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Forward supply Chain network design problem: Heuristic approaches

İleri tedarik zinciri ağ tasarımı problemi: Sezgisel yaklaşımlar

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Abstract

Determining positions and counting of actors, amount of product flow between and decreasing transportation costs are handled as a network design problem in supply chain management. Supply chain network design (SCND) problem belongs to the class of NP-hard problems. It has therefore appealed to a number of researchers' close attention. However, existing literature lacks of common benchmark instances for forward SCND problems so as to make a fair comparison between developed and applied heuristic approaches. To this end, 450 new benchmark instances ranging from small to large size for forward SCND problems with two, three and four-echelon are generated and a mathematical model for each of the problems is formulated. Due to the complexity issues, we develop two heuristic solution approaches, genetic algorithm (GA) and hybrid heuristic algorithm (HHA), and we apply them to the large pool of benchmark instances. Comparative experiments show that both the GA and HHA can yield feasible solutions in much less computational time and, in particular, outperforms CPLEX regarding the solution quality as the number of echelon grows.

Keywords: Supply chain network design, mixed integer programming; genetic algorithm; hybrid heuristic algorithm.

Öz

Tedarik zinciri içindeki tesislerin yerlerinin belirlenmesi, aralarındaki ürün akışlarının maliyeti minimize edecek şekilde optimize edilmesi tedarik zinciri ağ tasarımı (TZAT) problemi olarak karşımıza çıkmaktadır. TZAT problemleri NP-zor sınıfına girmektedir. Dolayısıyla çoğu araştırmacı tarafından üzerinde çalışılan bir konudur. Ancak literatürde araştırmacıların adil karşılaştırmalar yapabileceği test problemler mevcut değildir. Bu sebeple, küçük boyuttan büyük boyuta kadar iki, üç ve dört aşamalı olmak üzere 450 adet TZAT test problemi geliştirilmiş, matematiksel olarak da modellenmiştir. Problemin çözüm karmaşıklığından dolayı biri genetik algoritma diğeri de melez sezgisel bir yaklaşım olmak üzere iki farklı çözüm yöntemi önerilmiştir. Önerilen yaklaşımlar geliştirilen test problemlere uygulanmış ve karşılaştırmalar yapılmıştır. Elde edilen sonuçlara göre önerilen sezgisel yaklaşımlar küçük boyutlu problemler için CPLEX ile elde edilen optimal sonuçları yakalamış, büyük boyutlu problemler için ise çok daha kısa sürede kabul edilebilir sonuçlar elde etmiştir.

Anahtar kelimeler: Tedarik zinciri ağ tasarımı, karma tamsayılı programlama, genetik algoritma, melez sezgisel algoritma.

1 Introduction

A classical supply chain refers to a broad set of activities associated with the transformation and flow of goods and services, including the flow of information, from the sources of materials to end-users [1]-[3]. Nowadays, a supply chain network can take three main forms namely; forward, reverse and closed-loop supply chain [4]. Whereas forward supply chain (FSC) can be defined as flow of goods from source to end-users in a supply chain, reverse supply chain (RSC) can be defined as a process that includes all logistics activities and starts from the point of end-users to transform the used products to products which are reusable in the market [5],[6]. Finally, if all forward and reverse supply chain activities are combined is known to be one of a closed-loop, and research on such chains have given rise to the field of closed-loop supply chain (CLSC) [7] (see Figure 1).

The operation/distribution plans of a supply chain involving forward, reverse or closed-loop need to be optimized. Determining positions and counting of actors, amount of product flow between and decreasing transportation costs are handled as a network design problem in supply chain management.

The design task may include,

- location of facilities (plants, retailers, distribution centers, disassembly centers, collection centers etc.) to be opened,
- design of the network configuration,
- meeting customer's demand so as to minimize the total cost consist of fixed operating cost and transportation cost [8]-[11].

Most of the SCND problems can be reduced to the capacitated facility location problem, which is proven to be NP-hard; therefore, SCND problems belong to the class of NP-hard problems as well [8]. To cope with the complexity of the SCND problems and to obtain acceptable solutions in reasonable amount of time, many heuristic and meta-heuristics algorithms are developed and applied in the last decade [12]-[15].

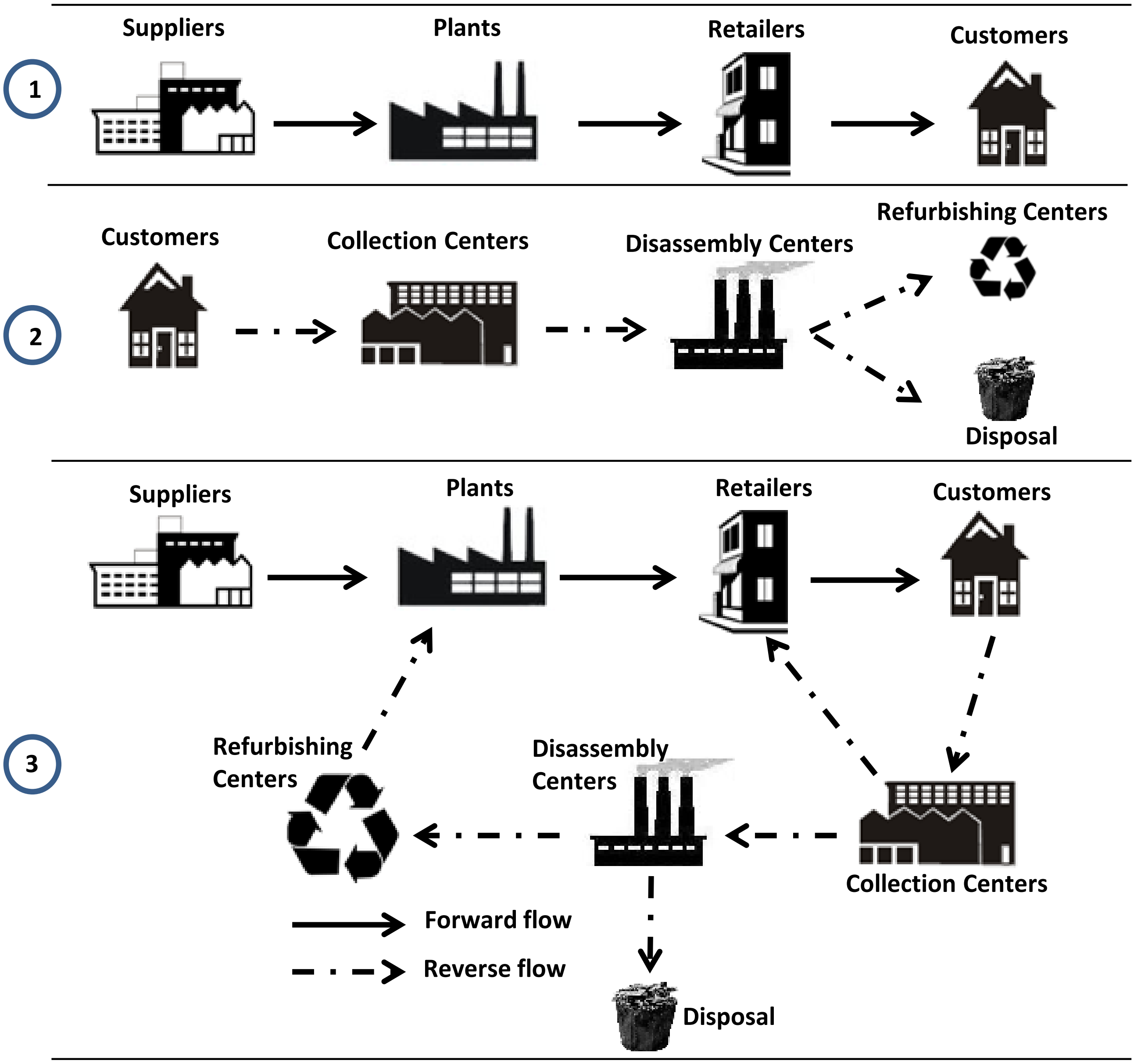

Figure 1: Typical FSC (1), RSC (2) and CLSC (3) networks.

However, literature lacks of benchmark problems for SCND problems to make a fair comparison between developed and applied approaches. Although there are well-known benchmark problems in traveling salesman problems [16], vehicle routing problem with time windows [17] and assembly line balancing problems [18], to the best of our knowledge, no benchmark or common problems are introduced in SCND problem area. A well-established set of benchmark instances provides a good base for future studies on the field of SCND.

The scientific contributions of this study are given as follows. We first model SCND problems as mixed integer linear programming formulations, and we develop two different solution approaches based on the genetic algorithm (GA) and hybrid heuristic algorithm (HHA). We then generate 450 test instances with varying number echelons through a broad problem set, and we comparatively analyze the effectiveness of the two GA and HHA.

The rest of the article is presented as follows. In the next part, we provide an overview and a summary of the existing literature on forward SCND problems. Basic formulation of forward SCND problem and generation of benchmark instances are given in Section 3. Sections 4 and 5 explain the adopted solution methodology based on GA and HHA, respectively. Section 6 discusses the comparative results on the set of instances. Last part of study (Section 7), conclusions and future directions are given.

