zhou, 2012; Qiang et al., 2013; Huseh, 2015; Qiang, 2015; Li & Nagurney, 2016; Nagurney et al., 2016), vertical competition (Chen et al., 2013; Wu, 2013; Zhao & Wang, 2015; Zhang et al., 2015; Bai et al., 2016; Bo & Li, 2016; Li & Nagurney, 2016; Huang et al., 2016; Wang et al., 2017; Genc & Giovanni, 2017; Chaeb & Rasti-Barzoki, 2017), and SC versus SC (Li et al., 2013; Chung & Kwon, 2016).

Contribution of This Paper

This paper addresses a simultaneous decentralized supply chain network design problem (SD-SCND) in which n decentralized SCs simultaneously enter a virgin market, shape their networks, set the wholesale and retail prices, and specify flows of products among the tiers in dynamic competition without any cooperation. This problem and this paper's proposed approach to solve it, is most like that described in Rezapour and Farahani (2010), Nagurney (1999), and a subsequent paper of Nagurney. However, this paper's main contribution is the addition of the location decision as 0-1 variables, which puts the problem in the class of mixed-integer, nonlinear programming models. Therefore, the proposed problem cannot be solved with the explicit solution algorithm. Thus, we propose a three-step algorithm to solve the problem and find an equilibrium solution. As the chains enter the dynamic competition, we use variational inequality formulation to find equilibrium results. However, VI is only applicable to models with continuous variables and convex functions; but, because our problem has 0-1 variables, we use the Wilson algorithm and specify some strategies related to the 0-1 variables to handle this matter. We define all the possible strategies based on location variables of the chains in the first stage of our algorithm and then use the VI formulation and modified projection method to obtain equilibrium results of continuous variables in the second stage. The third stage is constructed with the help of the Wilson algorithm, and we select the equilibrium locations in this step. With this three-step algorithm we are able to solve the problem of SD-SCND in dynamic competition.

Problem Definition

This paper considers the problem of simultaneous decentralized competitive supply chain network design (SD-CSCND) in which *n* SCs plan to enter into virgin market. Each chain has two independent tiers called plant and distribution center (DC) levels, which try to maximize the chain's profits by selecting the best locations for their facilities and setting wholesale and retail prices. All the entities make decisions simultaneously in a noncooperative manner. The chains produce either identical or highly substitutable products, and customer demand is elastic and price-dependent.

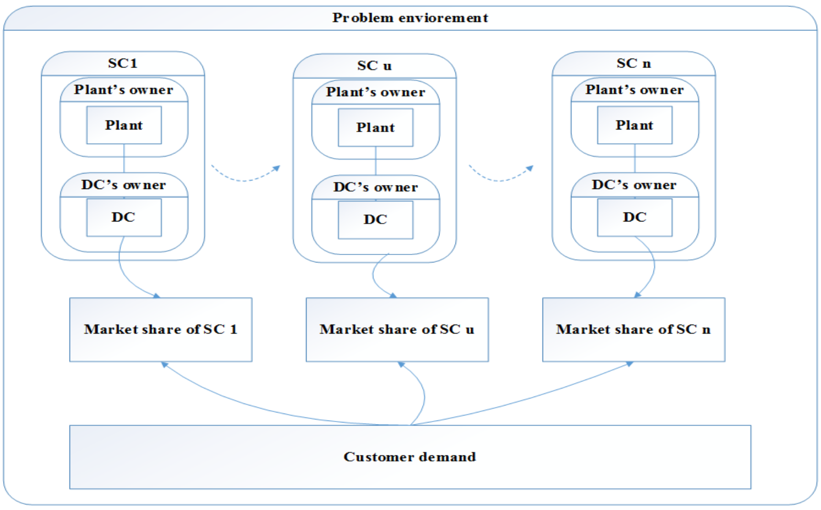

Fig. 1. Simultanous decentralized competitive supply chain network design problem

Before modelling the formulation, imagine there are n incoming SCs indexed by u; then, u th SC has s_u potential locations for opening plants, indexed by e_u and m_u, and potential locations for opening DCs, indexed by i_u. There exist l demand points indexed by k. Similar to the description provided by Tsay and Agrawal (2000), demand functions for u' th SC in market k can be defined as follows):

$$d_k^{(u')}(P_k) = d_k - \alpha P_k^{(u')} + \beta \sum_{\substack{u=1 \\ u \neq u'}}^{n} P_k^{(u)} \qquad (1)$$

The term d_k is the potential market size and α refers to self-price sensitivity. The term β represents the cross-price sensitivity. Since demand cannot be negative, we assume the following:

$$d_k - \alpha P_k^{(u')} \gg \beta \sum_{\substack{u=1 \\ u \neq u'}}^{n} P_k^{(u)} \qquad (2)$$

Now we can introduce parameters and variables as follows:

Parameters and variables

parameters

$P_{e_u}^{(1)}$	Number of opened facilities in plant level of SC u
$P_{i_u}^{(2)}$	Number of opened facilities in DC level of SC u

Cost structure of the problem

$F_{e_u}(q_{e_u}^{(1)})$	Cost of locating in order to produce $q_{e_u}^{(1)}$ units in the e_u th plant of SC u, we assume these functions are continuous and convex (Dong et al., 2004). $q_{e_u}^{(1)} = \sum_{i_u} q_{e_u i_u}^{(1)}$
$S_{e_u}(q_{e_u}^{(1)})$	Cost of procurement, producing and handling $q_{e_u}^{(1)}$ units in the e_u th plant of SC u, we assume these functions are continuous and convex (Nagurney et al., 2002). $q_{e_u}^{(1)} = \sum_{i_u} q_{e_u i_u}^{(1)}$
$C_{e_u i_u} q_{e_u i_u}^{(1)}$	Cost of transaction (ordering, transportation and other expenses) $q_{e_u i_u}^{(1)}$ units between plant e_u and DC i_u of SC u, we assume these functions are continuous and convex (Nagurney et al., 2002).

