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Benders Decomposition for Supply Chain Network Redesign with Capacity Planning and Multi-Period Pricing

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KEYWORDS

Supply Chain Network Redesign,
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ABSTRACT

Demand fluctuations, network cost increase, and new services proposition for customers make companies more interesting in network redesigning problems. These problems allow the existing network to increase or decrease its capacity in order to meet changing customers' demands. In this study, a linear mixed integer programming model is proposed to redesign a supply chain network which has price-sensitive customers. In addition, due to the nature of the problem, both strategic and tactical decisions are taken into account simultaneously. Strategic decisions consist of opening new facilities, closing existing ones, and adding discrete capacity levels to all network facilities. Tactical facilities are pricing and determining flow between different network echelons. Pricing is an important fragment of supply chain due to two reasons: first, it represents potential revenue of each product; second, based on supply-demand relations, it enables supply chain to provide demands by making suitable changes in number of facilities and their capacities. Therefore, this model aims to consider both pricing and redesigning decisions simultaneously in order to maximize the network profit. Based on the solution time of designing/redesigning problems with CPLEX solver in GAMS, these problems are among the complex and challenging ones. To overcome this problem in this study, Benders decomposition approach was used to solve a multi-product, multi-echelon and multi-period supply chain network redesigning problem with price-sensitive customers. Results prove the appropriate performance of the proposed algorithm for the model.

1. Introduction

Supply chain network design/redesign is a strategic planning through decision-making within an entire structure. This would result in a comprehensive and optimized system. Based on the horizon length, decisions will be tactical and technical or operational, strategically. Designing a supply chain network (SCN) consists of number and location of facilities, assigning capacities, using technology, pricing and flows between different sectors within the whole system. All these actions should meet every customer's demand with the lowest cost and the most profit.

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Based on the current economic environment, revenue management grows as an important aspect of supply chain planning. Real-world conditions make it possible for companies to plan for both designing and redesigning a supply chain. Redesigning would be a suitable decision if operational costs exceed expectations and customers look for new services. In these conditions, companies should develop their network or redesign it. As Ballou and et al. (1968) discussed, redesigning can reduce SCN costs from 5 to 15 percent[1]. In redesigning problems, there are several manufacturing and distribution centers in fixed locations. The main focus is developing or reducing the capacity of existing facilities, closing them, opening new centers, and allocating capacity levels. SCN Tactical decisions consist of two categories: pricing and quantity decisions. Tallury et al. (2006) mentioned that pricing determines the product price and their changes within the horizon[2]. Quantity decisions analyze amount of production of each item and the flow between different facilities, when to store them, and the appropriate time for customer delivery. Considering both of these facts simultaneously brings about a challenging issue on the tactical level. Pricing itself determines the income per each kind of products which along with supply-demand relations makes it possible to calculate necessary changes in facilities and their capacities to fulfill customers' demands.

Studies by Wagner et al. (1975), Hanjoul et al. (1990), Ahmadi-Javid et al. (2015), Fattahi et al. (2015), and Nobari et al. (2016) considered facilities location and profit in a SCN with price-sensitive customers [3-7]. Furthermore, combining issues, such as rapid fluctuations in market, budget restrict, increase in facilities operational cost, and considering possibility of redesign with pricing decision, would be useful.

Pricing is only possible with previous sale data and customer's behavior. This model considers redesigning supply chain network with pricing. Objective functions' parts and related constraints are described. Based on the basic model of this study, pricing is determined in tactical periods. One of the most serious challenging issues in the literature is proposing solution approaches for designing/redesigning networks with capacity planning. One of the contribution of this study is using Benders Decomposition Method for these kinds of problems. Comparison of solution time and results of using this exact approach with those of literature proves its effectiveness and performance.

2. Literature Review

In this paper, literature review is divided into two parts. At first, dynamic supply chain literature with capacity planning and then pricing can be reviewed.

2-1. Dynamic supply chain network design

Since the first studies of Geoffrion et al. (1974) designed a multi-product SCN, several optimization methods have been introduced [8]. Those efforts have remarkable impact on problem's model, algorithm and effectiveness of calculations.

Most of those models and papers such as those of Cordeau and et al. (2006), Olivares-Benitez and et al. (2012), and Sadjadi and et al. (2012) considered improvement issues and location problems within a single time horizon [9-11]. Although managers and decision-makers considered multi-period problems as crucial needs. Based on the importance of this subject, recently, many studies have considered their problem as multi period ones.

Moreover, based on complexity and supply chain levels, different papers have been proposed. For the first time, Ballou et al. (1968) considered dynamic network location including a two-echelon network[1]. Later, Scott et al. (1971) improved the problem for several facilities[12]. In recent years, some studies have mentioned multi-period design and redesign SCN with three and more echelons covering location decisions. Decisions assumed to be made by these papers in their models are represented in Table 1.

Based on the nature and characteristics of designing supply chain networks with capacity planning problems, time intervals would be divided into strategic periods, tactical periods, or a combination of them. Melo et al. (2006) represented a multi-level network redesign problem which makes changes possible in capacities through moving capacities from those existing to new centers in a period[13]. Also, strategic decisions such as opening-closing and moving facilities with respect to budget restrict for each period are considered. In addition, Hinojosa et al. (2000, 2008), Correia et al. (2013) used strategic periods in their models [14-16]. Longinidis et al. (2011), Georgiadis et al. (2011) used the tactical periods; for the first time, Salma et al. (2010) combined strategic and tactical periods recently used by Bashiri et al. (2012)[17-20].

Badri et al. (2013) proposed a three-level model with profit maximization objective which considered capacity improvement, opening new centers, transportation and inventory decision[21].

