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A Robust Competitive Global Supply Chain Network Design under Disruption: The Case of Medical Device Industry

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ABSTRACT

In this paper, a comprehensive model is proposed to design a Global Supply Chain (GSC) for a medical device manufacturer under disruption in the presence of pre-existing competitors and price inelasticity of product demand. Therefore, a static competition between the distributors' facilities to more efficiently gain a further market share under an Economic Cooperation Organization Trade Agreement (ECOTA) is considered. This competition condition is affected by disruption occurrence. The aim of the proposed model is to maximize the expected net after-tax profit of GSC under disruption and normal situation at the same time. To effectively deal with disruption, some restorative strategies are adopted in the design of GSC network. In addition, an uncertainty of the business environment is modeled using a robust optimization technique based on a concept of uncertainty budget. To tackle the proposed Mixed-Integer Nonlinear Programming (MINLP) model, a hybrid Taguchi-based Memetic Algorithm (MA) with an adaptive population size is developed that incorporates a customized Adaptive Large Neighborhood Search (ALNS) as its local search heuristic. A fitness landscape analysis is used to improve the systematic procedure of neighborhood selection in the proposed ALNS. A computational results illustrate the efficiency of the proposed model and solution algorithm in dealing with global disruptions under uncertainty and competition pressure.

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1. Introduction

As a competitive globalization continues to affect the business environment, Global Supply Chain Management (GSCM) is becoming an important issue for many corporations [1, 2]. The greater and more intense global competitions are leading to substantial shifts in what is expected of the Supply Chain (SC) functions. Today's business leaders are demanding more from their supply chains, including competitive

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advantage such as provide the desired level of service even in abnormal conditions [3]. Competitive advantages of a corporation in the global market are affected by more risks. During the past decade, uncomfortable disasters with dramatic costs which affect global business environment are frequently observed [4]. In addition to competition and disruption, environmental uncertainty is another challenge for GSC management. Additional agility and responsiveness are desired to satisfy customers' expectations along with the global expansion of supply chains borders in constantly changing and unpredictable business environment [5, 6]. Consequently, careful design of a GSC network, while considering the complexities of the real world such a competition condition, disruption and uncertainty has an important effect on the SC performance [7]. During the past two decades, international companies have been trying to enter new emerging global markets by means of expanding boundaries of their supply chains beyond their home countries' borders [1]. This global expansion allows exploiting various opportunities such as access to low-cost natural and human resources and financial incentives offered by other countries. However, relatively few studies in the SC management literature have dealt with GSCND [8, 9]. Various parameters as well as decision variables such as exchange rates, tax rates and export tariff, state regulations, international trade agreements, and transfer pricing should be considered in the GSCND models [8, 10-13].

As a result of globalization, competition is no longer between companies, but between supply chains [14]. Due to facing with high volatile in a global business environment, considering the impact of competition on GSC is more sophisticated. Many environmental factors such as uncertainty and disruption could impact on the condition of the GSC competition. There are three kinds of competition in context of competitive facility location including static, foresight, and dynamic. The static model represents a competition between new entrant of market and other pre-existing competitors with pre-known and fixed characteristics [15, 16]. The foresight model considers foresight of competition such as entrance of competitors into the market in the future. Finally, future changes in competitive characteristics of existing facilities are considered in dynamic models [3]. Rezapour et al., [15] proposed a deterministic model of Supply Chain Network Design (SCND) via considering the static competition. The interested reader is referred to Farahani et al., [3] for a more comprehensive review of competitive location and SC models. However, all of the previous studies of a GSCND model completely disregard the competitive environment.

Globalizing a SC and delocalizing its facilities around the world has made a SC more vulnerable against disruptions [17]. Park et al., [17] highlighted the role of a carefully designed GSC network as a mechanism to overcome undesirable SC disruptions based on the lessons from the catastrophic natural disasters that occurred in Japan. Despite the importance of this role, this issue has not been noted enough in GSC management literature. However, in recent years, different perspective of SCND under disruption has been investigated by researchers [18, 19]. Bunschuh et al., [20] applied multiple sourcing strategy to increase the SC performance under supplier capacity disruption. Tang [4] proposed a set of robust managerial strategies such as keeping an additional inventory as well as demand postponement to deal with disruption and satisfy customers' demand effectively. Chen et al., [21] proposed an inventory-location SC design model under disruption with site-dependent probabilities. In another study, Costantino et al. [1] presented a MILP model for designing an agile SC by considering multi-source supply for dealing with disruption. Li et al. [22] proposed the facility fortification strategy under budget constraint to improve reliability of distribution networks. Fang et al., [23] examined the performance of a wide variety of sourcing strategies for a manufacturer under supplier disruptions. Finally, Jabarzadeh et al., [24] proposed a comprehensive robust network design model for the supply of blood during and after disasters for real case study. Dealing with various uncertainties associated with internal and external sources is another key challenge of GSC managers [2]. The uncertainty of the parameters affecting the global supply chains should be considered while developing GSC design models [25]. Despite the importance of uncertainty's role, this issue has not been noted enough in the GSC management literature [26]. Goh et al., [2] handled various risks including demand, supply, exchange rate in a GSC via using a stochastic programming technique.

As mentioned before, competition, disruption, and uncertainty are key factors that have an important effect on performance of GSC in the real world. However, to the best of our knowledge, there is no study on competitive GSCND under disruption and highly volatile uncertainty. The results of studying the literature confirm the lack of models that incorporate all the mentioned issues for the GSCND problem at the same time, although highlighted by many recent papers as relevant important issues in global business environments.

In this study, a new comprehensive mathematical model for designing a robust competitive GSC network under uncertainty and disruption is presented. Several realistic assumptions are considered according to a case study performed on a medical device manufacturer in Iran under the ECOTA. This study differs from previous studies on GSCND in considering competition condition, disruption impact on competition condition, and applying multiple practical strategies at the same time to deal with disruption. In addition, to tackle the proposed mathematical model, a hybrid Taguchi-based MA is proposed that incorporate customized ALNS as its local search mechanism with new destroy and repair Neighborhood Structures (NS). A fitness landscape analysis is considered in the proposed ALNS to improve the systematic procedure of NS selection. A comprehensive set of computational experiments is performed to solve the proposed model for real-world instances and derive the managerial implications.