$F_{i_u}(S^{(2)}_{i_u})$	Cost of locating in order to distribute $S^{(2)}_{i_u}$ units in the i_u th DC of SC u, we assume these functions are continuous and convex, (Dong et al., 2004). $s^{(2)}_{i_u} = \sum_k s^{(2)}_{i_u k}$
h_i	Unit holding cost at DC i_u for SC u
$C^{(2)}_{i_u k}(S^{(2)}_{i_u k})$	Cost of transaction (ordering, transportation and other expenses ($S^{(2)}_{i_u k}$) units between DC i_u and customer k for SC u, we assume these functions are continuous and convex (Nagurney et al., 2002).

Variables

$w^{(1)}_{e_u i_u}$	Wholesale price of plant e to DC i in the u th SC
$W_1 = \left[w^{(1)}_{e_u i_u}\right]$	Vector of wholesale price of plants to DCs for all SCs
$q^{(1)}_{e_u i_u}$	Quantity of product shipped from plant e to DC i in the u th SC
$Q_{11} = \left[q^{(1)}_{e_u i_u}\right]$	Vector of quantity of product shipped from plants to DCs
$P^{(u)}_k$	Price of u th SC in market k
$P_1 = \left[P^{(u)}_k\right]$	Vector of price of SCs in market k
$s^{(2)}_{i_u k}$	Amount of product that DC i considers to satisfy for market k in the u th SC
$Q_{12} = \left[s^{(2)}_{i_u k}\right]$	Vector of amount of product that DC i considers to satisfy for market k in the u th SC
$y^{(1)}_{e_u}$	$\begin{cases} 1 \text{ if } SC\ u \text{ opens a plant in location } e_u \\ 0 \text{ otherwise} \end{cases}$
$y^{(2)}_{i_u}$	$\begin{cases} 1 \text{ if } SC\ u \text{ opens a DC in location } i_u \\ 0 \text{ otherwise} \end{cases}$
$Y_1 = \left[y^{(1)}_{e_u}\right]$	Vector of location variables of plants
$Y_2 = \left[y^{(2)}_{i_u}\right]$	Vector of location variables of DCs

Modelling Framework

Plants model

$$\max \sum_{e_u} \sum_{i_u} w^{(1)}_{e_u i_u} q^{(1)}_{e_u i_u} y^{(1)}_{e_u} - \left(\sum_{e_u} F_{e_u}(q^{(1)}_{e_u}) y^{(1)}_{e_u} + \sum_{e_u} s_{e_u}(q^{(1)}_{e_u})\, y^{(1)}_{e_u} + \sum_{e_u i_u} \sum_{e_u i_u} c_{e_u i_u}(\, q^{(1)}_{e_u i_u}) y^{(1)}_{e_u} \right) \qquad \forall u \qquad (3)$$

$s.t$

$$\sum_{e_u} y_{e_u}^{(1)} = P_{e_u}^{(1)} \qquad \forall u \quad (4)$$

$$q_{e_u i_u}^{(1)} \geq 0, y_{e_u}^{(1)} \in \{0,1\} \qquad \forall e_u, i_u, u \; (5)$$

Term (3) represents the objective function of the plants for each chain that includes total revenue from selling the product to the DCs of the chain minus total location and transaction costs. Constraint (4) specifies the number of opened plants in the chain, and constraint (5) is related to the binary and non-negativity restriction on the corresponding decision variables.

DC's model

$$\max \sum_{i_u} \sum_{k} p_k^{(u)} s_{i_u k}^{(2)} y_{i_u}^{(2)} - \left(\begin{array}{l} \sum_{i_u} F_{i_u}(s_{i_u}^{(2)}) y_{i_u}^{(2)} + \sum_{i_u} \sum_{k} \frac{h_{i_u}}{2} s_{i_u k}^{(2)} y_{i_u}^{(2)} + \\ \sum_{e_u} \sum_{i_u} c_{i_u k}^{(2)}(s_{i_u k}^{(2)}) y_{i_u}^{(2)} + \sum_{e_u} \sum_{i_u} w_{e_u i_u}^{(1)} q_{e_u i_u}^{(1)} y_{i_u}^{(2)} \end{array} \right) \qquad \forall u \quad (6)$$

$s.t$

$$\sum_{e_u} q_{e_u}^{(1)} \geq \sum_{i} s_{i_u k}^{(2)} \qquad \forall u, k \quad (7)$$

$$\sum_{i_u} y_{i_u}^{(2)} = P_{i_u}^{(2)} \qquad \forall u \quad (8)$$

$$s_{i_u k}^{(2)} \geq 0, y_{i_u}^{(2)} \in \{0,1\} \qquad \forall u, k, i_u \quad (9)$$

Term (6) represents the objective function of DCs of the chain which includes profits captured by selling the product to the customers minus total location and transaction costs. Constraint (7) is related to flow balance; constraint (8) specifies the number of opened DCs in each chain and constraint (9) is related to the binary and non-negativity restriction on the corresponding decision variables.