Existing papers within literature review used two common function objectives. Some of them proposed their model in the format of multi-objective problems. Most of the papers in the literature review mentioned cost reduction as an objective function. A few studies used profit maximization as their objective function.

Recently, in capacity planning and location issues, different aspects have gained attention and combined design and redesign problems. In location problems, assumptions such as opening new facilities, closing existing facilities, and reopening closed facilities are considered and in capacity planning issues, capacity expansion, capacity reduction, and transferring capacity levels seem to play great roles. In table 1, differences within several papers are shown. Recently, M.J. Cortinhal (2015) considered redesigning supply chain network with opening new facilities, closing the existing ones, and adding discrete capacity levels in strategic periods [22]. That study is the basic fundamental effect exerted on this paper. To make it more realistic, strategic periods consist of several tactical periods, and also pricing is added to the model.

In table 1, differences within several papers are shown.

Tab. 1. literature review

Author	Model	Network Redesign	Multi Product	Opening, Closing, Reopening			Capacity Planning				Dynamic Pricing	Exact Solution	Solution Approach
				Open New	Close Existed	Reopen closed	Modular	Relocate	Expansion	Reduction			
Aghezzaf (2005)[24]	MILP-TSSP			✓					✓			✓	Lagrangian Relax Decomposition
Badri (2013)[21]	MILP		✓	✓			✓		✓				Lagrangian-based Heuristic
Bashiri (2012)[20]	MILP			✓			✓		✓				Commercial Solver
Canel (2001)[23]	MILP		✓	✓	✓	✓						✓	Lagrangian Relax Decomposition
Correia (2013)[16]	MILP			✓			✓		✓				Commercial Solver
Dias (2007)[31]	MILP		✓	✓	✓	✓							Prime-dual Heuristic
Georgiadis (2011)[18]	MILP-TSSP		✓										Commercial Solver
Hinojosa (2008)[14]	MILP		✓	✓	✓								Lagrangian-based Heuristic
Hinojosa (2000)[15]	MILP		✓	✓	✓								Lagrangian-based Heuristic
Longinidis (2011)[17]	MILP-TSSP		✓										Commercial Solver
Melo (2006)[13]	MILP		✓	✓	✓		✓	✓	✓	✓			Commercial Solver
Melo (2012)[32]	MILP	✓	✓	✓	✓			✓					Tabu search meta heuristic
Melo (2014)[33]	MILP	✓	✓	✓	✓			✓					Linear Relax-base Heuristic
Melachrinoudis (2000)[34]	MILP	✓		✓	✓			✓					Commercial Solver
Nickel (2012)[35]	MILP-TSSP		✓	✓	✓	✓							Commercial Solver
Pimentel (2013)[36]	MILP-TSSP			✓	✓	✓	✓		✓				Lagrangian-based Heuristic
Thanh (2008)[37]	MILP		✓	✓			✓		✓				Commercial Solver
Thanh (2010)[38]	MILP		✓	✓			✓		✓				Linear Relax-base Heuristic
Wilhelm (2013)[39]	MILP	✓	✓	✓	✓				✓	✓			Commercial Solver
M.J. Cortinhal (2015)[22]	MILP	✓	✓	✓	✓		✓		✓				Commercial Solver
M. Fattahi (2015)[6]	MILP		✓	✓			✓		✓		✓		SA & Linear Relax-base Heuristic
Correia (2017)[40]	MILP	✓	✓	✓	✓		✓		✓				Commercial Solver
This Study	MILP	✓	✓	✓	✓		✓		✓		✓	✓	Benders Decomposition

MILP: Mixed-integer linear programming; TSSP: Two stage stochastic programming

Several different solving methods are used in this area. Canel et al. (2001), Aghezzaf et al. (2005), and others used exact approach to solving SCN problems in their studies [23, 24]. Besides, Lagrangian-based heuristic methods are among the most important heuristic methods in this field. Hinojosa et al. (2000, 2008) used such methods [14, 15]. In this model, the exact Bender decomposition method was used to solve SCN redesign problem.

2-2. Network design with pricing

Network design/redesign problems with maximization of profit objectives are divided into three categories. First, the competitive network design problems. In this category, equilibrium price and decisions related to facility location, such as new centers and plants, join the competitive environment. Aboolian et al. (2007), Plastria et al. (2009) considered equilibrium price and facility location decisions [25, 26]. Nagurney et al. (2010) mentioned capacity and equilibrium price[27]. The second approach deals with insensitive price customers.

Price plays a role, such as a binary variable, which determines whether a customer wants the provided services or not. Zhang et al. (2001) and Shen et al. (2006) reviewed such problems [28, 29].

The third approach includes price-sensitive customers and required pricing and quantity decisions to be made simultaneously. In this category, linear sensitive demand function or logit function is used. These functions are obtained based on previous sale's information and current competitors. Ahmadi-Javid and et al. (2014 and 2015), Fattahi and et al. (2015) and Nobari et al. (2016) assumed the third category [5-7, 30].

Due to reviewed studies, recent researches concentrate on dynamic and comprehensive models for planning and designing SCN; however, there are few attempts to consider different aspects with dynamic network simultaneously. There are possible opportunities within pricing and price-sensitive customer's problems. Recent studies have not considered redesigning and pricing. According to the functions obtained based on previous sale's information, in this way, we consider the redesign problem; the goal is to improve current capacities and open new centers and plants based on pricing and profit maximization. Besides, reducing capacity and closing current centers did not mention. In this study, capacity reduction is available because, in the real situation, it is possible that high pricing in response to profit increase makes it logical to forfeit operational cost by closing or limiting the capacity. Since decisions in redesigning problems are strategic and contain remarkable costs, using exact approaches seems necessary. In this model, for the first time, the exact Bender decomposition method is used to solve redesign SCN problem.