The remainder of this paper is structured as follows. In Section 2, the problem definition of the case studied in this paper is introduced. In Section 3, the proposed mathematical model for designing a robust competitive GSC is presented. In Section 4, a hybrid meta-heuristic method based on the MA and ALNS is introduced to tackle the proposed model. In section 5, computational experiments and results are presented. Finally, the paper is concluded in Section 6 and some of the future research directions are highlighted.

2. Problem Definition: The Case of Medical Device Industry

The aim of this study is to design an efficient network configuration for a competitive GSC under disruption and uncertainty. This network belongs to a medical device manufacturer in Iran, namely MDX Company for confidentiality reasons. The considered products in this study are used for diabetics. As the considered GSC encompasses three countries of Iran, Turkey, and Azerbaijan, it should observe the characteristics and regulations imposed by ECOTA (e.g., exchange rate, profit taxation, import duty rate, and transfer price limitation). In this business environment, pre-existing distributor facilities of competitors with known locations and level of attractiveness compete for increasing their market share and profit. The utility of each distributor is a function of customer access cost and available capacity to satisfy customer demand. The customer access cost is dependent on the total shipment cost from a demand point to distributor. According to the product and market characteristics, facility capacity is considered as a major factor which has the most important impact on the attractiveness of each distributor. Based on the conducted a wide variety of market research, the demands for medical care, medical device, and medicine is consistently found to be price inelastic [27]. In addition, characteristics of competition between new entrant of market and other pre-existing competitors are pre-known and fixed. Therefore, static competition between distributors of MDX supply chain and the other pre-existing competitor is considered in this study. MDX Company faces with various strategic decisions for designing the GSC network, including supplier selection, manufacturing sites establishment, selection of distributors sites, as well as SC facilities reinforcement. In addition, several decisions regarding component procurement, production of semi-manufactured and final products, selection of BOM type, product shipment, and transfer pricing have to be made. Finally, the aim of the proposed model is to maximize the expected net after-tax profit of the MDX Company.

The aforementioned decisions should be taken in a highly volatile business environment. In particular, disruption occurrence is one of the major threats to GSC performance. There are various risk regions within the borders of MDX supply chain. The level of risk in each region depends on various causes such as possibility of natural disaster (e.g., earthquake) occurrences. For instance, Tehran is at greater risk of earthquake occurrence than Isfahan based on the seismic map of Iran. According to the nature of the considered disruption, the occurrence and effect of disruption are defined by specific scenarios with predetermined probability of occurrence. Disruption occurrence has a significant impact on the capacity of each facility in all the tiers of the SC. Due to the direct relationship between the attractiveness of distributor facility and its capacity, effect of disruption occurrence in the upper tiers of the SC could be observed in the considered condition of competition among distributors. Therefore, the effect of GSC disruption on competition condition and SC decisions are considered in order to enhance competitive advantage and maintain captured market share even in an abnormal condition. Six practical strategies based on the experts' opinions of MDX Company as well as the other best practices in SC management are considered to design a competitive GSC under disruption. These strategies are including facility dispersion, facility reinforcement, production of semi-manufactured products, multiple sourcing, keeping an inventory, and considering primary and alternative BOM. In addition, uncertainties of the product demand as well as component purchasing cost are considered based on the real-world characteristics. Due to the lack of sufficient and reliable historical data, a robust optimization technique based on the concept of uncertainty budget is adopted to handle the uncertainty of parameters [5, 28]. Hence, the number of uncertain parameters deviating from their nominal values is bounded by a predetermined number, namely the uncertainty budget. This number represents the decision maker's degree of conservativeness. The smaller and larger values represent a limited effect of uncertainty (i.e., a risk-neutral model) and a more significant effect (i.e., a conservative model), respectively. Number of considered potential suppliers in Iran, Turkey, and Azerbaijan are 10, 6, and 4, respectively. Number of considered potential manufacturer in Iran, Turkey, and Azerbaijan are 8, 2, and 2, respectively. Number of considered potential warehouse in Iran, Turkey, and Azerbaijan are 18, 12, and 8, respectively.

3. Mathematical Model

In this section, a robust MINLP model for designing a GSC network under competition and disruption is presented.

3.1- Notation

- **Indices**
  - *N and T*: Sets of disruption scenarios and planning periods, respectively,
  - *C* and *S*: Set of distributors facilities controlled by competitors and MDX company, respectively,
  - *V* and *E:* Sets of final products and parts of products, respectively,
  - *O* and *R*: Sets of discrete demand point of customers and risk regions, respectively,

- *M* and *K:* Sets of manufacturer and supplier facilities, respectively, and
- *ZA*: Set of attractiveness attributes.