2 Literature review

One of the most popular problems is designing and optimizing forward SCND problem, received substantial attention from academicians, researchers and operators in supply chain management research field. For that reason, many heuristic algorithm and mathematical models have been presented. The literature on the forward SCND problem is fruitful and the readers are referred to the comprehensive surveys given in Table 1 for a recent coverage of the state-of-the-art on models and solution algorithms. Table 1 also lists the possible future research directions provided by the authors.

In addition to the surveys, current test problems generated by the researchers for forward SCND problems to test their proposed solution approaches are given in Table 2. Information in Table 2 is classified based on the number of facilities, number of the test problems, proposed approach and comparisons (if exists). The minimum and the maximum number of facilities are given in the cells with dash. With regard to the reviewed studies, the vast majority presents a three-echelon structure, and mainly combines the presence of suppliers, plants, distribution centers/retailers and customers.

While early studies consider single echelon structure [19]-[21], two echelon supply chains have recently drawn attention of some researchers [22],[23]. In modeling approach, a great deal of the studies reviewed for the linear programming-based modeling approach, especially mixed integer linear programming models [11],[24],[25]. On the contrary, nonlinear programming is only used in two papers [26]-[28].

The inclusion of uncertainty in the various models is achieved by stochastic programming [23],[26]. Likewise, heuristic and meta-heuristics are used as complementary techniques to solve mathematical programming models in a reasonable time [8],[9],[20],[22],[29]-[31]. In the objective frame, minimization of total costs (especially shipping and fixed costs) is the main objective of the studies reviewed while maximization of sales/revenues [11],[32] and customer service [27] are considered to a lesser extent.

Regarding costs, the minimization of shipping cost [8], fixed cost [22], inventory cost [33], backorder cost [34], production cost [35] are considered for forward SCND problems. The maximization of capacity utilization is also taken into account by Altıparmak et al. [27].

Table 1: Characteristics of earlier review studies on forward SCND problems.

Reference	Date range	No. of reviewed papers	Suggestions
Meixell and Gargeya [36]	1982-2005	18	• Need to address the composite supply chain design problem by extending models to include both external supplier locations and internal manufacturing. • The performance measures used in global supply chain models need to be broadened in definition to address alternative objectives. • More industry settings need to be explored in the context of global supply design.
Melo et al. [37]	1992-2008	60	• The integration of strategic and tactical / operational decisions in supply chain planning.
Mula et al. [38]	1984-2009	44	• Integration and/or the hierarchical structure of the tactical and operative planning levels in the supply chain context. • Consideration of the different forms of transport (routes, full truck load, grouping, milk round) products among the various nodes of the supply chain. • Comparisons made among the centralized and decentralized planning stages of the supply chain. • Applying the planning models to real case studies.
Badole et al. [12]	2001-2010	302	• Some of the missing and most critical performance measures should include information productivity, cost of data processing and information, risk of not using an information technology, and the implications of outsourcing. • Research on perishable products is comparatively scarce. • A need for the design and implementation of a humanitarian and disaster supply chain.
Fahimnia et al. [13]	1991-2011	135	• Needing a range of variables and constraints to be incorporated in supply chain models. • Requiring quantifying and formulating multiple supply chain performance indicators including both traditional and contemporary objective functions (e.g. cost, service level, social impact, environmental impact, and safety measures).
Lambiase et al. [14]	2000-2012	50	• Consideration the development of a supply chain model using a profit maximization objective function, including as many strategic decisions, economic parameters and financial aspects as possible, and in order to increase real applicability to the context of globalization.

Table 2: Forward SCND problems in the literature.

References	No. of products	No. of suppliers	No. of plants	No. of DC/warehouses	No. of retailers/customers	No. of test problems	Proposed method	Compared with	Max GAP
Qu et al. [19]	15-20	7	1	NA	NA	8	Heuristic	NA	NA
Sabri and Beamon [26]	2	5	1-3	1-4	5	5	LINGO	NA	NA
Jayaraman and Pirkul [24]	10	1-2	3-10	4-15	10-20	13	LR	LINGO	1.06%
Hwang [29]	1	NA	4	10-99	NA	4	GA	Heuristic	20.41%
Syarif et al. [8]	1	3-20	6-15	8-12	50-100	4	GA	LINDO	3.72%
Zhou et al. [20]	1	NA	NA	3-10	30-100	8	GA	Heuristic	39.36%
Syam [39]	1	10-100	2-20	NA	NA	30	LR	SA	7.75%
Jang et al. [25]	10	NA	5-15	10-20	10	9	LR	CPLEX	4.1%
Wang et al. [40]	2	NA	2	2	NA	1	CPLEX	NA	NA
Jayaraman and Ross [33]	2-3	NA	5	10-15	30-75	8	SA	LINGO	4%
Miranda and Garrido [21]	1	NA	10	20	NA	25	LR	LINGO	1.55%
Melachrinoudis et al. [41]	1	NA	1	21	281	1	LINGO	NA	NA
Altıparmak et al. [27]	1	5	3-8	6-20	63	5	GA	SA	5%
Amiri [42]	1	NA	10-20	10-30	100-500	28	LR	CPLEX	11.54%
Farahani and Elahipanah [34]	2-8	NA	2-8	2-15	4-60	9	GA	LINGO	4.7%
Altıparmak et al. [9]	2-3	2	2-25	5-50	10-300	16	LR, GA, SA	CPLEX	12.92%
Lee et al. [43]	1	3-8	2-3	2-3	3-8	5	LR	Xpress-MP	0%
Pishvaee and Rabbani [22]	1	NA	5-40	15-70	10-100	5	Heuristic	LINGO	3.7%
Babazadeh et al. [35]	1	NA	5-10	8-10	10-15	2	CPLEX	NA	NA
Paksoy et al. [11]	1	5-35	3-6	3-7	4-28	8	LINDO	NA	NA
Badri et al. [32]	5-15	5-35	5-20	5-22	10-120	10	LR	CPLEX	18.48%
Benyoucef et al. [28]	1	NA	3-30	10-160	NA	30	LR	CPLEX	8.1%
Hamta et al. [23]	7-10	NA	4-20	6-22	6-25	10	SAA	CPLEX	0.4%
Cheraghi et al. [44]	1	4-8	3-5	3-5	3-6	3	RO	NA	NA
Chiadamrong and Piyathanavong [45]	1	4	4	4	4	1	SOM	NA	NA
Proposed study	1	4-302	2-151	2-151	4-302	450	GA, HHA	CPLEX	17.11%

LR: Lagrangian relaxation, GA: Genetic algorithm, SA: Simulated annealing, SAA: Sample average approximation, RO: Robust optimization, SOM: Simulation based optimization model, HHA: Hybrid heuristic approach.

According to 248 forward SCND test problems in Table 2, following findings can be highlighted;

- Minimization of shipping and fixed costs is the most common objective function,
- Mixed integer programming is the main solution approach,
- While small size test problems are solved by either CPLEX or LINGO, medium and large size test problems are tackled by meta-heuristic approaches,
- Each paper generates the test problems on its own rather than a common test problem which can be used for comparison.

Unfortunately, test problems generated by the researchers in Table 2 are inaccessible.

3 Forward supply Chain network design problems

In this section, three forward supply chain network models, each with different number of echelons are presented. While the largest forward supply chain network model (i.e., four-echelon) consists of suppliers, plants, distribution centers (DC), retailers and customers, two echelon network includes suppliers, plants and customers as shown in Figure 2.

3.1 Two echelon forward SCND problem

Let S, P and D denote the set of suppliers, plants, and distribution centers, respectively. Two echelon SCN consists of $G^{two} = (N^{two}, A^{two})$, where $N^{two} = \{S \cup P \cup D\}$ is the set of nodes and $A^{two} = \{(i,j,k) | (i \in S, j \in P) \cup (j \in P, k \in D)\}$ is the sets of arcs. The suppliers are companies from which raw materials are purchased. There are vehicles transporting the raw materials to potential plants. The manufacturing plant is the site where the products are produced and some of the plants are not opened due to fixed costs. Distribution centers are the demand points that need to be satisfied. It is noted that all parameters and variables of the three models are given in Appendix A.

The formulation of the two-echelon mathematical model is given as follows:

$$Min \, (\sum_{s \in S} \sum_{p \in p} X_{sp} Di_{sp} t + \sum_{p \in P} \sum_{d \in D} Y_{pd} Di_{pd} t) + (\sum_{p \in P} \Delta_p \, FC_p) \tag{1}$$

Subject to

$$\textstyle\sum_{p \in P} X_{sp} \leq Ca_s \quad \forall \, s \in S \tag{2}$$

$$\textstyle\sum_{c \in C} Y_{pd} \leq Ca_p \Delta_p \qquad \forall \, p \in P \tag{3}$$

$$\textstyle\sum_{p \in P} Y_{pd} = De_d \quad \forall \, d \in D \tag{4}$$

$$\sum_{p \in P} \Delta_p \leq MaxP \tag{5}$$

$$\textstyle\sum_{s \in S} X_{sp} - \sum_{d \in D} Y_{pd} = 0 \quad \forall \, p \in P \tag{6}$$

$$X_{sp}, Y_{pd} \geq 0 \qquad \forall \, s \in S, p \in P \; and \; d \in D \tag{7}$$

$$\Delta_p \in \{0, 1\} \qquad \forall \, p \in P \tag{8}$$

The objective function has two components (Eq. 1). While the first component represents the cost of transportation on each arc of the network, the second component stands for the fixed costs associated with locating the plants.