3. Model Description and Formulation

In this section, indices, parameters, variables are defined. Afterwards, price levels are determined; finally, a mixed integer programming model is proposed based on the structure of Figure 1.

In this figure, existing facilities with dashed line are present, and new decisions, such as closing these centers or opening new facilities, are presented in dashed and full lines.

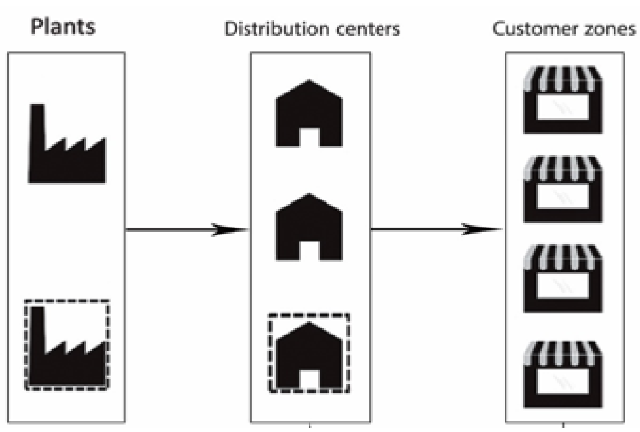

Fig. 1. Network Structure

In this study, several assumptions are considered. They are as follows:

- Supply chain network includes three layers: plants, distribution centers (DCs), and costumers' zones.
- Each strategic period (sp) includes tactical periods (tp).
- Customers demand in each tactical period depends on prices within that period.
- Objective is profit maximation.

- It is possible to open new centers and close current centers to reduce operational costs.
- Capacities are able to be increased in the discrete mode.
- Strategic and tactical decisions are mentioned concurrently to enhance real conditions.
- Accelerating Benders decomposition method is used.
- Model includes multi products within multi periods.

The notations in the paper are defined as follows:

Sets and indices:

Set	Description
T	Strategic periods
N	Tactical periods
C	Customer zones(Cz)
M	Products
OD	All origin-destination in network $OD=\{(p,m):p\in P,w\in W\}\cup\{(w,c):w\in W,c\in C\}$
L	Price levels
$Pe\cup We$	Existing plants and DCs
$Pn\cup Wn$	New plants and DCs
$P=Pe\cup Pn$	All plant locations
$W=We\cup Wn$	All DC locations
k_P,k_W	Discrete capacity levels

Parameters:

Parameters	Description
$D_{c,m,l,t,n}$	Demand of Cz in sp $t\in T/\{0\}$ and tp $n\in N$ for product $m\in M$ with price level $l\in L$
$PR_{c,m,l,t,n}$	Price of product $m\in M$ at price level $l\in L$ in sp $t\in T/\{0\}$ and tp $n\in N$
$FC_{j,t}$	Fixed cost of establishing a new facility $j\in Pn\cup Wn$ in sp $t\in T/\{0\}$
$CC_{j,t}$	Fixed cost of closing an existing facility $j\in Pe\cup We$ in sp $t\in T/\{0\}$
$AC_{j,k,t}$	Cost of adding capacity k_j in location $j\in P\cup W$ in sp $t\in T/\{0\}$
$OC_{j,k,t}$	Fixed cost of operating $j\in P\cup W$ in sp $t\in T/\{0\}$
$CU_{j,t}$	Fixed cost of each facility $j\in P\cup W$ in sp $t\in T/\{0\}$
$TC_{O,D,m,t,n}$	Variable cost per unit of product $m\in M$ between O and D in sp $t\in T/\{0\}$ and tp $n\in N$
$MC_{p,m}$	Manufacturing cost per unit of $m\in M$ at plant $p\in P$ in sp $t\in T/\{0\}$ and tp $n\in N$
Q_j^e	Capacity of existing facility $j\in Pe\cup We$
$Q_{j,k}$	Capacity of level $k\in K_p\cup K_w$
Q_j^{max}	Maximum capacity of facility $j\in P\cup W$ in each sp
$\gamma_{p,m},\gamma_{w,m}$	Coefficient for using storage capacity of each product $m\in M$ in each plant and DC
U_j^{max}	Maximum utilization rate of facility $j\in P\cup W$

Price-response related parameters:

Parameters	Description
$D_{c,m,t,n}^{max}$	Demand of Cz $c\in C$ for product $m\in M$ in sp $t\in T/\{0\}$ and tp $n\in N$

$P_{c,m,t,n}$	Price-sensitive parameter for customer $c \in C$, for product $m \in M$ in sp $t \in T \ / \{0\}$ and tp $n \in N$. If price of product is less than this value, the demand will be equal to $D^{max}_{c,m,t,n}$.
$P'_{c,m,t,n}$	Price-sensitive parameter for customer $c \in C$, for product $m \in M$ in sp $t \in T \ / \{0\}$ and tp $n \in N$. If price of product is more than this value, the demand will be equal to 0.