Solution Approach

This section presents our proposed algorithm for solving the SD-CSCND problem. The algorithm is essentially based on the chains' decision variables. Each SC has two different types of decision variables, including continuous and discrete (0-1) variables.

Continuous variables W_1, P_1, Q_{11}, Q_{12} are related to wholesale and retail prices and the amount of shipments among the tiers while discrete variables Y_1, Y_2 are related to the locations of the facilities. Also, they are intrinsically different decisions, as location is strategic while the other variables are related to operational decisions. On the other hand, they are related to each other, as each opened location has its own costs that affect the chains' prices, market shares, demands, and profits.

With the help of the Wilson algorithm, Wilson (1971), the variational inequality formulation, the modified projection method, and Nagurney et al. (2002), and references therein, we propose a three-step algorithm in which the first step defines basic strategies based on location variables. Each strategy contains a potential network design structure for the chains, as their location is fixed. In the second step, we use variational inequalities and the modified projection method to calculate the payoff for each potential network structure. After steps one and two, the payoff for all the possible structures of the chains is calculated. In step three and with the help of the Wilson algorithm, the Nash equilibrium locations can be found, and the chains' equilibrium network design is obtained. The algorithm procedure is as follows:

Initialize the whole strategies for the players:

1. Construct an empty poly-matrix by considering all pure strategies of the players (any combination of the facilities to be opened from all the potential facilities of each player).

Calculate Nash equilibrium prices and flows for all players in the chains in the defied strategies:

2. Develop VI formulation of the players' problems in each strategy and solve it with the help of the modified projection method.

Find the best response of all the players:

3. Fill the empty poly-matrix with the obtained payoffs from the previous stage and find the best network structure using the Wilson algorithm.

To clarify the proposed algorithm, consider an example in which one SC, composed of plant and DC levels, is planning to enter one virgin market in a decentralized manner, shape its network, and set wholesale and retail prices and flows. Imagine both plant and DC have two potential locations, and they intend to open one facility to capture the market demand. Table 1 shows the cost functions of the entities related to the places.

Table 1. Cost functions

Plant1 (fixed cost)	$F_{1_1}(q_{1_1}^{(1)}) = 4(q_{1_1}^{(1)})^2 + 5(q_{1_1}^{(1)})$	Plant 2 to DC2(transportation cost)	$c_{2_12_1}\left(q_{2_12_1}^{(1)}\right) = 0.3{q_{2_12_1}^{(1)}}^2 + 0.2q_{2_12_1}^{(1)}$
Plant2 (fixed cost)	$F_{2_1}(q_{2_1}^{(1)}) = 5(q_{2_1}^{(1)})^2 + 4(q_{2_1}^{(1)})$	DC1(fixed cost)	$F_{1_1}\left(s_{1_1}^{(2)}\right) = 3.5(s_{1_1}^{(2)})^2 + 4s_{1_1}^{(2)}$
Plant1 (production cost)	$g_{1_1}(q_{1_1}^{(1)}) = 0.2(q_{1_1}^{(1)})^2 + 0.1(q_{1_1}^{(1)})$	DC2(fixed cost)	$F_{2_1}\left(s_{2_1}^{(2)}\right) = 5(s_{2_1}^{(2)})^2 + 3s_{2_1}^{(2)}$
Plant2(production cost)	$g_{2_1}(q_{2_1}^{(1)}) = 0.15(q_{2_1}^{(1)})^2 + 0.1(q_{2_1}^{(1)})$	DC1(holding cost)	$h_{1_1}\left(s_{1_11}^{(2)}\right) = 0.58s_{1_11}^{(2)}$
Plant 1 to DC1 (transportation cost)	$c_{1_11_1}\left(q_{1_11_1}^{(1)}\right) = 0.2{q_{1_11_1}^{(1)}}^2 + 0.25q_{1_11_1}^{(1)}$	DC2(holding cost)	$h_{2_1}\left(s_{2_11}^{(2)}\right) = 0.4s_{2_11}^{(2)}$
Plant 2 to DC1 (transportation cost)	$c_{2_11_1}\left(q_{2_11_1}^{(1)}\right) = 0.3{q_{2_11_1}^{(1)}}^2 + 0.2q_{2_11_1}^{(1)}$	DC1 to market 1(transportation cost)	$c_{1_11}^{(2)}\left(s_{1_11}^{(2)}\right) = 0.16(s_{1_11}^{(2)})^2 + 0.18s_{1_11}^{(2)}$
Plant 1 to DC2 (transportation cost)	$c_{1_12_1}\left(q_{1_12_1}^{(1)}\right) = 0.2{q_{1_12_1}^{(1)}}^2 + 0.25q_{1_12_1}^{(1)}$	DC2 to market 1(transportation cost)	$c_{2_11}^{(2)}\left(s_{2_11}^{(2)}\right) = 0.2(s_{2_11}^{(2)})^2 + 0.3s_{2_11}^{(2)}$

According to step one, each player has $\binom{2}{1} = 2$ pure strategies; consequently, $\binom{2}{1}.\binom{2}{1} = 4$ potential strategies are available. The opened plant and DC can be as follows: $\{S_1 = \{plant1, DC1\}, S_2 = \{plant1, DC2\}, S_3 = \{plant2, DC1\}, S_4 = \{plant2, DC2\}\}$. Now, the algorithm can be applied to step two in which it can calculate the equilibrium prices and flows with the help of the VI formulation and the modified projection method. The results of this step are presented in Table 2.