Constraints (2) and (3) mean that the production and transportation amount cannot exceed the capacity of suppliers and potential plants, respectively. Constraints (4) ensure that demand of each distribution center must fully be met. Constraints (5) limit the number of plants that can be opened. Constraints (6) are the balance equation: the quantities that enter plants must be equal to the quantities of products that leave the plants. Constraints (7) enforce the non-negativity restriction on the decision variables. Finally, Constraints (8) are the integrality enforcements on binary variable Δ_p.

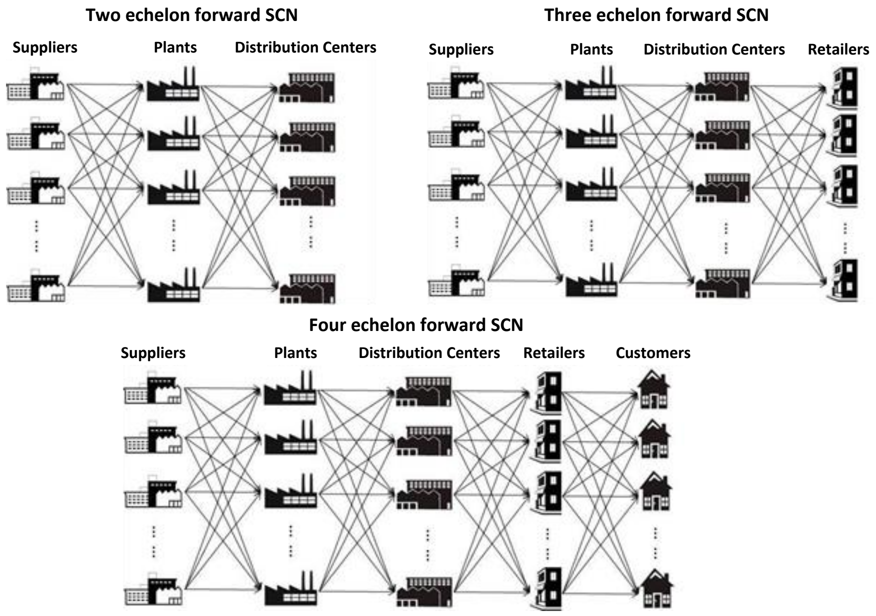

Figure 2: Forward supply chain networks with different echelons.

3.2 Three echelon forward SCND problem

Let S, P, D, and R denote the set of suppliers, plants, distribution centers, and retailers, respectively. Three echelon SCN consists of $G^{three} = (N^{three}, A^{three})$, where $N^{three} = \{S \cup P \cup D \cup R\}$ is the set of nodes and $A^{three} = \{(i,j,k,l) | (i \in S, j \in P) \cup (j \in P, k \in D) \cup (k \in D, l \in R)\}$ is the sets of arcs. Raw materials are shipped from suppliers to potential plants for production. Products are transported from plants to the distribution centers, where the products are distributed to the retailers. Some of the plants and distribution centers may not be opened depending on fixed costs.

The formulation of the three-echelon mathematical model is given as follows:

$$Min\ (\sum_{s\in S}\sum_{p\in p} X_{sp}Di_{sp}t + \sum_{p\in P}\sum_{d\in D} Y_{pd}Di_{pd}t + \sum_{d\in D}\sum_{r\in R} Z_{dr}Di_{dr}t) + (\sum_{p\in P} \Delta_p\, FC_p + \sum_{d\in D} \Gamma_d\, FC_d) \qquad (9)$$

Subject to

Constraints (2), (3), (5), (6), (7), (8) and

$$\textstyle\sum_{r\in R} Z_{dr} \leq Ca_d\Gamma_d\ \forall\, d \in D \qquad (10)$$

$$\textstyle\sum_{d\in D} Z_{dr} = De_r \quad \forall\, r \in R \qquad (11)$$

$$\sum_{d\in D} \Gamma_d \leq MaxD \qquad (12)$$

$$\textstyle\sum_{p\in P} Y_{pd} - \sum_{r\in R} Z_{dr} = 0 \quad \forall\, d \in D \qquad (13)$$

$$Z_{dr} \geq 0 \qquad \forall\, d \in D \text{ and } r \in R \qquad (14)$$

$$\Gamma_d \in \{0,1\} \qquad \forall\, d \in D \qquad (15)$$

The objective function has two components (Eq. 9). The first component represents the cost of transportation on each arc of the network (i.e., between suppliers-plants-distribution centers and retailers). The second component represents the fixed costs associated with locating the plants and distribution centers.

Constraints (10) guarantee that the production and transportation amount must not exceed the capacity of distribution centers. Constraints (11) ensure that demands of each retailer must fully be met. Constraints (12) limit the number of distribution centers that can be opened. Constraints (13) are the balance equation: the quantities that enter distribution centers must be equal to the quantity of products that leave the distribution centers. Constraints (14) enforce the non-negativity restriction on the decision variable (Z_{dr}). Finally, Constraints (15) are the integrality enforcements on binary variable Γ_d.

3.3 Four echelon forward SCND problem

Let S, P, D, R, and C denote the set of suppliers, plants, distribution centers, retailers and customers, respectively. Four echelon SCN consists of $G^{four} = (N^{four}, A^{four})$, where $N^{four} = \{S \cup P \cup D \cup R \cup C\}$ is the set of nodes and $A^{four} = \{(i,j,k,l,m) | (i \in S, j \in P) \cup (j \in P, k \in D) \cup (k \in D, l \in R) \cup (l \in R, m \in C)\}$ is the sets of arcs. Raw materials are shipped from suppliers to plants for production. Products are transported from plants to the distribution centers where the products are distributed to the retailers. At last step, customers' demands are met by retailers. Some of the plants, distribution centers and retailers may not be opened due to fixed costs.

The mathematical formulation of the three-echelon model is as follows:

$$Min\ (\textstyle\sum_{s\in S}\sum_{p\in p} X_{sp}Di_{sp}t + \sum_{p\in P}\sum_{d\in D} Y_{pd}Di_{pd}t + \sum_{d\in D}\sum_{r\in R} Z_{dr}Di_{dr}t + \sum_{r\in R}\sum_{c\in C} W_{rc}Di_{rc}t) + (\sum_{p\in P} \Delta_p\, FC_p + \sum_{d\in D} \Gamma_d\, FC_d + \sum_{r\in R} \Psi_r\, FC_r) \ (16)$$

Subject to

Constraints (2), (3), (5), (6), (10), (12), (13), (14), (15) and

$$\textstyle\sum_{c\in C} W_{rc} \leq Ca_r\Psi_r \qquad \forall\, r \in R \qquad (17)$$

$$\textstyle\sum_{r\in R} W_{rc} = De_c \quad \forall\, c \in C \qquad (18)$$

$$\sum_{r\in R} \Psi_r \leq MaxR \qquad (19)$$

$$\textstyle\sum_{r\in R} Z_{dr} - \sum_{c\in C} W_{rc} = 0 \quad \forall\, r \in R \qquad (20)$$

$$W_{rc} \geq 0 \ \ \forall\, r \in R \text{ and } c \in C \qquad (21)$$

$$\Psi_r \in \{0,1\} \qquad \forall\, r \in R \qquad (22)$$

The objective function has two components (Eq. 16). The first component represents the cost of transportation on each arc of the network (between suppliers-plants-distribution centers-retailers and customers). The second component represents the fixed costs associated with locating the plants, distribution centers and retailers.

Constraints (17) mean that the production and transportation quantity must not exceed the capacity of retailers. Constraints (18) ensure that demand of each customer must fully be met. Constraints (19) limit the number of retailers that can be opened. Constraints (20) are the balance equation: the quantities that enter retailers must be equal to the quantity of products that leave the retailers. Constraints (21) enforce the non-negativity restriction on the decision variable (W_{rc}). Lastly, Constraints (22) are the integrality enforcement on the binary variable Ψ_r.

3.4 Generation of benchmark instances

This section describes how the instances in the proposed SCND problem benchmark are generated. 450 different benchmark instances ranging from small to large size for forward SCND problems with two, three and four-echelon are generated in this study. As is the case in almost all the existing instances, the distances between all type problems are two-dimensional Euclidean. All facilities in two, three and four echelon structures have integer coordinates corresponding to points in a [0; 500]. Shipping cost (t) is set 0.05 monetary units. Fixed cost of potential plants, distribution centers and retailers in all network structures have integer coordinates corresponding to points in a [2750; 3250]. Maximum available numbers of plants, distribution centers and retailers to be opened are limited to upper bound of facility numbers. Other parameters with interval values are given in Table 3.