o **Parameters**

- $Prob_n$: Probability of scenario *n* occurrences,
- W_{ovt} and $W1_{ovt}$: Nominal shift value of demand weight of demand point *o* for product *v* in period *t*,
- D_{io}: Distance between distributor *i* and demand point *o,*
- α_i :Basic attractiveness level of distributor *i*,
- FM_{mt}, RFM_{mt}, and CFM_{mt}: Fixed cost of establishing, reinforcing, and keeping established manufacturer *m* for two consecutive periods, respectively,
- Bud_t: Total available budget for reinforcement in period *t*,
- FW_{it}, RFW_{it}, and CFW_{it}: Fixed cost of establishing, reinforcing, and keeping established distributor *i* for two consecutive periods, respectively,
- λ_v , β , and θ_z : The positive parameters of product *v* elasticity, distance sensitivity, and utility function sensitivity to attribute *z* (i.e., $\theta_z \le 1$), respectively,
- FS_{kt}, RFS_{kt}, and CFS_{kt}: Fixed cost of selecting, reinforcing, and resuming cooperation with supplier *k* for two consecutive periods, respectively,
- *M* and *r*: Sufficiently large positive number and interest rate, respectively,
- DOS_{nrt}: Disruption occurrence indicator in region *r* under scenario *n* in period *t*, (i.e., 1 indicated disruption occurs; 0 otherwise),
- $T1_{ke}$, $T2_{mv}$, $T3_{mv}$, and Vs_c: Occupied capacities of supplier *k* for supplying part *e*, of manufacturer *m* for producing final product *v* and completing semi-manufactured product *v*, and amount of space occupied by product *v*, respectively,
- μ_{ovnt} : Level of customer demand satisfaction at point *o* for product *v* in period *t*,
- *Snum*: Minimum number of supply sources,
- COP_{kevt} and $COPs_{kevt}$: Procurement cost and its shift value for a unit of component *e* of product *v* from supplier *k* in period *t*, respectively,
- UAS_{ek} : Upper bound on the amount of part *e* could be supplied by supplier *k*,
- $UTPSM_{kment}$ and $LTPSM_{kment}$: Upper and lower bound on the transfer price of part *e* transferred between supplier *k* and manufacture *m*, respectively,
- $UTPMW_{mivnt}$ and $LTPMW_{mivnt}$: Upper and lower bound on the transfer price of product *v* transferred between manufacture *m* and distributer *i*, respectively,
- $EXRS_k$, $EXRM_m$ and $EXRW_i$: Exchange rates for converting different currencies of suppliers, manufacturers, and distributors to the unique currency, respectively,
- $PATS_k$, $PATM_m$ *and* $PATW_i$: Profit tax rate of suppliers, manufacturers and distributors, respectively,
- HCO_{vit}: Cost of holding a unit of product *v* in facility of distributor *i* in period *t*,
- $SHPC1_{kmet}$, $SHPC2_{mivt}$, and $SHPC3_{iovt}$: Transportation costs of part *e* from supplier *k* to manufacturer *m*, product *v* from manufacturer *m* to warehouse *i,* and product *v* from distributor *i* to market *o* in period *t*, respectively,
- $Prdc_{vmt}$: Cost of producing a unit of product *v* by manufacturer *m* in period *t*,
- $Pcsc_{vot}$ and Shc_{vot}: Selling price and cost of not satisfying demand of product *v* at demand point *o* in period *t*, respectively,
- $CBud1_{kt}$, $CBud2_{kt}$, and $CBud3_{kt}$: Budgets of uncertainty of procurement cost of part,
- $DBud4_{ivt}$: Budgets of uncertainty of demand of final product,
- Con_{ve}: Consumption ratio of part *e* for manufacturing product *v*,
- $Tcapm_{mt}$ and $Rcapm_{mt}$: Total and reinforced production capacity of manufacturer *m* in period *t*, respectively,
- $Tcaprm_{mt}$ and $Rcaprm_{mt}$: Total and reinforced capacity of production semi-manufactured products of manufacturer *m* in period *t*, respectively,

- $Tcapw_{it}$ and $Rcapw_i$: Total and reinforced storage capacity of warehouse i in period t, respectively,
- $Tcaps_{kt}$ and $Rcaps_k$: Total and reinforced supply capacity of supplier k in period t, respectively,
- Trf_{kmet} and Trm_{mivt}: Import tariff rate of part e from supplier k to manufacturer m and product v from manufacturer m to distributor i in period t; respectively,
- Fn_{rt}, An_{rt}, *and* Wn_{rt}: Maximum number of selected supplier, established manufacturer and distributors in each risk region r in period t, respectively,
- $Dcapw_{int}$: Disrupted storage capacity of distributor i under scenario n in period t,
- $Dcaps_{kn}$: Disrupted supply capacity of supplier k under scenario n in period t, and
- $Dcaprm_{mn}$ and $Dcapm_{mn}$: Disrupted storage capacity of manufacturing semi-manufactured and final products of manufacturer m under scenario n in period t, respectively.

- **Variables**

- U_{oivnt} and MS_{oivnt}: Utility of providing product v and captured market share of demand of product v by distributor i under scenario n for demand point o in period t, respectively,
- TMS_{ovnt} and TU_{ovnt}: Total market share of product v and total utility of providing product v at market point o which is captured by MDX Company under scenario n in period t, respectively,
- At_{ivnt}: Attractiveness of distributor i for delivering product v under scenario n in period t (i.e., $A_{ivnt} > 0$),
- $g\ (TU_{ovnt})$: General demand function,
- $FU_{ovnt}(S)$ and $FU_{ovnt}(C)$: Total utility of the demand point o to supplied with product v via facilities which are controlled by MDX company and competitors under scenario n in period t, respectively,
- EF_{krt} and ERF_{krt}: 1 if supplier k in region r is selected and reinforced in period t, respectively; 0 otherwise,
- EW_{irt} and ERW_{irt}: 1 if distributor i in region r is established and reinforced in period t, respectively; 0 otherwise,
- EA_{mrt} and ERA_{mrt}: 1 if manufacturer m in region r is established and reinforced in period t, respectively; 0 otherwise,
- C_{iovtn}: Amount of product v transferred from distributor i to demand point o under scenario n in period t,
- CZ_{mivnt} and CRZ_{mivtn}: Amount of final product v transferred from manufacturer m to distributor i under scenario n in period t, respectively,
- Cfx_{km1vtn} and Cix_{kmevtn}: Quantity of component 1 and e of product v transferred from supplier k to manufacturer m in period t under scenario n, respectively,
- Csx_{kmevtn}: Quantity of component e of product v transferred from supplier k to manufacturer m to complete the semi-manufactured product v in period t under scenario n,
- CY_{mvtn}, $CSRM_{mvtn}$, and CIZ_{mvtn}, : Quantity of final and semi-manufactured product v, as well as amount of shortage of part 1 to manufacture product v via manufacturer m in period t under scenario n, respectively,
- $Cfxro_{kmvent}$, $Cpro_{kmvt}$, and $Czro_{it}$: First, second and third supplementary variables for creating the robust counterpart of purchasing cost uncertainty, respectively,
- Y_{iznt}: Level of improvement over the basic design of warehouse i with respect to the zth design attributes in period t for product v,
- ZS_{ket}: 1 if supplier k is selected for supplying part e in period t; 0 otherwise,
- CLW_{ovnt}: Amount of demand of product v at demand point o which is not satisfied under scenario n in period t,
- $DO1_{vnt}$: 1 if demand of product v is not satisfied under scenario n in period t; 0 otherwise,
- $TPSM_{kment}$: Transfer price of part e that is shipped between supplier k and manufacture m in period t under scenario n,
- $TPMW_{mivnt}$: Transfer price of product v that is shipped between manufacture m and distributor i in period t under scenario n,
- Inv_{ivnt}: Inventory of product v in distributor i at the end of the period t under scenario n,

- $CPW1_{ovt}$, $CPW2_{ovt}$, and $CPW3_{ovt}$: First supplementary variables for creating the robust counterpart of demand product uncertainty, and
- $CZW1_{ovt}$, $CZW2_{ovt}$, and $CZW3_{ovt}$: Second supplementary variables for creating the robust counterpart of demand product uncertainty.