Variable:

Variables	Description
$Yn_{j,t}$	1 if a new facility is established in location $j \in Pn \cup Wn$ in sp $t \in T \ / \{0\}$ and tp $n \in N$
$Ye_{j,t}$	1 if an existing facility is closed in location $j \in Pe \cup We$ in sp $t \in T \ / \{0\}$ and tp $n \in N$
$U_{j,k,t}$	1 if a capacity level $k \in K_p \cup K_w$ is installed in location $j \in P \cup W$ in sp $t \in T \ / \{0\}$ and tp $n \in N$
$x_{O,D,m,t,n}$	Quantity of product $m \in M$ shipped in sp $t \in T \ / \{0\}$ and tp $n \in N$ between O and D
$\Delta_{m,l,t,n}$	1 if price level $l \in L$ for per unit product $m \in M$ is selected in sp $t \in T \ / \{0\}$ and tp $n \in N$

3-1. Demand-price function modeling

In this study, the demand of each customer zone is sensitive to price. Figure 2 represents a logit price-demand function which shows the relation between $D_{c,m,t,n}$ and $PR_{c,m,t,n}$ for customer zone c, product m, in strategic period t, and tactical period n.

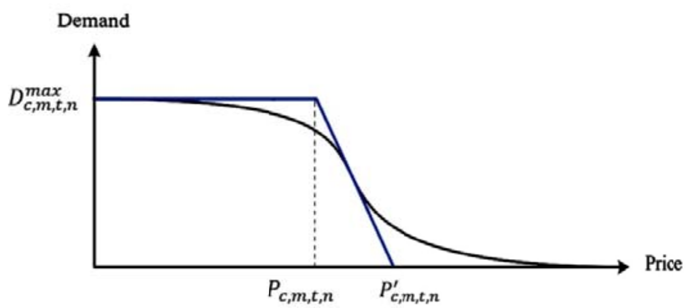

Fig. 2. Demand-Price relation

Demand for costumer zone c, product m, within strategic period t and tactical period n is calculated by:

$$D_{c,m,t,n} = \begin{cases} D^{max}_{c,m,t,n} & PR_{c,m,t,n} \leq P_{c,m,t,n} \\ D^{max}_{c,m,t,n}\left[\dfrac{P'_{c,m,t,n} - PR_{c,m,t,n}}{P'_{c,m,t,n} - P_{c,m,t,n}}\right] & P_{c,m,t,n} \prec PR_{c,m,t,n} \prec P'_{c,m,t,n} \\ 0 & PR_{c,m,t,n} \geq b_{c,m,t,n} \end{cases}$$

Demand-price function is a logit function. As Philip (2005) mentions, this kind of function is suitable for reflecting customers' behavior in response to changes in price [41]. Because a little change in price could make significant changes in demand. Figure 2 shows such a function. In this function, if price of $P_{c,m,t,n}$ is equal to zero and product price range is between $P'_{c,m,t,n}$ and

$P_{c,m,t,n}$, the function changes into a linear function.

In this study, assume that optimal price for each product is in reached. $PR_{c,m,t,n}$ shows the price of product m in zone c which is a non-negative continuous variable. Demand is obtained as follows:

$$D_{c,m,t,n} = \max\left\{\min\left\{D^{\max}_{c,m,t,n},\ D^{\max}_{c,m,t,n}\left[\frac{P'_{c,m,t,n} - PR_{c,m,t,n}}{P'_{c,m,t,n} - P_{c,m,t,n}}\right]\right\}, 0\right\}$$

Since using non-linear demand-price function leads to mixed non-linear programming, discrete price levels are used.

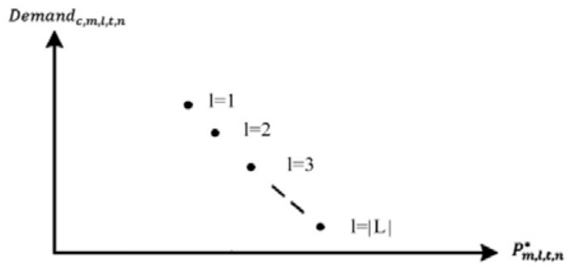

Fig. 3. discrete Demand-Price function

Tallury et al. (2006) utilized discrete price levels and mentioned that such an approach is applicable to many real-world problems[2]. Ahmadi-Javid et al. (2014, 2015) and Fattahi et al. (2015) also used discrete pricing [5, 6, 30]. For each product, in each zone and within each tactical period, the price is obtained by the following:

$$PR_{m,l,t,n} = \frac{\sum_c P_{c,m,t,n} D^{\max}_{c,m,t,n}}{\sum_c D^{\max}_{c,m,t,n}} + \frac{(l-1)}{(L-1)}\left(\frac{\sum_c P'_{c,m,t,n} D^{\max}_{i,m,t,n}}{\sum_c D^{\max}_{c,m,t,n}} - \frac{\sum_c P_{c,m,t,n} D^{\max}_{c,m,t,n}}{\sum_c D^{\max}_{c,m,t,n}}\right)$$

3-2. Mathematical model

In this section, the SCN redesign model is presented. This model contains location and capacity planning for a three-echelon network.

3-2-1. Objective function

Model's aim is to maximize supply chain network profit. The first sentence is the obtained revenue, and the rest cover all types of cost in an entire network. we supposed that to design/redesign the supply chain network in strategic period t+1, the needed capital should be devoted to strategic period t. Linguistic and symbolic forms of the objective function are as follows:

$$Maximizing\ Profit = Revenue - Strategic\ costs - Tactical\ costs - Operational\ costs$$