We randomly generate the data based on uniform distribution. For further details about the benchmark instances, we refer the reader to the Appendix B. All instances are available on the supply chain network design problem web page (scndp.info).

Table 3: Parameter intervals used to generate different problem sizes.

Two-Echelon Structure		
	Parameters	**Integer Interval**
Ca_s	Capacities of suppliers	950-1000
Ca_p	Capacities of plants	2500-3000
De_d	Demands of distribution centers	800-850
Three-Echelon Structure		
	Parameters	**Integer Interval**
Ca_s	Capacities of suppliers	950-1000
Ca_p	Capacities of plants	2500-3000
Ca_d	Capacities of distribution centers	2500-3000
De_r	Demands of retailers	800-850
Four-Echelon Structure		
	Parameters	**Integer Interval**
Ca_s	Capacities of suppliers	950-1000
Ca_p	Capacities of plants	2500-3000
Ca_d	Capacities of distribution centers	2500-3000
Ca_r	Capacities of retailers	2500-3000
De_c	Demands of customers	800-850

4 Description of the Genetic algorithm

This section describes the proposed GA to solve the generated forward SCND instances. The GA builds on several powerful evolutionary based meta-heuristic algorithms (see [9],[27],[46]-[49]).

The general scheme of the GA is shown in Algorithm 1. The initialization procedure (Line 1) is used to generate initial population. Two parents are selected (Line 3) for a crossover operation through a binary tournament process in order to creates a new offspring C (Line 4). The mutation technique is used on the offspring C (Line 5). Then, created offspring (offspring C) is added into the population (Line 6). As new offspring are added, the population size n_a, which is limited by $n_{p+}n_o$, changes over the iterations. The constant n_p denotes the size of the population initialized at the beginning of the algorithm and the constant n_o is the maximum allowable number of offspring that can be inserted into the population. If the population size n_a reaches $n_{p+}n_o$ at any iteration, then a survivor selection mechanism is applied (Line 7). When the number of Φ iterations without improvement in the incumbent solution is reached, the GA terminates (Line 8).

Algorithm 1: The general framework of the GA.

```
1  Initialization: Initialize a population with size $n_p$
2  while number of iterations without improvement < Φ
3      Parent selection: select parent solutions $P_1$ and $P_2$
4      Crossover: generate offspring $C$ from $P_1$ and $P_2$
5      Mutation: diversify the offspring $C$
6      Add offspring $C$ to the population
7      Survivor selection: if the population size $n_a$ reaches $n_p$+ $n_o$,
       then select survivors
8  end while
9  Return best feasible solution
```

The rest of the part presents basic elements of the GA. Section 4.1 offers representation and evaluation of the results. The initialization procedure is given Section 4.2 in detail. The selection of parent solutions and a segment-based crossover operator are then described in Section 4.3. The mutation procedure is presented in Section 4.4. Lastly, Section 4.5 presents the survivor selection mechanism.

4.1 Representation and evaluation

The priority-based encoding of Gen et al. is adapted [46] for the problems to represent our solutions within the population. For two-echelon SCND problem, the result includes of priorities of first echelon, containing first-level facilities (FL) and second-level facilities (SL), and second echelon including SL and third-level facilities (TL). Priority-based encoding for two-echelon SCND problem is illustrated in Figure 3.

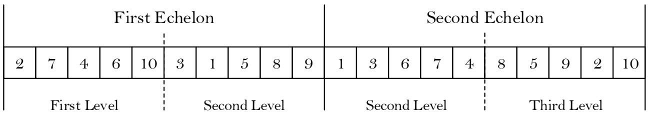

Figure 3: The representation of the priority-based encoding.

Each solution consists of a single-dimensional array and numbers representing the priority of each node. The total amount of echelons (|FL|+2*|SL|+|TL|) equals to the length of encoding. The transportation tree on a given solution is generated by sequential arc appending between levels. In accordance with priority-based encoding, we first consider the highest priority of TL, and we then open a SL to satisfy its demand. Depending on the selected TL, a SL is decided with taking into account minimum transportation cost and an arc between them. This process is iteratively applied to all facilities until all demands are satisfied. For three-echelon and four-echelon SCND problems, we applied same procedure with adapting the representation to each problem type. The fitness value of each solution is calculated by using the objective function of the considered problem (minimization of total transportation and fixed costs). These fitness values are used to select survivors during the algorithmic iterations. For further implementation details on representation and evaluation section, the reader is referred to Gen et al. [46].

4.2 Initialization, parent selection and crossover

We randomly generate the initial population. For example, we consider a two-echelon SCND problem in Figure 3. First echelon includes first-level and second-level facilities, where |FL|=5 and |SL|=5. The total length of the first-echelon is equal to |FL|+|SL|=10 such that a priority is assigned to each node within the range of 1 and 10.

Two parents are selected with use of the binary tournament for generate offspring C. The technique selects randomly two different individuals from the population. After that, it preserves the one of them having the best fitness value. Following the parent selection phase, two parents undergo the segment-based crossover operator, which is relied upon uniform crossover and tends to keep good gene segments of both parents. Representation of this operator is shown in Figure 4. Each echelon of offspring C is selected at random with equal probability over echelons of parents. These crossover operators use a binary mask where its length is equal to the number of echelons. Binary variables 0 and 1 are used to transfer the genetic materials from parents to offspring C. Each echelon of offspring C randomly takes 0 or 1 values, through which 0 implies the first parent and 1 implies the second parent transferring its genetic materials to the offspring C.

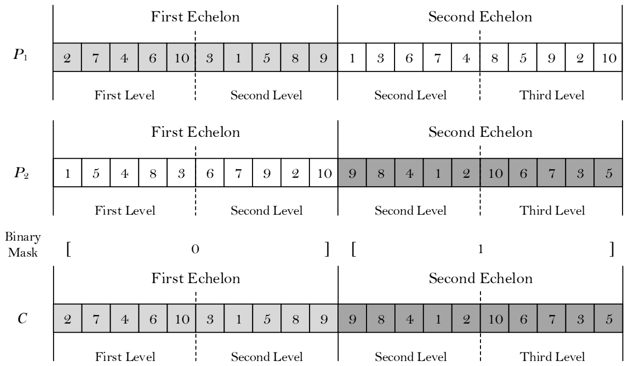

Figure 4: An illustration of the segment-based crossover operator.

4.3 Mutation

The effective controlling of results plays a important role in population variety. Therefore, a segment-based mutation operator after crossover, which is represented in Figure 5 has applied in order to improve the performance of the GA. In this step, selected two nodes are relocated in order to increase to the diversification of the results. First, an echelon is randomly selected with using a binary mask as in the crossover operator. Then, two nodes are randomly selected from the same echelon. Finally, these are exchanged by using swap method according to their priorities.

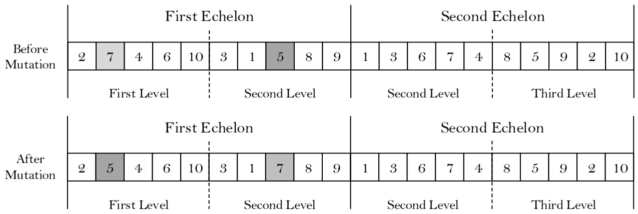

Figure 5: An illustration of the segment-based mutation operator.

4.4 Survivor selection

Avoiding premature convergence is a key challenge in population-based meta-heuristics. Population diversity or searching varied area in the solution space can help find best solution or optimal during the algorithm. To tackle with this issue, we used survivor selection method (see [48]), which intends to provide the diversity of the population and preserve the best solutions. Initially, the initial population is generated with the size of n_p, and then at each iteration a generated offspring is inserted into to the population after each iteration. The maximum number of allowable offspring in the population is denoted by n_o. When total population size n_a reaches the maximum limit $n_p + n_o$, the survivor selection mechanism works to select offspring for next generation. On other words, the technique, afterward, elects n_p and separate n_o individuals from the population. The rest of n_o individuals are selected based on their fitness. In this way, best individuals are protected.

5 Description of the hybrid heuristic algorithm

We develop a two-phase HHA based on the principles of heuristics and integer programming. The problem is divided into two sub-problems, which are finding feasible location plant (plant, distribution center and retailer) and transportation on each arc of the network (between suppliers-plants-distribution centers-retailers and customers). A constructive heuristic is used first generates feasible solutions for finding feasible location in order to meet customer demands. Second sub-problem is then solved to optimality with using first sub-problem solution by an integer programming solver. The decision variables in the sub-problems are the same as those found within the original formulation.

5.1 Constructive heuristic technique

To obtain optimal solution of the problem is not easy because of dependencies between finding feasible facility location and design of the network configuration. Therefore, the first part of the problem that is location of facilities (plants, distribution centers, retailers, collection centers, disassembly centers etc.) to be opened is determined by the proposed heuristic algorithm.