Table 2. Nash equilibrium solution of each potential strategy

	Amount of shipments between plant and DC	Amount of shipments between DC and market	Price of plant for DC	Price of DC in market	Market share	Income of plant	Cost of plant	Profit of plant	Income of DC	Cost of DC	Profit of DC
S_1	78.83	78.83	698.93	1280.8	78.83	55088	27755	24227	100971	23744	77227
S_2	66.61	66.61	591.40	1288.9	66.61	39386	22089	17297	85864	23323	62541
S_3	70.13	70.13	768.48	1286.6	70.13	53877	27089	26788	90225	18825	71400
S_4	60.29	60.29	661.33	1293.1	60.29	39864	20062	19802	77973	19130	58844

Step one trough step two result in an equilibrium solution for the continuous variables in each strategy. The algorithm can then be applied to step three in which it can select the equilibrium locations of the facilities in order to finalize the network design with the help of the Wilson algorithm. It is worth noting that in the case of two existing players, this step can also be conducted using the Lemke and Howson's (1964) algorithm. Table 3 presents this step. According to the constructed matrix, strategy S_2 is selected as the Nash equilibrium solution of the game.

Table 3. Final Nash equilibrium solution

DC's pure strategies / Plant's pure strategies	1	2
1	$(24227^*, 77227)$	$(17297^*, 62541^*)$
2	$(26788, 71400)$	$(19802, 58844^*)$

It is worth noting that since steps one and three are based on the players' potential strategies, and step two is based on variational inequality and the modified projection method. With respect to the fact that pure strategies are finite and the modified projection method has a convergence criterion, the proposed procedure converges to an equilibrium solution (*see* the convergence proof of the Wilson algorithm; Wilson (1971); the variational inequality formulation and the modified projection method; and Nagurney et al. (2002) and references therein).

Stage one

This stage defines the number of strategies and shapes the matrix that should be filled in the next stage. By examining the 0-1 decision variables in each chain, it is understandable that each plant has $\binom{s_u}{P_{e_u}^{(1)}}$ pure strategies, and each DC has $\binom{m_u}{P_{i_u}^{(2)}}$ pure strategies. So the dimension of the matrix is $\binom{s_1}{P_{e_1}^{(1)}} * \binom{m_1}{P_{i_1}^{(2)}} * \dots * \binom{s_u}{P_{e_u}^{(1)}} * \binom{m_u}{P_{i_u}^{(2)}} * \dots * \binom{s_n}{P_{e_n}^{(1)}} * \binom{m_n}{P_{i_n}^{(2)}}$.

Stage two

In this stage we should optimize the following models for the opened plants and DCs in each strategy to calculate payoff for the game.

Modified plants model

$$\max \sum_{e_u} \sum_{i_u} w_{e_u i_u}^{(1)} q_{e_u i_u}^{(1)} y_{e_u}^{(1)} - \left(\sum_{e_u} F_{e_u}(q_{e_u}^{(1)}) + \sum_{e_u} s_{e_u}(q_{e_u}^{(1)}) + \sum_{e_u i_u} \sum_{e_u i_u} c_{e_u i_u}(q_{e_u i_u}^{(1)}) \right) \qquad \forall u \qquad (10)$$

$s.t$

$$q_{e_u i_u}^{(1)} \geq 0 \qquad \forall e_u, i_u, u \qquad (11)$$

Term (10) represents the objective function of the opened plants for each chain that includes total revenue from selling the product to the DCs of the chain minus total location and transaction costs and; constraint (11) is related to the non-negativity restriction on the corresponding decision variables.

Modified DC's model

$$\max \sum_{i_u} \sum_{k} p_k^{(u)} s_{i_u k}^{(2)} y_{i_u}^{(2)} - \left(\begin{array}{l} \sum_{i_u} F_{i_u}(s_{i_u}^{(2)}) + \sum_{i_u} \sum_{k} \frac{h_{i_u}}{2} s_{i_u k}^{(2)} + \\ \sum_{e_u} \sum_{i_u} c_{i_u k}^{(2)}(s_{i_u k}^{(2)}) + \sum_{e_u} \sum_{i_u} w_{e_u i_u}^{(1)} q_{e_u i_u}^{(1)} \end{array} \right) \qquad \forall u \qquad (12)$$

$s.t$

$$\sum_{e_u} q_{e_u}^{(1)} \geq \sum_{i_u} s_{i_u k}^{(2)} \qquad \forall u,k \qquad (13)$$

$$s_{i_u k}^{(2)} \geq 0 \qquad \forall u,k,i_u \qquad (14)$$

Term (12) represents the objective function of opened DCs of the chain which includes profits captured by selling the product to the customers minus total transaction costs. Constraint 15 is related to flow balance between opened plants and DCs; constraint 16 is related to the non-negativity restrictions on the corresponding decision variables.

The modified plant and DC model should be formulated as VI model (according to Rezapour & Farahani (2010), Nagurney (1999), and a subsequent paper of Nagurney). The VI is solvable by several algorithms as modified projection method, like Nagurney and Toyasaki (2005), Rezapour and Farahani (2010), the Euler-type model (Nagurney et al., 2003; Santibanez-Gonzalez & Diabat, 2016), some evolutionary algorithm (Majig et al., 2007), and extended mathematical programming (EMP) of GAMS (Santibanez-Gonzalez & Diabat, 2016). In this article, we use modified projection method to solve the model.