$$\begin{aligned}
Max\ Z = & \sum\nolimits_{c,m,l,t/\{0\},n} PR_{c,m,l,t,n} Demand_{c,m,l,t,n} \Delta_{l,m,t,n} \\
& - \sum\nolimits_{w,c,m,t/\{0\},n} TC_{w,c,m,t} x_{w,c,m,t,n} - \sum\nolimits_{p,w,m,t,n} (MC_{p,m,t} + TC_{p,w,m,t}) x_{p,w,m,t,n} \\
& - \sum_{t/\{0\}} \Big(\sum_{j \in p \cup w} \sum_{k_j} \sum_{1}^{t} U_{j,k,\tau} OC_{j,k,\tau} \Big) - \sum_{t/\{0\}} \sum_{j \in Pn \cup Wn} Yn_{j,t} CU_{j,t} - \sum_{t/\{0\}} \sum_{j \in Pe \cup We} (1 - Ye_{j,t}) CU_{j,t} \\
& - \sum_{t/\{T\}} \sum_{j \in Pn \cup Wn} (Yn_{j,t+1} - Yn_{j,t}) FO_{j,t+1} - \sum_{t/\{T\}} \sum_{j \in Pe \cup We} (Ye_{j,t} - Ye_{j,t}) CC_{j,t+1} \\
& - \sum_{t/\{T\}} \sum_{j \in p \cup w} U_{j,k,t+1} AC_{j,k,t+1}
\end{aligned}$$

3-2-2. Equations

This section deals with constraints of the proposed model and their explanations.

$$Yn_{j,t-1} \le Yn_{j,t} \quad j \in Pn \cup Wn, t \in T / \{0\} \tag{1}$$

$$Ye_{j,t-1} \le Ye_{j,t} \quad j \in Pe \cup We, t \in T / \{0\} \tag{2}$$

$$\sum_{k_j} U_{j,k,t} \le Yn_{j,t} \quad j \in Pn \cup Wn, t \in T / \{0\} \tag{3}$$

$$\sum_{k_j} U_{j,k,t} \le 1 - Ye_{j,t} \quad j \in Pe \cup We, t \in T / \{0\} \tag{4}$$

$$\sum_{1}^{t} \sum_{k_j} Q_{j,k} U_{j,k,\tau} \le Q_j^{\max} Yn_{j,t} \quad j \in Pn \cup Wn, t \in T / \{0\} \tag{5}$$

$$\sum_{1}^{t} \sum_{k_j} Q_{j,k} U_{j,k,\tau} + Q_j^{e}(1 - Ye_{j,t}) \le Q_j^{\max} (1 - Ye_{j,t}) \quad j \in Pe \cup We, t \in T / \{0\} \tag{6}$$

$$\sum_{m} \gamma_m^{p} \sum_{w} x_{j,w,m,t,n} \le U_j^{\max} \sum_{1}^{t} \sum_{k_j} Q_{j,k} U_{j,k,\tau} \quad j \in Pn, t \in T / \{0\}, n \in N \tag{7}$$

$$\sum_{m} \gamma_m^{p} \sum_{w} x_{j,w,m,t,n} \le U_j^{\max} \sum_{1}^{t} \sum_{k_j} Q_{j,k} U_{j,k,\tau} + Q_j^{e}(1 - Ye_{j,t}) \quad j \in Pe, t \in T / \{0\}, n \in N \tag{8}$$

$$\sum_{m} \gamma_m^{w} \sum_{w} x_{j,c,m,t,n} \le U_j^{\max} \sum_{1}^{t} \sum_{k_j} Q_{j,k} U_{j,k,\tau} \quad j \in Wn, t \in T / \{0\}, n \in N \tag{9}$$

$$\sum_{m} \gamma_m^{w} \sum_{w} x_{j,c,m,t,n} \le U_j^{\max} \sum_{1}^{t} \sum_{k_j} Q_{j,k} U_{j,k,\tau} + Q_j^{e}(1 - Ye_{j,t}) \quad j \in We, t \in T / \{0\}, n \in N \tag{10}$$

$$\sum_{l} \Delta_{m,l,t,n} = 1 \quad m \in M, t \in T / \{0\}, n \in N \tag{11}$$

$$\sum_{w} x_{w,c,m,t,n} = \sum_{l} \Delta_{m,l,t,n} Demand_{c,m,l,t,n} \quad c \in C \;\; m \in M, t \in T / \{0\}, n \in N \tag{12}$$

$$\sum_{c} x_{w,c,m,t,n} = \sum_{p} x_{p,w,m,t,n} \quad w \in W, m \in M, t \in T / \{0\}, n \in N \tag{13}$$

$$x_{O,D,m,t,n} \ge 0$$

$$Yn_{j,t}, Ye_{j,t}, U_{j,k,t}, \Delta_{m,l,t,n} \in \{0,1\}$$

The first part of the objective function determines the income from the sale. Other parts represent costs. The first part includes the costs related to distribution from distribution centers to retailer's zones. The second sentence is production and distribution costs from production plants. The third part represents operational cost of added capacity. The fourth and fifth parts represent operational cost of new and existing plants and distribution centers. The sixth and seventh parts cover the establishing cost of new and existing plants and distribution centers. The last part is fixed cost of added capacity to them. Constraints 1-6 include conditions required for opening new facilities, closing existing facilities, and assigning capacity to them. Constraint (1) insists that if a facility opens in period t, it could not be closed for the next period. Constraint (2) shows that a closing facility in period t should remain closed for the next period. Constraints (3) and (4) represent how to assign capacity to facilities. New facilities have the same capacity during a strategic period. A closed facility does not have any capacity and a new facility will have capacity after establishment. Constraints (5) and (6) limit the improvement of facilities' capacities within their total possible capacity. Constraints (7) and (8) guarantee that all produced products by a plant within a period is less than its capacity. Constraints (9) and (10) provide the same condition for distribution centers. According to constrain (11), for each product in a tactical period, there is only one price level. Forcing to meet all demands in every customer zone is represented in constraint (12). In the 13th constraint, the sum of sent products from a distribution center to customers must be equal to products sent to distribution center. Other constraints determine if variables are non-negative or binary.