The first algorithm, constructive heuristic, builds the solution based on the fixed costs (associated with locating the plants, distribution centers and retailers) and costumer demand. First of all, two lists, which are UnexploredNodes, and *ExploredNodes* list are built to start solution. In the beginning, while *UnexploredNodes* list includes all potential facility in order to assign solution, *ExploredNodes* is empty list. When a potential facility selects, that facility moves to *ExploredNodes* list. Second, the heuristic technique produces root nodes from lists of unexplored nodes at the first level. Then, descendant nodes are generated for each root nodes. If capacity of nodes (root and descents nodes) is greater than total customer demand, these nodes are transferred to list of Solutions. If the size of the list is larger than predetermined size (2*β), certain solutions are selected according to routhwell selection method to BestSolution list up to the number of β solutions. The objective function, fixed costs associated with locating the plants, is used in routhwell selection method. The general structure of the constructive heuristic algorithm is shown in Algorithm 2.

Algorithm 2: The general framework of the constructive algorithm.

```
Set Solutions=null and BestSolutions = null
Build two lists UnexploredNodes and ExploredNodes
Build an empty solution and add it to UnexploredNodes
For iter = 1,…, MaxIter (increasing iter by 1)
    Assign the all potential facility in ExploredNodes and select it as Parent
    For each node
        Update lists of UnexploredNodes
        Create a descentes nodes from the parent
        if capacity of nodes (root and descentes nodes) >= Total customer demands
            Update Solutions list
        end if
        if size of Solution ≥2∗β
            Select the solutions according to Routhwell selection from list of Solution and update BestSolutions list
        End if
    End For
End For
Output: BestSolutions
```

5.2 Integer programming procedure

In this section, after generating initial solution from constructive heuristic, a new procedure based on mathematical approach is proposed. In the proposed model, binary variables of Δ_p,Γ_d, Ψ_r are transformed to parameters. Thus, fixed costs associated with locating the plants in the objective function is removed and new objective function for all echelons models are given as follows:

$$\text{Min} \sum_{s\in S}\sum_{p\in p} X_{sp}Di_{sp}t + \sum_{p\in P}\sum_{d\in D} Y_{pd}Di_{pd}t \tag{23}$$

$$\begin{aligned}\text{Min} \sum_{s\in S}\sum_{p\in p} X_{sp}Di_{sp}t + \sum_{p\in P}\sum_{d\in D} Y_{pd}Di_{pd}t \\ + \sum_{d\in D}\sum_{r\in R} Z_{dr}Di_{dr}t\end{aligned} \tag{24}$$

$$\begin{aligned}\text{Min} \sum_{s\in S}\sum_{p\in p} X_{sp}Di_{sp}t + \sum_{p\in P}\sum_{d\in D} Y_{pd}Di_{pd}t \\ + \sum_{d\in D}\sum_{r\in R} Z_{dr}Di_{dr}t + \sum_{r\in R}\sum_{c\in C} W_{rc}Di_{rc}t\end{aligned} \tag{25}$$

The objective is to minimize the cost of transportation on each arc of the network. After determination of Δ_p,Γ_d, Ψ_r as parameters, certain constraints are eliminated from the mathematical model. The modifications in all mathematical models are given follows.

In two echelons model: The variable of Δ_p is modified as a parameter, which is obtained from the proposed heuristic algorithm in the Constraints (3). Also, the Constraints (5) are eliminated from model.

In three echelons model: The variables of Δ_p, Γ_d are changed as parameters in Constraints (3) and (10) respectively. In addition, Constraints (5) and (12) are removed from the model.

In four echelons model: Similarly in the previous models, the variables of $\Delta_p, \Gamma_d, \Psi_r$ are modified as parameters in the Constraints (3), (10), and (17), respectively. Constraints (5), (12) and (19) are also eliminated from model.

6 Comparative results

In this section, we present the comparative results in order to show the performance of the formulations, the GA and the HHA. All computational experiments are conducted on a server with one gigabyte RAM and Intel Xeon 2.6 GHz processor. We used CPLEX 12.5 with its default settings as the optimizer to solve the integer programming formulations. The GA is coded in C++ and HHA is coded in MATLAB. Maximum allowable computational time is set three hours for each instance in the mathematical formulation solutions. For the GA and the HHA, ten separate runs are performed for each instance and the best one is reported.

Three different network structures (i.e., two, three and four echelons) are solved to evaluate the performance of the formulations, the proposed heuristic algorithms. Summary information about solutions obtained by GAMS, GA and HHA are given in Table 4. All detailed solutions of 450 instances can be found on website scndp.info.

The results show that the GA yields optimal solutions for 21, 16 and 6 test instances out of 150 for two, three and four echelon configurations, respectively. On the other hand, the HHA finds also optimal solution for 32, 20, and 11 problems for the configuration, respectively. In total, 308 of 450 test problems are solved optimality by CPLEX. However, no solutions are obtained in 109 test problems. CPLEX finds a feasible solution within three hours-time limit for the rest 33 the test problems. While the GA finds optimal solutions in 43 test problems, HHA produces optimal solution in 63 test problems. Both algorithms yield good quality solutions in the remaining test problems within a reasonable computation time as well. Expectedly, increasing the size of the network also increases the computation time of the problem. Solution time dramatically increases when the size of the network grows. As can be seen from Table 4, while average CPU time is 386.47 sec. for two echelon network, it jumps to 6266.22 sec., which is 16 times higher than that for four echelon network.

Detailed average results are given in Tables 5-7. It is shown that GA and HHA produce optimal/feasible solutions in all the test problems. For two-echelon test problems, both algorithms are capable of finding the optimal solution in small sizes but the HHA shows better performance than the GA. However, the possibility of finding optimal results decreases in larger echelon structures in the both algorithm. The results clearly indicate that the GA and HHA require quite less computational time and memory than does CPLEX (Tables 5-7). Numbers in bold indicates that HHA performs better than GA in most of the test problems. From Tables 6 and 7, three and four-echelon networks, involving more than hundred facilities cannot even produce feasible solutions within the given time limit (see Figure 6). It must be noted that the capacity and demand values of each problem are not investigated to see the effects on solution time.

Table 4: A summary of solution obtained by CPLEX, GA and HHA.

Test Groups	**CPLEX**				
	Optimal	**Feasible**	**NA**	**Average Time(sec.)**	
Two Echelon	149	1	0	386.47	
Three Echelon	93	7	50	4460.10	
Four Echelon	66	25	59	6266.22	
	GA				
	Optimal	**Feasible**	**NA**	**Average Time(sec.)**	**Average Gap (%)**[a]
Two Echelon	21	129	0	17.60	2.96
Three Echelon	16	134	0	92.81	3.23
Four Echelon	6	144	0	104.90	2.59
	HHA				
	Optimal	**Feasible**	**NA**	**Average Time(sec.)**	**Average Gap (%)**[b]
Two Echelon	32	118	0	21.80	2.47
Three Echelon	20	130	0	111.21	2.95
Four Echelon	11	139	0	223.45	2.22

[a](GA-GAMS)/GAMS×100; [b](HHA-GAMS)/GAMS×100.

Table 5: Average results of two echelon test problems.

Instance set	**CPLEX**		**GA**			**HHA**		
	Total Cost	**Time (s)**	**Total Cost**	**Time (s)**	**Gap (%)**	**Total Cost**	**Time (s)**	**Gap (%)**
2Ech_F1 (1-10)	122374.79	0.01	122374.79	1.60	0.00	122374.79	2.60	0.00
2Ech_F2 (11-20)	213572.04	0.16	213572.04	1.78	0.00	213572.04	3.78	0.00
2Ech_F3 (21-30)	298143.84	0.43	299411.03	2.27	0.43	298143.84	3.27	0.00
2Ech_F4 (31-40)	344712.50	1.21	352132.69	3.24	2.15	348754.50	4.87	1.17
2Ech_F5 (41-50)	397433.25	3.12	407892.02	4.43	2.63	409878.25	5.02	3.13
2Ech_F6 (51-60)	450919.48	6.15	462753.30	5.48	2.62	463456.81	5.45	2.78
2Ech_F7 (61-70)	501853.49	15.40	517483.93	7.67	3.11	516878.72	6.90	2.99
2Ech_F8 (71-80)	534133.54	25.76	568344.99	9.06	6.41	553876.67	6.45	3.70
2Ech_F9 (81-90)	584866.67	58.18	608512.10	11.02	4.04	593453.54	7.25	1.47
2Ech_F10 (91-100)	624841.59	116.18	650806.72	13.05	4.16	643334.25	8.30	2.96
2Ech_F11 (101-110)	659888.85	293.50	691024.20	18.23	4.72	674563.32	10.34	2.22
2Ech_F12 (111-120)	697923.56	267.47	730800.37	21.58	4.71	724563.46	11.30	3.82
2Ech_F13 (121-130)	728565.32	671.41	761192.41	36.58	4.48	742323.64	14.45	1.89
2Ech_F14 (131-140)	787289.91	1418.81	824241.77	48.96	4.69	810345.87	26.94	2.93
2Ech_F15 (141-150)	823307.80	2916.86	862463.40	79.00	4.76	854356.67	52.34	3.77

Table 6: Average results of three echelon test problems.