Stage three

Now, we can find the Nash equilibrium locations and shape the network structure of the chains by the specified prices and amount of shipments. This step is conducted with the help of the Wilson algorithm (Wilson, 1971).

Computational Results

This section presents a real-world problem occurring in the Iranian capacitor industry and inspired us to propose the problem and solution described in this paper. The first subsection describes the problem environment, and the second subsection provides discussions of the results.

Case study

As a consulter group, we study a real-world problem in which two

SCs are planning to enter the capacitor industry in the Iranian market. These two SCs want to produce a special type of capacitor that is used in refrigerators. This type of capacitor is solely imported, and there is no domestic producer for it, so they decided to enter this virgin market by shaping their SC domestically. They want to open one plant and two DCs from two and four potential locations and shape their networks in a decentralized manner in a dynamic competition and set the wholesale and retail prices. Table 4 represents their cost structures, and Table 5 represents the achieved results. Both chains open a plant at location one and DCs in location one and two to obtain Nash equilibrium locations. The proposed algorithm was implemented in Matlab 2014a. The convergence criterion used was that the absolute value of the flows and prices between two successive iterations differed by no more than 10^{-6}, and the computational time is negligible.

Table 4. Cost structure of the Chains

Cost functions	SC1	SC2
Plant1(fixed cost)	$F_{1_1}(q^{(1)}_{1_1}) = 4.5(q^{(1)}_{1_1})^2 + 5(q^{(1)}_{1_1})$	$F_{1_2}(q^{(1)}_{1_2}) = 4(q^{(1)}_{1_2})^2 + 5(q^{(1)}_{1_2})$
Plant2(fixed cost)	$F_{2_1}(q^{(1)}_{2_1}) = 6(q^{(1)}_{2_1})^2 + 3(q^{(1)}_{2_1})$	$F_{2_2}\left(q^{(1)}_{2_2}\right) = 5(q^{(1)}_{2_2})^2 + 4.5(q^{(1)}_{2_2})$
Plant1 (production cost)	$g_{1_1}\left(q^{(1)}_{1_1}\right) = 0.2(q^{(1)}_{1_1})^2 + 0.1(q^{(1)}_{1_1})$	$g_{1_2}\left(q^{(1)}_{1_2}\right) = 0.15(q^{(1)}_{1_2})^2 + 0.13(q^{(1)}_{1_2})$
Plant2 (production cost)	$g_{2_1}\left(q^{(1)}_{2_1}\right) = 0.14(q^{(1)}_{2_1})^2 + 0.17(q^{(1)}_{2_1})$	$g_{2_2}\left(q^{(1)}_{2_2}\right) = 0.1(q^{(1)}_{2_2})^2 + 0.2(q^{(1)}_{2_2})$
Plant 1 to DC1 (transportation cost)	$c_{1_11_1}\left(q^{(1)}_{1_11_1}\right) = 0.2{q^{(1)}_{1_11_1}}^2 + 0.25q^{(1)}_{1_11_1}$	$c_{1_21_2}\left(q^{(1)}_{1_21_2}\right) = 0.2{q^{(1)}_{1_21_2}}^2 + 0.3q^{(1)}_{1_21_2}$
Plant 2 to DC1 (transportation cost)	$c_{2_11_1}\left(q^{(1)}_{2_11_1}\right) = 0.15{q^{(1)}_{2_11_1}}^2 + 0.17q^{(1)}_{2_11_1}$	$c_{2_21_2}\left(q^{(1)}_{2_21_2}\right) = 0.2{q^{(1)}_{2_21_2}}^2 + 0.35q^{(1)}_{2_21_2}$
Plant 1 to DC2 (transportation cost)	$c_{1_12_1}\left(q^{(1)}_{1_12_1}\right) = 0.16{q^{(1)}_{1_12_1}}^2 + 0.27q^{(1)}_{1_12_1}$	$c_{1_22_2}\left(q^{(1)}_{1_22_2}\right) = 0.19{q^{(1)}_{1_22_2}}^2 + 0.22q^{(1)}_{1_22_2}$
Plant 2 to DC2 (transportation cost)	$c_{2_12_1}\left(q^{(1)}_{2_12_1}\right) = 0.16{q^{(1)}_{2_12_1}}^2 + 0.19q^{(1)}_{2_12_1}$	$c_{2_22_2}\left(q^{(1)}_{2_22_2}\right) = 0.17{q^{(1)}_{2_22_2}}^2 + 0.16q^{(1)}_{2_22_2}$
Plant 1 to DC3 (transportation cost)	$c_{1_13_1}\left(q^{(1)}_{1_13_1}\right) = 0.22{q^{(1)}_{1_13_1}}^2 + 0.1q^{(1)}_{1_13_1}$	$c_{1_23_2}\left(q^{(1)}_{1_23_2}\right) = 0.16{q^{(1)}_{1_23_2}}^2 + 0.17q^{(1)}_{1_23_2}$
Plant 2 to DC3 (transportation cost)	$c_{2_13_1}\left(q^{(1)}_{2_13_1}\right) = 0.3{q^{(1)}_{2_13_1}}^2 + 0.09q^{(1)}_{2_13_1}$	$c_{2_23_2}\left(q^{(1)}_{2_23_2}\right) = 0.13{q^{(1)}_{2_23_2}}^2 + 0.19q^{(1)}_{2_23_2}$