4. Solution Approach

As mentioned in the previous part, the model is a mixed integer programing. Previous researches used heuristic, meta-heuristic and exact approaches to solving SCDN problems [42]. There are two reasons which make using exact approaches more appropriate for these kinds of problems. On the one hand, remarkable cost of strategic decisions in designing/redesigning of supply chain networks makes precise choosing within available decisions necessary. Therefore, it seems reasonable to implement exact approaches to solve these problems. On the other hand, such problems are high-dimensional problems and the solution time increases even more by increasing the dimension. For example, by optimization software such as Gams, Lingo and CPLEX, solution time is not reasonable as problem's size increases. Recently, this exact method with a significant performance has been used to solve network design problems [43, 44]. Capability of this model, dividable into smaller problems, makes Benders decomposition method a useful exact approach with suitable productivity in high-dimensional problems.

4-1. Benders decomposition method

In this part, benders decomposition method is represented. Suppose that the original problem is as follows (model A):

$$\min = \sum_{i=1}^{n} C_i X_i + \sum_{j=1}^{m} D_j Y_j$$

s.t:

$$\sum_{i=1}^{n} A_{li} X_i + \sum_{j=1}^{m} E_{lj} Y_j \le B^{(l)}, l = 1,...,q \tag{14}$$

$$0 \le X_i \le X_i^{up}, i = 1,...,n \tag{15}$$

$$0 \le Y_j \le Y_j^{up}, j = 1,...,m \tag{16}$$

In this model, x variables are complicated variables in which fixed temporary decreases solution time remarkably[45]. Binary variables are complicated variables.

(Model B)

$$\min = \sum_{i=1}^{n} C_i X_i + \alpha$$

S.t:

$$\sum_{i=1}^{n} Y_i^{(k)} (X_i - X_i^{(k)}) + \sum_{j=1}^{m} D_j Y_j^{(k)} \le \alpha, k = 1,...,(rep-1) \tag{17}$$

$$0 \le X_i \le X_i^{up}, i = 1,...,n \tag{18}$$

$$\alpha^{down} \le \alpha \tag{19}$$

Model B is called master problem which includes only complicated variables. Constrain (17) is known as benders decomposition cut (BDC). For the first repetition, master problem is solved without BDCs and results will be used for Sup problem. In the next repeat, based on Sup problem results, a new cut will be added. This process will continue till optimal results are achieved. As noted in master problem, *rep* is the number of repetition and α-down is a lower bound for α which is obtained from specialists. A suitable lower bound could reduce the time significantly.

(Model C)

$$\min = \sum_{i=1}^{n} C_i X_i + \sum_{j=1}^{m} D_j Y_j$$

S.t:

$$\sum_{i=1}^{n} A_{li} X_i + \sum_{j=1}^{m} E_{lj} Y_j \le B^{(l)}, l = 1,...,q \tag{20}$$

$$0 \le Y_j \le Y_j^{up}, j = 1,...,m \tag{21}$$

$$X_i = x_i^{(k)} : \gamma_i \; i = 1,...,n \tag{22}$$

Model C is called Sup problem and is the same as the model A, yet without complicated variables. γ_i used in BDC is equal to the optimal value of dual variable of constraint (22).

4-2. Benders decomposition method implementation

According to the Benders decomposition, the model in this paper can be implemented to deal with the problem of this research as follows:

Master problem:

$$Max\ Z = \sum_{c,m,l,t/\{0\},n} PR_{c,m,l,t,n} Demand_{c,m,l,t,n} \Delta_{l,m,t,n}$$
$$-\sum_{t/\{0\}} \Big(\sum_{j \in p \cup w} \sum_{k_j} \sum_{1}^{t} U_{j,k,\tau} OC_{j,k,\tau} \Big) - \sum_{t/\{0\}} \sum_{j \in P \cup W} Yn_{j,t} CU_{j,t} - \sum_{t/\{0\}} \sum_{j \in Pe \cup We} (1 - Ye_{j,t}) CU_{j,t} \quad (23)$$
$$-\sum_{t/\{0\}} \sum_{j \in Pn \cup Wn} (Yn_{j,t+1} - Yn_{j,t}) FO_{j,t+1} - \sum_{t/\{0\}} \sum_{j \in Pe \cup We} (Ye_{j,t} - Ye_{j,t}) CC_{j,t+1}$$
$$-\sum_{t/\{0\}} \sum_{j \in p \cup w} U_{j,k,t+1} AC_{j,k,t+1}$$

Equations

$$Yn_{j,t-1} \le Yn_{j,t} \quad j \in Pn \cup Wn, t \in T / \{0\} \quad (24)$$
$$Ye_{j,t-1} \le Ye_{j,t} \quad j \in Pe \cup We, t \in T / \{0\} \quad (25)$$
$$\sum_{k_j} U_{j,k,t} \le Yn_{j,t} \quad j \in Pn \cup Wn, t \in T / \{0\} \quad (26)$$
$$\sum_{k_j} U_{j,k,t} \le 1 - Ye_{j,t} \quad j \in Pe \cup We, t \in T / \{0\} \quad (27)$$
$$\sum_{1}^{t} \sum_{k_j} Q_{j,k} U_{j,k,\tau} \le Q_j^{max} Yn_{j,t} \quad j \in Pn \cup Wn, t \in T / \{0\} \quad (28)$$
$$\sum_{1}^{t} \sum_{k_j} Q_{j,k} U_{j,k,\tau} + Q_j^{e} (1 - Ye_{j,t}) \le Q_j^{max} (1 - Ye_{j,t}) \quad j \in Pe \cup We, t \in T / \{0\} \quad (29)$$
$$\sum_{l} \Delta_{m,l,t,n} = 1 \quad m \in M, t \in T / \{0\}, n \in N \quad (30)$$
$$Yn_{j,t}, Ye_{j,t}, U_{j,k,t}, \Delta_{m,l,t,n} \in \{0,1\} \quad (31)$$