Instance set	**CPLEX**		**GA**			**HHA**		
	Total Cost	**Time (s)**	**Total Cost**	**Time (s)**	**Gap (%)**	**Total Cost**	**Time (s)**	**Gap (%)**
3Ech_F1 (1-10)	188409.08	0.03	188409.08	2.01	0.00	**188409.08**	**2.09**	0.00
3Ech_F2 (11-20)	330404.62	0.44	330588.42	2.05	0.05	**330404.62**	**3.03**	**0.00**
3Ech_F3 (21-30)	442498.54	2.59	450293.09	4.24	1.76	**448939.56**	**5.03**	**1.45**
3Ech_F4 (31-40)	552731.83	7.57	568136.48	5.46	2.78	**567854.42**	**6.00**	**2.73**
3Ech_F5 (41-50)	627773.99	20.85	647751.95	7.06	3.18	**639864.78**	**7.08**	**1.92**
3Ech_F6 (51-60)	690874.80	66.72	718016.64	8.88	3.92	**709345.62**	**11.03**	**2.67**
3Ech_F7 (61-70)	787846.31	276.00	823966.76	15.40	4.58	**813464.87**	**20.17**	**3.25**
3Ech_F8 (71-80)	855301.36	1519.48	903561.68	29.55	5.64	**897844.12**	**29.75**	**4.97**
3Ech_F9 (81-90)	948197.90	4038.77	1002084.67	73.25	5.68	**995643.25**	**53.45**	**5.00**
3Ech_F10 (91-100)	1006877.01	6969.03	1071230.95	125.13	6.39	**1065984.40**	**110.24**	**5.87**
3Ech_F11 (101-110)	NA	NA	1127126.23	175.87	NA	**1039125.50**	**174.70**	**NA**
3Ech_F12 (111-120)	NA	NA	1208267.74	204.79	NA	**1128964.75**	**210.25**	**NA**
3Ech_F13 (121-130)	NA	NA	1273912.63	226.97	NA	**1263456.56**	**227.30**	**NA**
3Ech_F14 (131-140)	NA	NA	1354553.31	243.31	NA	**1294535.87**	**251.30**	**NA**
3Ech_F15 (141-150)	NA	NA	1416876.41	268.21	NA	**1405743.46**	**260.74**	**NA**

Table 7: Average results of four echelon test problems.

Instance set	**CPLEX**		**GA**			**HHA**		
	Total Cost	**Time (s)**	**Total Cost**	**Time (s)**	**Gap (%)**	**Total Cost**	**Time (s)**	**Gap (%)**
4Ech_F1 (1-10)	261446.77	0.05	261776.77	1.52	0.12	**261446.77**	**2.03**	**0.00**
4Ech_F2 (11-20)	446461.55	1.48	455425.90	1.76	2.00	**447212.60**	**3.04**	**0.16**
4Ech_F3 (21-30)	593410.62	5.18	611467.39	3.61	3.04	**609842.50**	**4.60**	**2.76**
4Ech_F4 (31-40)	722069.96	23.84	739428.04	5.56	2.40	**737843.76**	**6.40**	**2.18**
4Ech_F5 (41-50)	854909.84	235.70	874909.84	11.00	2.33	**866905.32**	**10.50**	**1.40**
4Ech_F6 (51-60)	955781.62	2475.83	983781.68	17.24	2.92	**979842.45**	**22.40**	**2.51**
4Ech_F7 (61-70)	1061234.46	5672.01	1238973.74	31.58	16.74	**1213563.87**	**30.60**	**14.35**
4Ech_F8 (71-80)	1154708.33	9158.50	1423015.61	64.42	23.23	**1352343.65**	**60.65**	**17.11**
4Ech_F9 (81-90)	1272519.58	10800.00	1402673.84	111.72	10.22	**1394564.50**	**110.30**	**9.59**
4Ech_F10 (91-100)	1375804.31	10800.00	1684762.24	130.45	22.45	**1503435.89**	**125.65**	**9.27**
4Ech_F11 (101-110)	NA	NA	2531983.63	167.44	NA	**2523436.78**	**165.70**	**NA**
4Ech_F12 (111-120)	NA	NA	2739308.44	189.23	NA	**2703445.40**	**185.60**	**NA**
4Ech_F13 (121-130)	NA	NA	2981610.61	222.04	NA	**2974563.31**	**225.09**	**NA**
4Ech_F14 (131-140)	NA	NA	3170228.58	261.55	NA	**3164635.90**	**260.40**	**NA**
4Ech_F15 (141-150)	NA	NA	3405414.13	354.40	NA	**3304567.50**	**350.45**	**NA**

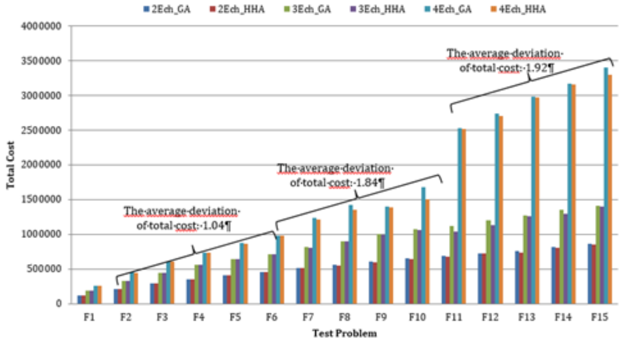

Figure 6: Comparisons of GA and HHA in terms of average total cost.

Results show that the gap between CPLEX and GA-HHA in three different network structures. As is clear from mentioned tables, the maximum gap interval is observed in four echelon test problems, minimum gap interval is observed in two echelon test problems.

In general, the results reveal that the gaps with respect to solution quality go between 0.00 and 23.23% for GA, and between 0.00 and 17.11% for HHA. Thus, the proposed HHA and GA perform very well in terms of quality of solutions and computational time.

Figure 6 indicates that HHA provides less total cost than GA in all test problem types. Average gap values between GA and HHA are also shown within Figure 6. According to this, average gap between GA and HHA is increased from 1.04% to 1.92% for small (two echelons) and large (four echelons) size problems, respectively.

7 Conclusions

In this paper, we have studied different scenarios of the well-known forward supply chain network design (SCND) problem where two, three and four echelons are taken into account. Two-echelon SCND is composed of suppliers, production plants and distribution centers. Three and four-echelon SCND problems are extensions of the two-echelon form by adding retailer and customer, respectively. We have formulated each problem with mixed integer programming formulation. Since the problem belongs to NP-Hard problem class, mathematical formulations show poor performance as the number of echelon increases. We therefore develop two heuristic methods; GA and HHA. We compare the effectiveness of the proposed algorithms versus mathematical formulations.

Comparative results substantiate the outstanding performance of the GA and HHA. Based on the computational time measurement, GA and HHA show similar performance.

For future studies, proposed GA and HHA approaches can be compared with other heuristic and meta-heuristics techniques using current benchmark instances. Additionally, uncertainty of costs, demands and capacities can be considered in the model and new solution methodologies including uncertainty can be developed. Finally, similar benchmark instances can be developed for reverse and closed-loop supply chain networks.

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9 References

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Appendix A

Variables of two echelon forward SCND problem for quantities are as follows:

X_{sp}	Amount shipped from supplier s to plant p; $\forall\, s \in S$ and $p \in P$
Y_{pd}	Amount shipped from plant p to distribution center d; $\forall\, p \in P$ and $d \in D$
Δ_p	Binary variable which takes a value of *1* if plant p is open, *0*, otherwise; $\forall\, p \in P$

The variable notations of two echelon forward SCND problem for model parameters are:

Di_{sp}	Distance between supplier s and potential plant p; $\forall\, s \in S$ and $p \in P$
Di_{pd}	Distance between potential plant p and distribution center d; $\forall\, p \in P$ and $d \in D$
Ca_s	Capacity of supplier s; $\forall\, s \in S$
Ca_p	Capacity of potential plant p; $\forall\, p \in P$
De_d	Demand of distribution center d; $\forall\, d \in D$
t	Unit shipping cost between facilities
FC_p	Fixed cost of opening plant p; $\forall\, p \in P$
$MaxP$	Maximum available number of plants to be opened

Variables of three echelon forward SCND problem for quantities are as follows (in addition to the previous model):

Z_{dr}	Amount shipped from distribution center d to retailer r; $\forall\, d \in D$ and $r \in R$
Γ_d	Binary variable which takes value of *1* if distribution center d is open. *0*, otherwise $\forall\, d \in D$

The variable notations of three echelon forward SCND problem for model parameters are (in addition to the previous model):

Di_{dr}	Distance between potential distribution center d and retailer r; $\forall\, d \in D$ and $r \in R$
Ca_d	Capacity of potential distribution center d; $\forall\, d \in D$
De_r	Demand of retailer r; $\forall\, r \in R$
FC_d	Fixed cost of opening distribution center d; $\forall\, d \in D$
$MaxD$	Maximum available number of distribution centers to be opened

Variables of four echelon forward SCND problem for quantities are as follows (in addition to the previous models):

W_{rc}	Amount shipped from retailer r to customer c; $\forall\, r \in R$ and $c \in C$
Ψ_r	Binary variable which takes value of *1* if retailer r is open. *0*, otherwise $\forall\, c \in C$

The variable notations of four echelon forward SCND problem for model parameters are (in addition to the previous models):

Di_{rc}	Distance between potential retailer r and customer c; $\forall\, r \in R$ and $c \in C$
Ca_r	Capacity of potential retailer r; $\forall\, r \in R$
De_c	Demand of customer c; $\forall\, c \in C$
FC_r	Fixed cost of opening retailer r; $\forall\, r \in R$
$MaxR$	Maximum available number of distribution centers to be opened.