Continue Table 4. Cost structure of the Chains

Cost functions	SC1	SC2
Plant 1 to DC4 (transportation cost)	$c_{1_14_1}\left(q^{(1)}_{1_14_1}\right) = 0.16{q^{(1)}_{1_14_1}}^2 + 0.14q^{(1)}_{1_14_1}$	$c_{1_24_2}\left(q^{(1)}_{1_24_2}\right) = 0.19{q^{(1)}_{1_24_2}}^2 + 0.17q^{(1)}_{1_24_2}$
Plant 2 to DC4 (transportation cost)	$c_{2_14_1}\left(q^{(1)}_{2_14_1}\right) = 0.17{q^{(1)}_{2_14_1}}^2 + 0.13q^{(1)}_{2_14_1}$	$c_{2_24_2}\left(q^{(1)}_{2_24_2}\right) = 0.16{q^{(1)}_{2_24_2}}^2 + 0.19q^{(1)}_{2_24_2}$
DC1(fixed cost)	$F_{1_1}\left(s^{(2)}_{1_1}\right) = 3.5(s^{(2)}_{1_1})^2 + 4s^{(2)}_{1_1}$	$F_{1_2}\left(s^{(2)}_{1_2}\right) = 4.2(s^{(2)}_{1_2})^2 + 5s^{(2)}_{1_2}$
DC2(fixed cost)	$F_{2_1}\left(s^{(2)}_{2_1}\right) = 5.1(s^{(2)}_{2_1})^2 + 3.9s^{(2)}_{2_1}$	$F_{2_2}\left(s^{(2)}_{2_2}\right) = 4.1(s^{(2)}_{2_2})^2 + 3.2s^{(2)}_{2_2}$
DC3(fixed cost)	$F_{3_1}\left(s^{(2)}_{3_1}\right) = 4.8(s^{(2)}_{3_1})^2 + 5.5s^{(2)}_{3_1}$	$F_{3_2}\left(s^{(2)}_{3_2}\right) = 5.25(s^{(2)}_{3_2})^2 + 4.2s^{(2)}_{3_2}$
DC4(fixed cost)	$F_{4_1}\left(s^{(2)}_{4_1}\right) = 3.8(s^{(2)}_{4_1})^2 + 4.5s^{(2)}_{4_1}$	$F_{4_2}\left(s^{(2)}_{4_2}\right) = 4.1(s^{(2)}_{4_2})^2 + 3.9s^{(2)}_{4_2}$
DC1(holding cost)	$h_{1_1}\left(s^{(2)}_{1_11}\right) = 0.58s^{(2)}_{1_11}$	$h_{1_2}(s^{(2)}_{1_2}) = 0.35(s^{(2)}_{1_2})$
DC2(holding cost)	$h_{2_1}\left(s^{(2)}_{2_11}\right) = 0.35s^{(2)}_{2_11}$	$h_{2_2}(s^{(2)}_{2_2}) = 0.45(s^{(2)}_{2_2})$
DC3(holding cost)	$h_{3_1}\left(s^{(2)}_{3_11}\right) = 0.7s^{(2)}_{3_11}$	$h_{3_2}(s^{(2)}_{3_2}) = 0.28(s^{(2)}_{3_2})$
DC4(holding cost)	$h_{4_1}\left(s^{(2)}_{4_11}\right) = 0.25s^{(2)}_{4_11}$	$h_{4_2}(s^{(2)}_{4_2}) = 0.44(s^{(2)}_{4_2})$
DC1 to market 1(transportation cost)	$c^{(2)}_{1_11}\left(s^{(2)}_{1_11}\right) = 0.26(s^{(2)}_{1_11})^2 + 0.18s^{(2)}_{1_11}$	$c^{(2)}_{1_21}\left(s^{(2)}_{1_21}\right) = 0.19(s^{(2)}_{1_21})^2 + 0.23s^{(2)}_{1_21}$
DC2 to market 1(transportation cost)	$c^{(2)}_{2_11}\left(s^{(2)}_{2_11}\right) = 0.29(s^{(2)}_{2_11})^2 + 0.28s^{(2)}_{2_11}$	$c^{(2)}_{2_21}\left(s^{(2)}_{2_21}\right) = 0.16(s^{(2)}_{2_21})^2 + 0.12s^{(2)}_{2_21}$
DC3 to market 1(transportation cost)	$c^{(2)}_{3_11}\left(s^{(2)}_{3_11}\right) = 0.22(s^{(2)}_{3_11})^2 + 0.2s^{(2)}_{3_11}$	$c^{(2)}_{3_21}\left(s^{(2)}_{3_21}\right) = 0.17(s^{(2)}_{3_21})^2 + 0.29s^{(2)}_{3_21}$
DC4 to market 1(transportation cost)	$c^{(2)}_{4_11}\left(s^{(2)}_{4_11}\right) = 0.23(s^{(2)}_{4_11})^2 + 0.19s^{(2)}_{4_11}$	$c^{(2)}_{4_21}\left(s^{(2)}_{4_21}\right) = 0.25(s^{(2)}_{4_21})^2 + 0.29s^{(2)}_{4_21}$
DC1 to market 2(transportation cost)	$c^{(2)}_{1_12}\left(s^{(2)}_{1_12}\right) = 0.15(s^{(2)}_{1_12})^2 + 0.2s^{(2)}_{1_12}$	$c^{(2)}_{1_22}\left(s^{(2)}_{1_22}\right) = 0.15(s^{(2)}_{1_22})^2 + 0.21s^{(2)}_{1_22}$
DC2 to market 2(transportation cost)	$c^{(2)}_{2_12}\left(s^{(2)}_{2_12}\right) = 0.25(s^{(2)}_{2_12})^2 + 0.28s^{(2)}_{2_12}$	$c^{(2)}_{2_22}\left(s^{(2)}_{2_22}\right) = 0.15(s^{(2)}_{2_22})^2 + 0.18s^{(2)}_{2_22}$
DC3 to market 2(transportation cost)	$c^{(2)}_{3_12}\left(s^{(2)}_{3_12}\right) = 0.25(s^{(2)}_{3_12})^2 + 0.23s^{(2)}_{3_12}$	$c^{(2)}_{3_22}\left(s^{(2)}_{3_22}\right) = 0.17(s^{(2)}_{3_22})^2 + 0.25s^{(2)}_{3_22}$
DC4 to market 2(transportation cost)	$c^{(2)}_{4_12}\left(s^{(2)}_{4_12}\right) = 0.24(s^{(2)}_{4_12})^2 + 0.12s^{(2)}_{4_12}$	$c^{(2)}_{4_22}\left(s^{(2)}_{4_22}\right) = 0.18(s^{(2)}_{4_22})^2 + 0.15s^{(2)}_{4_22}$