3.2- Mathematical Model Formulation

This will be particularly necessary in SCND models to adequately measure the cost/benefit trade-offs in the design choice, especially in a GSC context. Therefore, in this study, maximize the expected net after-tax profit is considered as a single objective function of the proposed model under static competition [29, 30]. The first to third terms of the objective function (1) denote the NPV of the after-tax profit share in for the supplier, manufacturer, and distributor tiers under scenario n in period t, respectively.

Constraints (2), (3) and (4) calculate the total after-tax profit of each supplier, manufacturer, and distributor tiers for each planning period, respectively. Constraint (5) calculates the utility of the demand point o for distributor i. The market share of each customer which is captured by distributor i is calculated by constraint (6). Constraint (7) computes total captured market share of market o via MDX Company. Constraint (8) indicates the exponential form of the demand function that is used in this study following of [16]. Constraint (9) calculates the attractiveness A_{tivnt} of a distributor i. Constraint (10) indicates that Y_{ivzt} is a function of total available capacity of distributor i which is affected by the disruption occurrence in all of the upper tiers of the GSC. Constraints (11-16) are added as part of the robust counterpart of the constraint (3) due to interval uncertainty of the purchasing cost of parts. Constraint (17) shows the reinforcement budget limitation of GSC in each period. Constraints (18-20) show supplying capacity of each supplier in each period via considering the effects of disruption occurrence and reinforcement strategy. Constraints (21-23) ensure supplying each raw material from multiple sources. This strategy depends on the company policies of the strategic supplier relationship management. Constraint (24) ensures consumption ratio of components for each product is satisfied according to the product BOM. Constraints (25-27) show production capacity of each manufacturer in each period via considering the effects of disruption occurrence and reinforcement strategy. Constraints (28-30) show storage capacity of each distributor in each period via considering the effects of disruption occurrence and reinforcement strategy. Constraints (31-33) ensure that the facilities of GSC are dispersed within the different risk regions to reduce their vulnerability against disruption via decentralizing SC. Constraints (34-35) ensure that required components are shipped to each established manufacturer based on the allocated demand. Constraints (36-37) calculate the amount of semi-manufactured products that are manufactured in each period due to a shortage of a specific part (i.e., part *1*). Constraint (38) ensures that the amount of semi-manufactured products in each period is less than the manufacturer storage capacity. Quantities of final products produced via completing the semi-manufactured products after receiving component *1* are calculated by constraints (39-41). Constraint (42) calculates quantities of remaining products in a distributor i after satisfying wholesalers' demand. Constraint (43) ensures that amount of products sent from all manufacturers to all distributors in each period is less than or equal to the total amount of incoming products from all manufacturers in that period and the remaining products from the previous period. Constraints (44, 45, and 50) ensure the desired level of demand satisfaction of each demand point. This level changes during the disruption (see constraint 50). A lost sale is considered during a shortage of required products. The uncertainty of the weight of demand point is handled via a robust optimization method. Constraints (46-49) and (51-53) are added as part of the robust counterpart of the constraint (44-45) and (50) due to interval uncertainty of the demand weight, respectively. Constraints (54-55) enforce that transfer price of products shipped between different facilities of GSC tiers should observe its lower and upper limits, which are defined based on the ECOTA and each country's regulations. It should be noted that nonlinear constraints of the proposed GSCND model is reformulated to linearize constraints as much as possible. However, some constraints could not be linearized including 2-4, 9, 10, 44, 45, and 50.

$$\text{Maximize}\ \sum_{t,n} Prob_n \times \frac{1}{(1+r)^{t-1}} \times \left(\begin{aligned} &\sum_k EXRS_{kt} \times \left((1-PATS_{kt}) \times \pi 1^{+}_{ktn} - \pi 1^{-}_{ktn} \right) \\ &+\sum_m EXRM_{mt} \times \left((1-PATM_{mt}) \times \pi 2^{+}_{mtn} - \pi 2^{-}_{mtn} \right) \\ &+\sum_i EXRW_{it} \times \left((1-PATW_{it}) \times \pi 3^{+}_{itn} - \pi 3^{-}_{itn} \right) \end{aligned} \right) \tag{1}$$

$$\begin{aligned} \pi 1^{+}_{ktn} - \pi 1^{-}_{ktn} = &\sum_{m,v} TPSM_{kment} \times \left(Cfx_{kmv11n} + \left(Csx_{ikmv11n} \right)\Big|_{t\neq 1} \right) + \sum_{m,v,e\in(E\cup E'-\{1\})} TPSM_{kment} \times Cix_{kmv11n} \\ &-\sum_{m,v} \left(SHPC1_{kmet} + COP_{kevt} \right) \times \left(Cfx_{kmv11n} + \left(Csx_{ikmv11n} \right)\Big|_{t\neq 1} \right) - \sum_{m,v} Cfpro_{kmv11n} \times CBud1_{k1} \\ &-\sum_r FS_{kt} \times \max\left(EF_{krt} - EF_{kr,t-1}\Big|_{t\geq 2}, 0 \right) - \sum_{m,v,e\in(E\cup E'-\{1\})} \left(SHPC1_{kmet} + COP_{kevt} \right) \times \left(Csx_{ikmv11n} \right)\Big|_{t\neq 1} \\ &-\left(\sum_{m,v} Cizro_{k1n} - \sum_{m,v,e} Cipro_{kmve1n} \times CBud2_{k1} \right)\Bigg|_{e\neq 1} - \sum_r RFS_{kt} \times ERF_{krt} - CFS_k \times SF_{k,r,t-1} \times SF_{krt}\Big|_{t\geq 2} \\ &-\left(\sum_{m,v} Cszro_{k1n} - \sum_{m,v,e} Cspro_{kmve1n} \times CBud3_{k1} \right)\Bigg|_{e\neq 1} - \sum_{m,v} Cfzro_{k1n} \forall k,t,n \end{aligned} \tag{2}$$