Appendix B

Tables A.1-A.3 present all 450 forward SCND instances (150 two-echelon, 150 three-echelon and 150 four-echelon) with number of facilities.

Table A: 1. Generated two echelons FSCN design instances with number of facilities.

Test Problem	**S**	**P**	**D**	**Test Problem**	**S**	**P**	**D**	**Test Problem**	**S**	**P**	**D**	**Test Problem**	**S**	**P**	**D**
2Ech_1	4	2	4	2Ech_39	80	40	80	2Ech_77	156	78	156	2Ech_114	230	115	230
2Ech_2	6	3	6	2Ech_40	82	41	82	2Ech_78	158	79	158	2Ech_115	232	116	232
2Ech_3	8	4	8	2Ech_41	84	42	84	2Ech_79	160	80	160	2Ech_116	234	117	234
2Ech_4	10	5	10	2Ech_42	86	43	86	2Ech_80	162	81	162	2Ech_117	236	118	236
2Ech_5	12	6	12	2Ech_43	88	44	88	2Ech_81	164	82	164	2Ech_118	238	119	238
2Ech_6	14	7	14	2Ech_44	90	45	90	2Ech_82	166	83	166	2Ech_119	240	120	240
2Ech_7	16	8	16	2Ech_45	92	46	92	2Ech_83	168	84	168	2Ech_120	242	121	242
2Ech_8	18	9	18	2Ech_46	94	47	94	2Ech_84	170	85	170	2Ech_121	244	122	244

Table A: 1. Cont.

2Ech_9	20	10	20	2Ech_47	96	48	96	2Ech_85	172	86	172	2Ech_122	246	123	246
2Ech_10	22	11	22	2Ech_48	98	49	98	2Ech_86	174	87	174	2Ech_123	248	124	248
2Ech_11	24	12	24	2Ech_49	100	50	100	2Ech_87	176	88	176	2Ech_124	250	125	250
2Ech_12	26	13	26	2Ech_50	102	51	102	2Ech_88	178	89	178	2Ech_125	252	126	252
2Ech_13	28	14	28	2Ech_51	104	52	104	2Ech_89	180	90	180	2Ech_126	254	127	254
2Ech_14	30	15	30	2Ech_52	106	53	106	2Ech_90	182	91	182	2Ech_127	256	128	256
2Ech_15	32	16	32	2Ech_53	108	54	108	2Ech_91	184	92	184	2Ech_128	258	129	258
2Ech_16	34	17	34	2Ech_54	110	55	110	2Ech_92	186	93	186	2Ech_129	260	130	260
2Ech_17	36	18	36	2Ech_55	112	56	112	2Ech_93	188	94	188	2Ech_130	262	131	262
2Ech_18	38	19	38	2Ech_56	114	57	114	2Ech_94	190	95	190	2Ech_131	264	132	264
2Ech_19	40	20	40	2Ech_57	116	58	116	2Ech_95	192	96	192	2Ech_132	266	133	266
2Ech_20	42	21	42	2Ech_58	118	59	118	2Ech_96	194	97	194	2Ech_133	268	134	268
2Ech_21	44	22	44	2Ech_59	120	60	120	2Ech_97	196	98	196	2Ech_134	270	135	270
2Ech_22	46	23	46	2Ech_60	122	61	122	2Ech_98	198	99	198	2Ech_135	272	136	272
2Ech_23	48	24	48	2Ech_61	124	62	124	2Ech_99	200	100	200	2Ech_136	274	137	274
2Ech_24	50	25	50	2Ech_62	126	63	126	2Ech_100	202	101	202	2Ech_137	276	138	276
2Ech_25	52	26	52	2Ech_63	128	64	128	2Ech_101	204	102	204	2Ech_138	278	139	278
2Ech_26	54	27	54	2Ech_64	130	65	130	2Ech_102	206	103	206	2Ech_139	280	140	280
2Ech_27	56	28	56	2Ech_65	132	66	132	2Ech_103	208	104	208	2Ech_140	282	141	282
2Ech_28	58	29	58	2Ech_66	134	67	134	2Ech_104	210	105	210	2Ech_141	284	142	284
2Ech_29	60	30	60	2Ech_67	136	68	136	2Ech_105	212	106	212	2Ech_142	286	143	286
2Ech_30	62	31	62	2Ech_68	138	69	138	2Ech_106	214	107	214	2Ech_143	288	144	288
2Ech_31	64	32	64	2Ech_69	140	70	140	2Ech_107	216	108	216	2Ech_144	290	145	290
2Ech_32	66	33	66	2Ech_70	142	71	142	2Ech_108	218	109	218	2Ech_145	292	146	292
2Ech_33	68	34	68	2Ech_71	144	72	144	2Ech_109	220	110	220	2Ech_146	294	147	294
2Ech_34	70	35	70	2Ech_72	146	73	146	2Ech_110	222	111	222	2Ech_147	296	148	296
2Ech_35	72	36	72	2Ech_73	148	74	148	2Ech_111	224	112	224	2Ech_148	298	149	298
2Ech_36	74	37	74	2Ech_74	150	75	150	2Ech_112	226	113	226	2Ech_149	300	150	300
2Ech_37	76	38	76	2Ech_75	152	76	152	2Ech_113	228	114	228	2Ech_150	302	151	302
2Ech_38	78	39	78	2Ech_76	154	77	154								

Table A: 2. Generated three echelons FSCN design instances with number of facilities.

Test Problem	**S**	**P**	**D**	**R**	**Test Problem**	**S**	**P**	**D**	**R**	**Test Problem**	**S**	**P**	**D**	**R**
3Ech_1	4	2	2	4	3Ech_51	104	52	52	104	3Ech_101	204	102	102	204
3Ech_2	6	3	3	6	3Ech_52	106	53	53	106	3Ech_102	206	103	103	206
3Ech_3	8	4	4	8	3Ech_53	108	54	54	108	3Ech_103	208	104	104	208
3Ech_4	10	5	5	10	3Ech_54	110	55	55	110	3Ech_104	210	105	105	210
3Ech_5	12	6	6	12	3Ech_55	112	56	56	112	3Ech_105	212	106	106	212
3Ech_6	14	7	7	14	3Ech_56	114	57	57	114	3Ech_106	214	107	107	214
3Ech_7	16	8	8	16	3Ech_57	116	58	58	116	3Ech_107	216	108	108	216
3Ech_8	18	9	9	18	3Ech_58	118	59	59	118	3Ech_108	218	109	109	218
3Ech_9	20	10	10	20	3Ech_59	120	60	60	120	3Ech_109	220	110	110	220
3Ech_10	22	11	11	22	3Ech_60	122	61	61	122	3Ech_110	222	111	111	222
3Ech_11	24	12	12	24	3Ech_61	124	62	62	124	3Ech_111	224	112	112	224
3Ech_12	26	13	13	26	3Ech_62	126	63	63	126	3Ech_112	226	113	113	226
3Ech_13	28	14	14	28	3Ech_63	128	64	64	128	3Ech_113	228	114	114	228
3Ech_14	30	15	15	30	3Ech_64	130	65	65	130	3Ech_114	230	115	115	230
3Ech_15	32	16	16	32	3Ech_65	132	66	66	132	3Ech_115	232	116	116	232
3Ech_16	34	17	17	34	3Ech_66	134	67	67	134	3Ech_116	234	117	117	234
3Ech_17	36	18	18	36	3Ech_67	136	68	68	136	3Ech_117	236	118	118	236
3Ech_18	38	19	19	38	3Ech_68	138	69	69	138	3Ech_118	238	119	119	238
3Ech_19	40	20	20	40	3Ech_69	140	70	70	140	3Ech_119	240	120	120	240
3Ech_20	42	21	21	42	3Ech_70	142	71	71	142	3Ech_120	242	121	121	242
3Ech_21	44	22	22	44	3Ech_71	144	72	72	144	3Ech_121	244	122	122	244
3Ech_22	46	23	23	46	3Ech_72	146	73	73	146	3Ech_122	246	123	123	246

Table A: 2. Cont.