Table 5. Computational results for SCs

	SC1	SC2
Amount of shipments between plant 1 and DC1	4694.3	4472.9
Amount of shipments between plant 1 and DC2	4165.3	4518.2
Amount of shipments between DC1 and market 1	1574.5	1583
Amount of shipments between DC1 and market 2	3119.8	2889.9
Amount of shipments between DC2 and market 1	1546.2	1595.8
Amount of shipments between DC2 and market 2	2619.2	2922.4
Price of plant 1 for DC1	41315.09012	38919.48382
Price of plant 1 for DC2	36327.07227	39223.30433
Price of DCs in market 1	52844.97657	52823.45377
Price of DCs in market 2	64094.66474	64067.50132
Market share 1	3120.678925	3178.79216
Market share 2	5739.003739	5812.346629
Income of plant	345259305.3	351300806.8
Cost of plant	195122565.1	175674633.4
Profit of plant	150136740.1	175626173.3
Income of DC	532750281.5	540295763.9
Cost of DC	94475846.25	94517840.4
Profit of DC	438274435.2	445777923.5
Landa 1	41315	38919
Landa 2	36327	39223

Discussion

The case study presented in this paper reflects an SD-CSCND problem that has nonlinear, fixed production and transaction costs related to the producers and DCs. Moreover, the demand function at each market is related to the retail prices of the chains and the prices relate to the costs of the players; therefore, the chains can use different locations for their facilities or marketing activities to influence the costs of the chains and parameter values of the demand function. Here, we discuss the sensitivity analysis for SCs with respect to the cross-price and self-price parameters.

Tables 6 and 7 represent the sensitivity analysis for SCs with respect to cross price effect while the self-price parameter is set to 1.2. Tables 8 and 9 represent the sensitivity analysis for SCs with respect to self-price effect while the cross-price parameter is set to 1.5.

Table 6. Sensitivity analysis for SC 1 with respect to cross price effect

beta,SC1	1	0.9	0.85	0.8	0.75	0.7	0.65	0.6	0.4	0.2	0.1	0.05	0.005
Price of plant 1 for DC1	26978	22990	21407	20029	18817	17743	16785	15926	13218	11298	10533	10188	9896
Price of plant 1 for DC2	23722	20215	18824	17612	16546	15602	14760	14004	11624	9262	9262	8959	8702
Price of DCs in market 1	34088	28934	26899	25130	23578	22206	20985	19891	16457	14032	13069	12636	12269
Price of DCs in market 2	42273	36137	33694	31561	29683	28016	26527	25188	20959	17948	16745	16202	15743
Market share 1	1941	1627	1505	1400	1308	1227	1156	1092	894	756	702	678	657
Market share 2	3844	3302	3085	2895	2727	2577	2443	2323	1940	1666	1556	1506	1464
Income of plant	147212824	106897379	92685914	81130824	71609105	63670228	56981864	51294533	35333885	25810276	22431937	20986276	19801434
Cost of plant	83201732	60417960	52386438	45856103	40474886	35988183	32208187	28993914	19973383	14590741	12681297	11864199	11194512
Profit of plant	64011092	46479419	40299476	35274720	31134219	27682045	24773676	22300620	15360502	11219535	9750640	9122078	8606922
Income of DC	228664090	166418094	144431952	126535207	111772510	99452183	89063436	80222414	55370805	40507524	35227392	32966521	31112881
Cost of DC	41033043	29983401	26066489	22871675	20231465	18024326	16160325	14571745	10093382	7403927	6446059	6035468	5698621
Profit of DC	187631047	136434693	118365463	103663532	91541045	81427857	72903111	65650669	45277422	33103597	28781333	26931053	25414260