$$\begin{aligned} \pi^{+}_{mtn} - \pi^{-}_{mtn} = &\sum_{i,v} TPMW_{mivnt} \times \left(CZ_{mivnt} + CRZ_{mivnt} \right) - \sum_{k,e} \left(1+Trf_{kmet} \right) \times TPSM_{kment} \times Cix_{kmevtn} \\ &-\sum_k \left(1+Trf_{kmet} \right) \times TPSM_{kment} \times Cfx_{km1vtn} - \sum_{i,v} SHPC2_{miv} \times \left(CZ_{mivnt} + CRZ_{mivnt} \right) \\ &+\sum_v Prdc_{vmt} \times \left(CY_{mvtn} + CSRM_{mvtn} \right) - \sum_r FW_{mt} \times \max\left(EA_{mrt} - \left(EA_{mr,t-1}\Big|_{t\geq 2} \right), 0 \right) \\ &-CFM_{mt} \times \left(EA_{m,r,t-1} \times EA_{mrt} \right)\Big|_{t\geq 2} - \sum_r RFM_{mt} \times ERA_{mt} \\ &-\sum_{k,e} \left(1+Trf_{kmet} \right) \times TPSM_{kment} \times Csx_{kmevtn} \quad \forall m,t,n \end{aligned} \tag{3}$$

$$\begin{aligned} \pi^{+}_{itn} - \pi^{-}_{itn} = &\sum_{o,v} P\,\mathrm{csc}_{vot} \times C_{iovnt} - \sum_v HCO_{vit} \times Inv_{ivnt} - \sum_{o,v} SHPC3_{iovt} \times C_{iovnt} \\ &-\sum_{o,v} SHC_{vot} \times LW_{ovnt} - \sum_r RFW_{it} \times ERW_{irt} \\ &-\sum_{m,v} \left(1+Trm_{mivt} \right) \times TPMW_{mivnt} \times \left(CZ_{mivnt} + CRZ_{mivnt} \right) \\ &-\sum_r FW_{it} \times \max\left(EW_{irt} - \left(EW_{irt}\Big|_{t\geq 2} \right), 0 \right) - CFW_i \times \left(EW_{ir,t-1} \times EW_{irt} \right)\Big|_{t\geq 2} \quad \forall i \in S, \forall n, \forall t \end{aligned} \tag{4}$$

$$u_{o\,\mathrm{iv\ nt}} = \frac{At_{\mathrm{iv\ nt}}}{SHPC3_{iovt} \times \left(1+D_{oi} \right)^{\beta}} \quad \forall t,o,n,v,i \in \left(S \cup C \right) \tag{5}$$

$$Ms_{o\,\mathrm{iv\ nt}} = \frac{u_{o\,\mathrm{iv\ nt}}}{\sum_{i\in S\cup C} u_{o\,\mathrm{iv\ nt}}} \quad \forall o,n,t,v,i \in \left(S \cup C \right) \tag{6}$$

$$TMs_{ovnt} = \frac{\sum_{i\in S} u_{o\,\mathrm{iv\ nt}}}{\sum_{i\in S} u_{o\,\mathrm{iv\ nt}} + \sum_{i\in C} u_{o\,\mathrm{iv\ nt}}} = \frac{\sum_{i\in S} u_{o\,\mathrm{iv\ nt}}}{\sum_{i\in S\cup C} u_{o\,\mathrm{iv\ nt}}} \quad \forall o,n,t,v \tag{7}$$

$$g(TU_{ovnt}) = 1 - e^{-\lambda \times \sum_{i \in S \cup C} u_{o\,\mathrm{iv\,nt}}} \qquad \forall o,n,t,v \tag{8}$$

$$At_{\mathrm{iv\,nt}} = EW_{it} \times \alpha_i \times \prod_{z=1}^{|ZA|} \left(1 + Y_{ivzt}\right)^{\theta_z} \qquad \forall i,n,t,v \tag{9}$$

$$Y_{ivzt} = \begin{cases} \dfrac{\left(Tcapw_i\right)\big|_{i \in C}}{Min\left(Tcapw_i\big|_{i \in C}, \left(Tcapw_i - DO_{nt} \times Dcapw_{\mathrm{int}} + Rcapw_i \times RXW_{it}\right)\big|_{i \in S}, \sum_m \left(CZ_{mivnt} + \left(CRZ_{mivnt}\right)\big|_{t \neq 1}\right) + \left(Inv_{ivnt}\right)\big|_{t \neq 1}\right)} & \forall i,v,z,t \\ \dfrac{\left(Tcapw_i - DO_{nt} \times Dcapw_{\mathrm{int}} + Rcapw_i \times RXW_i\right)\big|_{i \in S}}{Min\left(Tcapw_i\big|_{i \in C}, \left(Tcapw_i - DO_{nt} \times Dcapw_{\mathrm{int}} + Rcapw_i \times RXW_{it}\right)\big|_{i \in S}, \sum_m \left(CZ_{mivnt} + \left(CRZ_{mivnt}\right)\big|_{t \neq 1}\right) + \left(Inv_{ivnt}\right)\big|_{t \neq 1}\right)} & \end{cases} \tag{10}$$

$$-Cfzro_{ktn} - Cfpro_{kmv1tn} \geq C1s_{k1vt} \times Cfxro_{kmv1tn} \qquad \forall k,m,v,t,n \tag{11}$$

$$-Cfxro_{kmv1tn} \leq Cfx_{kmv1tn} \leq Cfxro_{kmv1tn} \qquad \forall k,m,v,t,n \tag{12}$$

$$-Cizro_{ktn} - Ckpro_{kmvetn} \geq COPs_{kmven} \times Cixro_{kmvetn} \qquad \forall k,m,v,t,n,e \in \{2,3\} \tag{13}$$

$$-Cixro_{kmvetn} \leq Cix_{kmvetn} \leq Cixro_{kmvetn} \qquad \forall k,m,v,t,n,e \in \{2,3\} \tag{14}$$

$$-Cszro_{ktn} - Cspro_{kmv1tn} \geq COPs_{km1n} \times Csxro_{kmv1tn} \qquad \forall k,m,v,n,t \geq 2 \tag{15}$$

$$-Csxro_{kmv1tn} \leq Csx_{kmv1tn} \leq Csxro_{kmv1tn} \qquad \forall k,m,v,n,t \geq 2 \tag{16}$$

$$\sum_k \left(RFS_{kt} \times ERF_{kt}\right) + \sum_m \left(RFM_{mt} \times ERA_{mt}\right) + \sum_i \left(RFW_{it} \times ERW_{it}\right) \leq Bud_t \qquad \forall t \tag{17}$$

$$\begin{pmatrix} \sum_{v,m} T1_{kmv1t} \times \left(Cfx_{kmv1tn} + Csx_{kmv1tn}\big|_{t \geq 2}\right) + \\ \sum_{v,m,e \neq 1} T1_{kmvet} \times Cix_{kmvetn} \end{pmatrix} \leq \begin{pmatrix} Tcaps_{kt} \\ -DO_{nt} \times Dcaps_{kn} + Rcaps_{kt} \times ERF_{krt} \end{pmatrix} \times EF_{krt} \qquad \forall k,n,r,t \tag{18}$$