The sub-problem can be defined as follows:

$$Max\ Z = -\sum_{w,c,m,t/\{0\},n} TC_{w,c,m,t} x_{w,c,m,t,n} - \sum_{p,w,m,t,n} (MC_{p,m,t} + TC_{p,w,m,t}) x_{p,w,m,t,n} \quad (32)$$

S.t:

$$\sum_{m} \gamma_m^{p} \sum_{w} x_{j,w,m,t,n} \le U_j^{max} \sum_{1}^{t} \sum_{k_j} Q_{j,k} \overline{U}_{j,k,\tau} \quad j \in Pn, t \in T / \{0\}, n \in N \quad (33)$$
$$\sum_{m} \gamma_m^{p} \sum_{w} x_{j,w,m,t,n} \le U_j^{max} \sum_{1}^{t} \sum_{k_j} Q_{j,k} \overline{U}_{j,k,\tau} + Q_j^{e} (1 - \overline{Ye}_{j,t}) \quad j \in Pe, t \in T / \{0\}, n \in N \quad (34)$$
$$\sum_{m} \gamma_m^{w} \sum_{w} x_{j,c,m,t,n} \le U_j^{max} \sum_{1}^{t} \sum_{k_j} Q_{j,k} \overline{U}_{j,k,\tau} \quad j \in Wn, t \in T / \{0\}, n \in N \quad (35)$$
$$\sum_{m} \gamma_m^{w} \sum_{w} x_{j,c,m,t,n} \le U_j^{max} \sum_{1}^{t} \sum_{k_j} Q_{j,k} \overline{U}_{j,k,\tau} + Q_j^{e} (1 - \overline{Ye}_{j,t}) \quad j \in We, t \in T / \{0\}, n \in N \quad (36)$$
$$\sum_{w} x_{w,c,m,t,n} = \sum_{l} \overline{\Delta}_{m,l,t,n} Demand_{c,m,l,t,n} \quad c \in C, m \in M, t \in T / \{0\}, n \in N \quad (37)$$
$$\sum_{c} x_{w,c,m,t,n} = \sum_{p} x_{p,w,m,t,n} \quad w \in W, m \in M, t \in T / \{0\}, n \in N \quad (38)$$
$$x_{O,D,m,t,n} \ge 0$$

Table 2 shows dual variables of sub-problem obtained by solving the subproblem (dual problem).

Tab. 2. Dual variables

Constraint	Dual variable
(31)	$A_{Pn,t,n}$
(32)	$A_{Pe,t,n}$
(33)	$A_{Wn,t,n}$
(34)	$A_{We,t,n}$
(35)	$\partial_{c,m,t,n}$
(35)	$\theta_{w,m,t,n}$

After defining dual variables of the subproblem, dual sub problem can be defined as follows:

$$\min = \sum_{j\in Pn\cup Wn}(U_j^{\max}\sum_1^t\sum_{kj}Q_{j,k}\overline{U}_{j,k,\tau})A_{j,t,n}+\sum_{j\in Pe\cup We}(U_j^{\max}\sum_1^t\sum_{kj}Q_{j,k}\overline{U}_{j,k,\tau}+Q_j^e(1-\overline{Y}e_{j,t}))A_{j,t,n} \quad (39)$$
$$+\sum_{c,m,l,t,n}Demand_{c,m,l,t,n}\overline{\Delta}_{m,l,t,n}\partial_{c,m,t,n}$$

Equation

$$-\theta_{w,m,t,n}+\gamma_m^jA_{j,t,n}\geq -MC_{j,m,t}-TC_{j,w,m,t} \qquad j\in pn,w,m,t,n \quad (40)$$
$$-\theta_{w,m,t,n}+\gamma_m^jA_{j,t,n}\geq -MC_{j,m,t}-TC_{j,w,m,t} \qquad j\in pe,w,m,t,n \quad (41)$$
$$\theta_{j,m,t,n}+\gamma_m^jA_{j,t,n}+\partial_{c,m,t,n}\geq -TC_{j,c,m,t} \qquad j\in wn,c,m,t,n \quad (42)$$
$$\theta_{j,m,t,n}+\gamma_m^jA_{j,t,n}+\partial_{c,m,t,n}\geq -TC_{j,c,m,t} \qquad j\in we,c,m,t,n \quad (43)$$
$$A_{j,t,n}\geq 0$$
$$\theta_{j,m,t,n},\partial_{c,m,t,n}\sim URS$$