3Ech_23	48	24	24	48	3Ech_73	148	74	74	148	3Ech_123	248	124	124	248
3Ech_24	50	25	25	50	3Ech_74	150	75	75	150	3Ech_124	250	125	125	250
3Ech_25	52	26	26	52	3Ech_75	152	76	76	152	3Ech_125	252	126	126	252
3Ech_26	54	27	27	54	3Ech_76	154	77	77	154	3Ech_126	254	127	127	254
3Ech_27	56	28	28	56	3Ech_77	156	78	78	156	3Ech_127	256	128	128	256
3Ech_28	58	29	29	58	3Ech_78	158	79	79	158	3Ech_128	258	129	129	258
3Ech_29	60	30	30	60	3Ech_79	160	80	80	160	3Ech_129	260	130	130	260
3Ech_30	62	31	31	62	3Ech_80	162	81	81	162	3Ech_130	262	131	131	262
3Ech_31	64	32	32	64	3Ech_81	164	82	82	164	3Ech_131	264	132	132	264
3Ech_32	66	33	33	66	3Ech_82	166	83	83	166	3Ech_132	266	133	133	266
3Ech_33	68	34	34	68	3Ech_83	168	84	84	168	3Ech_133	268	134	134	268
3Ech_34	70	35	35	70	3Ech_84	170	85	85	170	3Ech_134	270	135	135	270
3Ech_35	72	36	36	72	3Ech_85	172	86	86	172	3Ech_135	272	136	136	272
3Ech_36	74	37	37	74	3Ech_86	174	87	87	174	3Ech_136	274	137	137	274
3Ech_37	76	38	38	76	3Ech_87	176	88	88	176	3Ech_137	276	138	138	276
3Ech_38	78	39	39	78	3Ech_88	178	89	89	178	3Ech_138	278	139	139	278
3Ech_39	80	40	40	80	3Ech_89	180	90	90	180	3Ech_139	280	140	140	280
3Ech_40	82	41	41	82	3Ech_90	182	91	91	182	3Ech_140	282	141	141	282
3Ech_41	84	42	42	84	3Ech_91	184	92	92	184	3Ech_141	284	142	142	284
3Ech_42	86	43	43	86	3Ech_92	186	93	93	186	3Ech_142	286	143	143	286
3Ech_43	88	44	44	88	3Ech_93	188	94	94	188	3Ech_143	288	144	144	288
3Ech_44	90	45	45	90	3Ech_94	190	95	95	190	3Ech_144	290	145	145	290
3Ech_45	92	46	46	92	3Ech_95	192	96	96	192	3Ech_145	292	146	146	292
3Ech_46	94	47	47	94	3Ech_96	194	97	97	194	3Ech_146	294	147	147	294
3Ech_47	96	48	48	96	3Ech_97	196	98	98	196	3Ech_147	296	148	148	296
3Ech_48	98	49	49	98	3Ech_98	198	99	99	198	3Ech_148	298	149	149	298
3Ech_49	100	50	50	100	3Ech_99	200	100	100	200	3Ech_149	300	150	150	300
3Ech_50	102	51	51	102	3Ech_100	202	101	101	202	3Ech_150	302	151	151	302

Table A: 3. Generated four echelons FSCN design instances with number of facilities.

Test Problem	S	P	D	R	C	Test Problem	S	P	D	R	C	Test Problem	S	P	D	R	C
4Ech_1	4	2	2	2	4	4Ech_51	104	52	52	52	104	4Ech_101	204	102	102	102	204
4Ech_2	6	3	3	3	6	4Ech_52	106	53	53	53	106	4Ech_102	206	103	103	103	206
4Ech_3	8	4	4	4	8	4Ech_53	108	54	54	54	108	4Ech_103	208	104	104	104	208
4Ech_4	10	5	5	5	10	4Ech_54	110	55	55	55	110	4Ech_104	210	105	105	105	210
4Ech_5	12	6	6	6	12	4Ech_55	112	56	56	56	112	4Ech_105	212	106	106	106	212
4Ech_6	14	7	7	7	14	4Ech_56	114	57	57	57	114	4Ech_106	214	107	107	107	214
4Ech_7	16	8	8	8	16	4Ech_57	116	58	58	58	116	4Ech_107	216	108	108	108	216
4Ech_8	18	9	9	9	18	4Ech_58	118	59	59	59	118	4Ech_108	218	109	109	109	218
4Ech_9	20	10	10	10	20	4Ech_59	120	60	60	60	120	4Ech_109	220	110	110	110	220
4Ech_10	22	11	11	11	22	4Ech_60	122	61	61	61	122	4Ech_110	222	111	111	111	222
4Ech_11	24	12	12	12	24	4Ech_61	124	62	62	62	124	4Ech_111	224	112	112	112	224
4Ech_12	26	13	13	13	26	4Ech_62	126	63	63	63	126	4Ech_112	226	113	113	113	226
4Ech_13	28	14	14	14	28	4Ech_63	128	64	64	64	128	4Ech_113	228	114	114	114	228
4Ech_14	30	15	15	15	30	4Ech_64	130	65	65	65	130	4Ech_114	230	115	115	115	230
4Ech_15	32	16	16	16	32	4Ech_65	132	66	66	66	132	4Ech_115	232	116	116	116	232
4Ech_16	34	17	17	17	34	4Ech_66	134	67	67	67	134	4Ech_116	234	117	117	117	234
4Ech_17	36	18	18	18	36	4Ech_67	136	68	68	68	136	4Ech_117	236	118	118	118	236
4Ech_18	38	19	19	19	38	4Ech_68	138	69	69	69	138	4Ech_118	238	119	119	119	238
4Ech_19	40	20	20	20	40	4Ech_69	140	70	70	70	140	4Ech_119	240	120	120	120	240
4Ech_20	42	21	21	21	42	4Ech_70	142	71	71	71	142	4Ech_120	242	121	121	121	242
4Ech_21	44	22	22	22	44	4Ech_71	144	72	72	72	144	4Ech_121	244	122	122	122	244
4Ech_22	46	23	23	23	46	4Ech_72	146	73	73	73	146	4Ech_122	246	123	123	123	246
4Ech_23	48	24	24	24	48	4Ech_73	148	74	74	74	148	4Ech_123	248	124	124	124	248

Table A: 3. Cont.

4Ech_24	50	25	25	25	50	4Ech_74	150	75	75	75	150	4Ech_124	250	125	125	125	250
4Ech_25	52	26	26	26	52	4Ech_75	152	76	76	76	152	4Ech_125	252	126	126	126	252
4Ech_26	54	27	27	27	54	4Ech_76	154	77	77	77	154	4Ech_126	254	127	127	127	254
4Ech_27	56	28	28	28	56	4Ech_77	156	78	78	78	156	4Ech_127	256	128	128	128	256
4Ech_28	58	29	29	29	58	4Ech_78	158	79	79	79	158	4Ech_128	258	129	129	129	258
4Ech_29	60	30	30	30	60	4Ech_79	160	80	80	80	160	4Ech_129	260	130	130	130	260
4Ech_30	62	31	31	31	62	4Ech_80	162	81	81	81	162	4Ech_130	262	131	131	131	262
4Ech_31	64	32	32	32	64	4Ech_81	164	82	82	82	164	4Ech_131	264	132	132	132	264
4Ech_32	66	33	33	33	66	4Ech_82	166	83	83	83	166	4Ech_132	266	133	133	133	266
4Ech_33	68	34	34	34	68	4Ech_83	168	84	84	84	168	4Ech_133	268	134	134	134	268
4Ech_34	70	35	35	35	70	4Ech_84	170	85	85	85	170	4Ech_134	270	135	135	135	270
4Ech_35	72	36	36	36	72	4Ech_85	172	86	86	86	172	4Ech_135	272	136	136	136	272
4Ech_36	74	37	37	37	74	4Ech_86	174	87	87	87	174	4Ech_136	274	137	137	137	274
4Ech_37	76	38	38	38	76	4Ech_87	176	88	88	88	176	4Ech_137	276	138	138	138	276
4Ech_38	78	39	39	39	78	4Ech_88	178	89	89	89	178	4Ech_138	278	139	139	139	278
4Ech_39	80	40	40	40	80	4Ech_89	180	90	90	90	180	4Ech_139	280	140	140	140	280
4Ech_40	82	41	41	41	82	4Ech_90	182	91	91	91	182	4Ech_140	282	141	141	141	282
4Ech_41	84	42	42	42	84	4Ech_91	184	92	92	92	184	4Ech_141	284	142	142	142	284
4Ech_42	86	43	43	43	86	4Ech_92	186	93	93	93	186	4Ech_142	286	143	143	143	286
4Ech_43	88	44	44	44	88	4Ech_93	188	94	94	94	188	4Ech_143	288	144	144	144	288
4Ech_44	90	45	45	45	90	4Ech_94	190	95	95	95	190	4Ech_144	290	145	145	145	290
4Ech_45	92	46	46	46	92	4Ech_95	192	96	96	96	192	4Ech_145	292	146	146	146	292
4Ech_46	94	47	47	47	94	4Ech_96	194	97	97	97	194	4Ech_146	294	147	147	147	294
4Ech_47	96	48	48	48	96	4Ech_97	196	98	98	98	196	4Ech_147	296	148	148	148	296
4Ech_48	98	49	49	49	98	4Ech_98	198	99	99	99	198	4Ech_148	298	149	149	149	298
4Ech_49	100	50	50	50	100	4Ech_99	200	100	100	100	200	4Ech_149	300	150	150	150	300
4Ech_50	102	51	51	51	102	4Ech_100	202	101	101	101	202	4Ech_150	302	151	151	151	302