$$ERF_{krt} \leq EF_{krt} \qquad \forall k,r,t \tag{19}$$

$$\sum_t ERF_{krt} \leq 1 \qquad \forall k,r \tag{20}$$

$$M \times (ZS_{ket} - 1) < \sum_{m,v} \left(Cfx_{kme1tn} + Csx_{kmv1tn}\big|_{t \geq 2}\right) \leq M \times ZS_{ket} \qquad \forall k,n,t \tag{21}$$

$$M \times (ZS_{ket} - 1) < \sum_{m,v} Cix_{kmvetn} \leq M \times ZS_{ket} \qquad \forall k,n,t,e \neq 1 \tag{22}$$

$$\sum_k ZS_{ket} \geq Snum \qquad \forall t,e \tag{23}$$

$$\begin{aligned} &\frac{Con_{ve}}{B_{v1}} \times \left(\sum_{k,t} \left(Cfx_{kmv1tn} + Csx_{kmv1tn}\right)\right) = \frac{Con_{ve}}{B_{v2}} \times \left(\sum_{k,t} Cix_{kmv2tn}\right) = \\ &\ldots = \frac{Con_{ve}}{B_{c|E|}} \times \left(\sum_{k,t} Cix_{kmv|E|tn}\right) = \sum_{i \in S,t} \left(Cz_{mlvtn} + Crzw_{mlvtn}\right) \qquad \forall m,v,n \end{aligned} \tag{24}$$

$$\sum_v (T2_{\mathrm{mv}} \times \mathrm{CY}_{mvtn} + T3_{mv} \times CRZ_{mvtn}\big|_{t \geq 2}) \leq \begin{pmatrix} Tcapm_{mt} - DO_{nrt} \times Dcapm_{mn} \\ +Rcapm_{mt} \times ERA_{mrt} \end{pmatrix} \times EA_{mrt} \qquad \forall m,n,r,t \tag{25}$$

$$ERA_{mrt} \leq EA_{mrt} \qquad \forall m,r,t \tag{26}$$

$$\sum_t ERA_{mrt} \leq 1 \qquad \forall m,r \tag{27}$$

$$\sum_{m,v} Vs_v \times (CZ_{mivtn} + S_{iv,t-1,n}\big|_{t \geq 2}) \leq \begin{pmatrix} Tcapw_{it} - DO_{nrt} \times Dcapw_{in} \\ +Rcapw_{it} \times ERW_{irt} \end{pmatrix} \times EW_{it} \qquad \forall i,n,t \tag{28}$$

$$ERw_{irt} \le EW_{irt} \quad \forall i, r, t \tag{29}$$

$$\sum_t ERw_{irt} \le 1 \quad \forall i, r \tag{30}$$

$$\sum_k EF_{krt} \le Fn_{rt} \quad \forall r, t \tag{31}$$

$$\sum_m EA_{mrt} \le An_{rt} \quad \forall r, t \tag{32}$$

$$\sum_i EW_{irt} \le Wn_{rt} \quad \forall r, t \tag{33}$$

$$\sum_k (Cfx_{kmv1tn} + Csx_{kmv1tn}\big|_{t\ge 2}) \ge \sum_i (CZ_{mivtn} + CRZ_{mivtn}\big|_{t\ge 2}) \quad \forall m, v, n, t \tag{34}$$

$$\sum_k Cix_{kmvetn} \ge \sum_i CZ_{mivtn} \quad \forall m, v, n, t, e \in \{2,3\} \tag{35}$$

$$CIZ_{mvtn} \ge \sum_k Cix_{kmvetn} - \sum_k Cfx_{kmv1tn} \quad \forall v, m, n, t, e \ne 1 \tag{36}$$

$$CSRM_{mvtn} = CIZ_{mvtn} + CSRM_{mv,t-1,n}\big|_{t\ge 2} - CRZ_{mvtn}\big|_{t\ge 2} \quad \forall v, m, v, t \tag{37}$$

$$\sum_v V_v \times CSRM_{mvtn} \le \begin{pmatrix} Ccaprm_{mtn} - DO_{mtn} \times Dcaprm_{mtn} \\ +Rcaprm_{mtn} \times ERA_{mt} \end{pmatrix} \times EA_{mt} \quad \forall m, n, t \ge 2 \tag{38}$$

$$CRZ_{mvtn} \ge Csx_{mvtn} \quad \forall v, m, n, t \ge 2 \tag{39}$$

$$CRZ_{mvtn} \ge CSRM_{mvtn} \quad \forall v, m, n, t \ge 2 \tag{40}$$

$$CRZ_{mvtn} = \sum_i Crzw_{mivtn} \quad \forall v, m, n, t \ge 2 \tag{41}$$

$$Inv_{ivtn} = \sum_m (CZ_{mivtn} + Crzw_{mivtn}\big|_{t\ge 2}) + Inv_{iv,t-1,n}\big|_{t\ge 2} - \sum_o C_{iovtn} \quad \forall v, i, n, t \tag{42}$$

$$\sum_o C_{iovtn} \le \sum_m (CZ_{mivtn} + Crzw_{mivtn}\big|_{t\ge 2}) + Inv_{iv,t-1,n}\big|_{t\ge 2} \quad \forall v, i, n, t \tag{43}$$

$$W_{ovt} \times g(U_{ovnt}) \times Ms_{ov\,\mathrm{nt}} - \sum_{i\in S} C_{iovnt} + CZW\,3_{ov\,\mathrm{t}} \times C\Gamma W\,3_{ov\,\mathrm{t}} + CPW\,3_{ov\,\mathrm{t}} \le 0 \quad \forall o, n, t, v \tag{44}$$

$$-W_{ovt} \times g(U_{ovnt}) \times Ms_{ov\,\mathrm{nt}} + \sum_{i\in S} C_{iovnt} + CZW\,4_{ov\,\mathrm{t}} \times C\Gamma W\,4_{ov\,\mathrm{t}} + CPW\,4_{ov\,\mathrm{t}} \le 0 \quad \forall o, n, t, v \tag{45}$$

$$CZW\,3_{ovt} + CPW\,3_{ovt} \ge W\,1_{ovt} \times CYW\,3_{ovt} \quad \forall o, t, v \tag{46}$$