Now, based on sub-problem (dual problem), master problem can determine an upper bound in each iteration for the original problem. Optimal and feasible cuts for this model are as follows:

$$UB\leq \sum_{j\in Pn\cup Wn,t,n}(U_j^{\max}\sum_1^t\sum_{k_j}Q_{j,k}\overline{U}_{j,k,\tau})A_{j,t,n}+\sum_{j\in Pe\cup We,t,n}(U_j^{\max}\sum_1^t\sum_{k_j}Q_{j,k}\overline{U}_{j,k,\tau}+Q_j^e(1-\overline{Ye}_{j,t}))A_{j,t,n}$$
$$+\sum_{c,m,l,t,n}Demand_{c,m,l,t,n}\overline{\Delta}_{m,l,t,n}\sigma_{c,m,t,n}+\sum_{c,m,l,t/\{0\},n}PR_{c,m,l,t,n}Demand_{c,m,l,t,n}\Delta_{l,m,t,n} \quad (44)$$
$$-\sum_{t/\{0\}}(\sum_{j\in p\cup w}\sum_{k_j}\sum_1^tU_{j,k,\tau}OC_{j,k,\tau})-\sum_{t/\{0\}}\sum_{j\in P\cup W}Yn_{j,t}CU_{j,t}-\sum_{t/\{0\}}\sum_{j\in Pe\cup We}(1-Ye_{j,t})CU_{j,t}$$
$$-\sum_{t/\{0\}}\sum_{j\in Pn\cup Wn}(Yn_{j,t+1}-Yn_{j,t})FO_{j,t+1}-\sum_{t/\{0\}}\sum_{j\in Pe\cup We}(Ye_{j,t}-Ye_{j,t})CC_{j,t+1}$$

$$0\leq \sum_{j\in Pn\cup Wn,t,n}(U_j^{\max}\sum_1^t\sum_{k_j}Q_{j,k}\overline{U}_{j,k,\tau})A_{j,t,n}+\sum_{j\in Pe\cup We,t,n}(U_j^{\max}\sum_1^t\sum_{k_j}Q_{j,k}\overline{U}_{j,k,\tau}+Q_j^e(1-\overline{Ye}_{j,t}))A_{j,t,n} \quad (45)$$
$$+\sum_{c,m,l,t,n}Demand_{c,m,l,t,n}\overline{E}_{m,l,t,n}\sigma'_{c,m,t,n}$$

Now, based on the proposed description of benders decomposition method, its algorithm is formed as follows:

ABD algorithm

1. LB= $-\infty$ and UB= $+\infty$
2. Consider the initial feasible solution
3. Iter = 1
4. While (UB-LB)>ε
   Solve DSP with object function (39) subject to (40-43)
   If solved optimally,
   - add optimal cut
   - Update LB
   - Solve MP with object function (23) subject to (24-31) and (44)

   Else
   - add feasibility cut and solve MP with object function (23) subject to (24-31) and (45)

5.iter = iter+1

Results

For analyzing efficiency of benders decomposition method, 10 different samples are solved and the results are gathered in Tables 3 and 4. Size and solution time by benders decomposition and Gams and gap between objective values of CPLEX and BD are presented in tables 3 and 4. For solving the samples, a PC is used with Intel® core i7-4790k, CPU @ 4.00 GHz and 16.0 GB RAM and commercial software GAMS 24.1.2 and CPLEX solver for MILP. It is obvious that the new method improves solution time for every problem remarkably.

To show the effectiveness of benders decomposition method, 10 different problems in small, medium, and large scales are used. Table 3 represents the characteristics of these problems. To analyze the performance of the proposed algorithm, samples used in Fattahi' [6] paper are solved.

As showed in table 4, small- and medium-scale problems are solved in less than 160 seconds with gap fewer than 1 percent and large-scale ones solved with benders decomposition method less than 1000 seconds and gap less than 1.67 percent. Fattahi's large-scale results show that the minimum solution time takes around 6000 seconds. Therefore, the proposed benders decomposition algorithm can be suitable for redesigning a supply chain network with pricing.

Tab. 3. Sample' size

Size	num	PE	PN	WE	WN	m	c	l	k	t	n
small	T1	1	3	1	4	3	8	4	4	4	4
	T2	1	4	2	4	3	10	4	4	4	4
	T3	1	4	2	6	4	10	4	4	4	4
medi um	T4	1	5	2	8	5	12	4	4	4	4
	T5	2	6	4	10	6	16	5	5	4	4
	T6	2	6	4	12	7	17	5	5	4	5
large	T7	2	7	4	14	7	18	5	5	4	5
	T8	2	10	4	15	10	30	5	5	4	5
	T9	2	12	4	17	11	40	5	5	4	5
	T10	2	15	4	20	15	50	5	5	4	5

Tab. 4. Comparison of Results

Size	Cplex Time(second)	BD Time(second)	Iter	Gap
1	615	41	49	0
2	4032	26	30	0.4%
3	15105	64	66	0.18%
4	17706	89	48	0.02%
5	$\geq$ 20000	94	49	0.68%
6	$\geq$ 20000	154	43	0.61%
7	$\geq$ 20000	186	33	1.3%
8	$\geq$ 20000	467	39	1.67%
9	$\geq$ 20000	683	29	1.17%
10	$\geq$ 20000	917	31	1.76%

Conclusion

In this study, a new model for redesigning a multi-period and multi-product supply chain network considering pricing was proposed. In the represented model, reducing price would lead to an increase in demand; therefore, the need for adding more capacities and opening new facilities within SCN and increasing the price have opposite effects. This model helps choosing the best price in order to maximize network's revenue. There are several opportunities to develop the current paper. All the parameters in this paper are assumed to be determined which is unlikely to happen under real conditions. In this way, it would be appropriate to consider parameters such as transportation cost and stochastic demand. This paper only considers the effect of price on customer's behavior. However, there are other characteristics such as quality that might change customer's choice. Therefore, it would be appropriate to consider stochastic pricing. In this model, fixed and unique prices are assigned to each of customer zones. Assigning different prices to different zones would make the problem more interesting and a good chance to analyze network profit under this situation. In this study, benders decomposition method was applied which reduces solution time significantly. In this model, all of the parameters are fixed and determined. It is also suggested to use accelerated benders algorithm methods to improve benders decomposition methods, such as valid inequalities, L-shape and Pareto optimal accelerator.

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