Table 7. Sensitivity analysis for SC 2 with respect to cross price effect

beta,SC2	1	0.9	0.85	0.8	0.75	0.7	0.65	0.6	0.4	0.2	0.1	0.05	0.005
Price of plant 1 for DC1	25414	21657	20166	18867	17725	16714	15811	15002	12451	10641	9920	9595	9320
Price of plant 1 for DC2	25612	21825	20322	19014	17863	16844	15934	15118	12548	10724	9997	9670	9393
Price of DCs in market 1	34073	28921	26886	25118	23567	22195	20975	19881	16447	14023	13061	12627	12261
Price of DCs in market 2	42254	36120	33678	31546	29668	28001	26513	25174	20947	17936	16733	16191	15731
Market share 1	1978	1659	1535	1427	1334	1251	1179	1114	912	771	716	691	670
Market share 2	3892	3343	3123	2931	2760	2609	2473	2351	1964	1686	1575	1524	1482
Income of plant	149780530	108758285	94297726	82540132	72851566	64773591	57968049	52181085	35940810	26250210	22812537	21341451	20135749
Cost of plant	74906086	54392624	47161416	41281810	36436816	32397199	28993866	26099880	17978154	13131727	11412442	10676696	10073674
Profit of plant	74874444	54365662	47136310	41258322	36414750	32376392	28974183	26081205	17962656	13118483	11400095	10664755	10062075
Income of DC	231874114	168744755	146447143	128297111	113325673	100831283	90295871	81330115	56128280	41055677	35701108	33408326	31528496
Cost of DC	41060166	30004662	26085363	22888467	20246438	18037704	16172299	14582478	10100362	7408408	6449579	6038559	5701350
Profit of DC	190813948	138740094	120361780	105408644	93079235	82793579	74123572	66747636	46027918	33647269	29251529	27369767	25827146

Table 8. Sensitivity analysis for SC 1 with respect to self-price effect

alpha,SC1	1.8	2	2.2	2.5	2.8	3	3.5	4	4.5	5	5.5	6	7
Price of plant 1 for DC1	22989	17742	14445	11296	9274	8285	6541	5404	4603	4009	3551	3187	2644
Price of plant 1 for DC2	20214	15601	12702	9933	8155	7286	5753	4753	4049	3526	3123	2803	2326
Price of DCs in market1	28933	22205	18010	14030	11489	10251	8075	6660	5668	4932	4366	3916	3247
Price of DCs in market2	36136	28014	22877	17944	14763	13203	10444	8639	7366	6420	5690	5108	4242
Market share 1	1627	1227	983	756	614	545	426	349	296	257	227	203	168
Market share 2	3302	2577	2114	1665	1374	1231	976	809	690	602	534	480	398
Income of plant	106887635	63660351	42195734	25801375	17389832	13878621	8650209	5902527	4282538	3248072	2547554	2051324	1411767
Cost of plant	60412453	35982601	23851547	14585710	9831432	7846793	4891405	3338152	2422314	1837451	1441368	1160771	799093
Profit of plant	46475182	27677750	18344187	11215665	7558400	6031828	3758805	2564375	1860224	1410620	1106187	890553	612673
Income of DC	166402867	99436696	66062896	40493516	27337986	21836891	13632051	9312135	6761835	5131704	4026974	3243928	2234019
Cost of DC	29980640	18021502	12022637	7401355	5011986	4009756	2510608	1718664	1250021	949926	746263	601734	415081
Profit of DC	136422227	81415194	54040259	33092162	22326000	17827135	11121443	7593471	5511814	4181778	3280711	2642194	1818938

Table 9. Sensitivity analysis for SC 2 with respect to self-price effect

alpha,SC2	1.8	2	2.2	2.5	2.8	3	3.5	4	4.5	5	5.5	6	7
Price of plant 1 for DC1	21657	16715	13609	10643	8738	7806	6164	5092	4338	3778	3346	3003	2492
Price of plant 1 for DC2	21826	16845	13715	10726	8806	7867	6212	5132	4372	3808	3373	3027	2512
Price of DCs in market1	28922	22197	18004	14026	11486	10248	8073	6659	5666	4931	4365	3915	3246
Price of DCs in market2	36122	28004	22869	17939	14759	13199	10441	8637	7365	6419	5689	5107	4241
Market share 1	1659	1251	1003	772	626	556	435	357	302	262	231	207	171
Market share 2	3343	2609	2140	1686	1391	1246	988	819	699	610	541	486	403
Income of plant	108768184	64783629	42942146	26259252	17699271	14125971	8804891	6008358	4359492	3306545	2593488	2088360	1437311
Cost of plant	54397573	32402219	21479543	13136250	8855073	7067843	4406280	3007347	2182444	1655622	1298824	1046047	720204
Profit of plant	54370610	32381410	21462603	13123003	8844198	7058128	4398611	3001012	2177048	1650923	1294664	1042313	717107
Income of DC	168760176	100846973	67001154	41069884	27727921	22148768	13827315	9445850	6859130	5205673	4085106	3290817	2266377
Cost of DC	30007422	18040529	12036735	7410985	5018988	4015567	2514507	1721469	1252139	951586	747600	602835	415866
Profit of DC	138752754	82806444	54964419	33658898	22708933	18133201	11312808	7724381	5606991	4254088	3337507	2687982	1850511

It is worth noting that in our case, the change of self-price and cross-price parameters have no effects on location decision variables, but changes in location decision variables by change in these parameters are possible, and in these circumstances the shape of the networks will change.

Conclusion

This paper presents an important real-world problem in which *n* decentralized SCs simultaneously enter the virgin market to shape their networks, set the wholesale and retail prices, and specify their market shares in dynamic competition. This problem is essential, as several developing countries are trying to omit monopoly and open their markets to international investors. These investors then encounter virgin markets and competition simultaneously.

We propose a three-step algorithm to reach a Nash equilibrium network design in which step one constructs all the potential network structures; step two computes the related decisions in dynamic competition for all the potential structures through VI formulation and the modified projection method, and step three determines the Nash structures for the SD-CSCND problem with the help of the Wilson algorithm.

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