$$-CYW\,3_{ovt} \le g\left(U_{ovnt}\right) \times MS_{ovnt} \le CYW\,3_{ovt} \quad \forall o, n, t, v \tag{47}$$

$$CZW\,4_{ovt} + CPW\,4_{ovt} \ge -W\,1_{ovt} \times CYW\,4_{ovt} \quad \forall o, n, t, v \tag{48}$$

$$-CYW\,4_{ovt} \le g\left(U_{ovnt}\right) \times MS_{ovnt} \le CYW\,4_{ovt} \quad \forall o, n, t, v \tag{49}$$

$$\begin{pmatrix} -W_{ovt} \times g(U_{ovnt}) \times MS_{ovnt} \\ +CZW\,1_{ovt} \times C\Gamma W\,1_{ovt} + CPW\,1_{ovt} \\ +CZW\,2_{ovt} \times C\Gamma W\,2_{ovt} + CPW\,2_{ovt} \end{pmatrix} \le \begin{pmatrix} -W_{ovt} \times \mu_{vnt} \times DO_{nt} \\ -(1 - DO_{nt}) \times W_{ovt} - CLW_{ovnt} \end{pmatrix} \quad \forall o, n, t, v \tag{50}$$

$$CZW\,1_{ovt} + CPW\,1_{ovt} \ge W\,1_{ovt} \times CYW\,1_{ovt} \quad \forall o, v, t \tag{51}$$

$$-CYW\,1_{ovt} \le g(U_{ovnt}) \times MS_{ovnt} \le CYW\,1_{ovt} \quad \forall o, v, t \tag{52}$$

$$CZW\,2_{ovt} + CPW\,2_{ovt} \ge W\,1_{ovt} \times \left(\mu_{ovnt} \times DO_{nt} - (1 - DO_{nt})\right) \quad \forall o, v, n, t \tag{53}$$

$$LTPSM_{kment} \le TPSM_{kment} \le UTPSM_{kment} \quad \forall k, m, e, n, t \tag{54}$$

$$LTPMW_{mivnt} \le TPMW_{mivnt} \le UTPMW_{mivnt} \quad \forall m, i, v, n, t \tag{55}$$

4. Solution method

Since the SCND is an NP-hard problem, solving large instances of this problem efficiently, in a reasonable amount of time is a challenging task [31]. The results of applying GA to a wide variety of SCND problems have been very promising among the other evolutionary algorithms [31]. In spite of its strengths, GA has a weakness of limited efficiency in strengthening the local search process [26]. To address this challenge, MA was proposed by Moscato and Norman [32]. In this study, an efficient meta-heuristic based on the MA is proposed. The proposed MA incorporates Taguchi-based GA and ALNS. In this algorithm, investigation of the solution space for a single objective is handled by Taguchi-based GA with an adaptive population size, while the improvement of the best solution by each generation of Taguchi-based GA is done via a customized ALNS. The proposed ALNS investigates the solution space via the customized new neighborhood structures. In addition, a more in-depth search is done via a hill climbing heuristic within the proposed ALNS. A fitness landscape analysis is used to improve the performance of the systematic NS selection in the proposed ALNS via determining the effective order of the neighborhood structures.

4.1- Encoding and fitness evaluation of the solution chromosomes

In the proposed MA, a two-dimensional binary array is used to represent each solution chromosome. The size of the proposed binary array is $(3\times|S|+2\times|A|+2\times|L|).|t|$. Evaluating each chromosome's fitness is based on the value of the objective function. This evaluation is performed using two consecutive procedures. The binary decision variables are generated from values of chromosome's genes. After this solution decoding scheme, MINLP problem transforms into an NLP one that is calculated by solving a nonlinear optimization problem via a nonlinear programming solver, named as LINDOGLOBAL in GAMS 24.1.2. Obtained solutions in each iteration are sorted according to their fitness function values.

4.2- Initial and next generation population

In this study, initial population is generated randomly. The part of each next population generation is randomly generated using Taguchi-based crossover and mutation operators. The rest of the population for that generation is generated via transferring a specific percent of the best solutions of the previous generation to the next generation.

4.2.1- Dynamic adaptive population size

Various dynamic population size strategies are presented in GA literatures [33]. In this study, population size of each generation is based on the age concept of chromosomes that is proposed by Michalewicz [33]. During the step of fitness function evaluation, life time (LT) parameter is assigned once for each chromosome. The LT parameter is calculated after chromosome generation and it is updated during the other next generation of GA via increasing by one unit. The chromosome dies when its age exceeds its lifetime value. The LT parameter is calculated by a bi-linear allocation constraint that is proposed by Michalewicz [33].

4.2.2-Selection procedure of chromosomes for mating pool

A roulette-wheel selection scheme is adopted for applying next generation operators [34]. Hence, the mating pool fills up with chromosomes that are selected via roulette-wheel selection procedure. Selected individuals from the mating pool could be used in a crossover or mutation process with a pre-determined probability.

4.2.3- Next generation operators: Taguchi-based Crossover and multi-point mutation

A wide variety of approaches have been suggested for applying crossover and mutation operators in the literature [35]. In this study, Taguchi-based crossover and multi-point mutation operators are used according to the proposed chromosome structure. Procedure of the proposed Taguchi-based crossover operation is based on the study of Yang et al., [36]. The employed multi-point mutation operator flips the value of the selected gene randomly with probability 0.5 (i.e., 0 goes to 1 and 1 goes to 0). Genes in each segment are selected randomly with a probability of 0.5. The new solution which is obtained from mutation operator should satisfy the constraints of the proposed problem such as limitation number of reinforcement for each facility.

4.3- The proposed ALNS algorithm

Ropke and Pisinger [37] proposed ALNS, that is an effective expansion of large neighborhood search that uses various destroy and repair NS. The general NS selection process is based on the statistics and performance of adopting them during neighborhood search. Using a various destroy and repair neighborhood structures during the search process prevents the algorithm from getting stuck in a local optimal solution of a specific NS as well as intensify the local search process. In recent years, ALNS has been successfully applied to solve different large scale and more complex problems [38]. Complementary of the selected neighborhood structures during a search process is a main requirement to have an effective solution space search with ALNS. Therefore, the order of NS selection should be determined properly. In this study, a fitness landscape approach is adopted to determine the most effective order of neighborhood selection. This approach could realize that who and where neighborhood structures work efficiently (see Section 5.1). The interested reader is referred to Talbi [34] for overviews of the landscape approach. To analyze the landscape of the proposed problem, the normalized average distance is adopted for population. Due to binary representation in the proposed search space, the Hamming distance is used [35].

Steps of the employed ALNS are demonstrated in Figure 1. Two destroy NS and four repair neighborhood structures are adopted in the proposed ALNS. These customized neighborhood structures are designed based on the structure of the employed chromosomes. The selected repair NS is employed after applying the selected destroy NS. The details of these structures are as follows:

- Destroy structures:
  - DNS1: Sets of different non-adjacent genes in a specific segment are selected randomly. Each set is a sequence of genes with a random size. The number of selected sets is determined randomly, and
  - DNS2: Set of adjacent genes in a specific segment is selected randomly. The Set size is determined randomly.
- Repair structures:
  - RNS1: The selected set is located at its initial place with a new randomly-ordered for each sequence of genes,
  - RNS2: The selected set is located at its initial place with a new reversed-ordered for each sequence of genes,
  - RNS3: The selected set is shifted to a new random location with its initial order. Selection of the new location depends on the number of sets that are selected. If number of sets is equal to 1, then the new location is randomly selected in that segment. Otherwise, sets are shifted randomly to right or left only one or more units. The shift direction is determined randomly with an equal probability of 0.5 for each direction. In addition, the random shifting unit is equal for all of the selected sets, and
  - RNS4: The selected set is shifted to a new random location with random order. All of the above mentioned considerations for employing RNS3 should be considered for employing RNS4 as well.

5. Computational Experiments and Results

In this section, the effectiveness of the proposed solution algorithm is investigated using a series of computational experiments. For this matter, 40 test problems are defined based on the opinions of the experts of the DMX Company (see Table 1). The generation scheme of parameters of the proposed model is based on the test generation scheme which is proposed by Hasani et al., [26]. Parameters of the proposed method are set via a statistical design of experiments method, named as the Taguchi method [26] (see Table 2). The proposed solution algorithm and the mathematical model are coded in C# and LINDOGLOBAL in GAMS 24.1.2, respectively. All of the coded programs in this study are run on a PC with a single 2.67 GHz CPU and four GB of RAM.

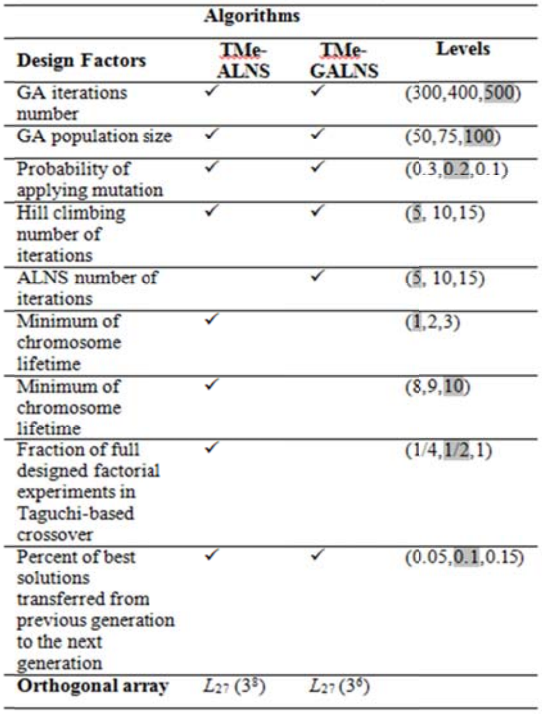
```
Inputs :
A set of destroy and repair neighborhood structure
$N_S\ (s = 1,\ldots,\ S_{max})$ for intensifying local search
process,a best solution obtained via Taguchi-based
GA, an order list and initial probability of
neighborhood structure selection, and stop criteria.
Output :
Improved solution
$i = 1,\quad Dp^- = (1,\ldots,\ 1)\quad Rp^+ = (1,\ldots,\ 1)$
$x \longleftarrow$ best solution
Repeat (The iteration number is pre-determined)
    1.Select the neighborhood structure based on
    the selection order list and the best of the
    $dp^- \in Dp^-$ and $rp^+ \in Rp^+$
    2.Generate new solution $x'$ via applying the
    selected $dp^-$ and $rp^+$ sequentially
    3.Evaluate the fitness function of the obtained
        solution, IF $\left(\text{Fitness}(x') > \text{Fitness(x)}\right)$ then $\left(x \leftarrow x'\right)$
Updating $dp^-$ and $rp^+$ based on the performance
(i.e., obtained fitness function) of applied selected structures
via $\pi_{i,n+1} = r \times \frac{w_i}{\theta_i} + (1-r) \times \pi_{n,t}$ (i.e.,$W_i$ is the score of the neighborhood structure $i$ ),
$w_i$ equals to a predetermined positive
number (i.e., when solution is improved);
otherwise it equals to zero, $\theta_i$ is the number
of time the neighborhood structure $i$
is used since the last weight update. $r$ is the
reaction factor which indicates how much the
roulette weight depends on the previous success.
$i \leftarrow i + 1$
Until the stop criteria is satisfied
```

Figure 1. The pseudo-code of the proposed ALNS heuristic

Table 1. Proposed test problems (i.e., budget of uncertainty decreases 20 % per each set of instances)

	Parameters					
Instances	Bud1= Bud2= Bud3	Bud4	Scenario number	β	λ	μ
(1-5)	(120-0)	1	5	1	1	0.45
(6-10)	(120-0)	1	5	1	1	0.5
(11-15)	(120-0)	1	5	2	2	0.45
(16-20)	(120-0)	1	5	2	2	0.5
(21-25)	(120-0)	1	10	1	1	0.45
(26-30)	(120-0)	1	10	1	1	0.5
(31-35)	(120-0)	1	10	2	2	0.45
(36-40)	(120-0)	1	10	2	2	0.5

Table 2. The design and noise factors for parameter tuning using the Taguchi method



	Algorithms		
Design Factors	TMe-ALNS	TMe-GALNS	Levels
GA iterations number	✓	✓	(300,400,500)
GA population size	✓	✓	(50,75,100)
Probability of applying mutation	✓	✓	(0.3,0.2,0.1)
Hill climbing number of iterations	✓	✓	(5, 10,15)
ALNS number of iterations		✓	(5, 10,15)
Minimum of chromosome lifetime	✓		(1,2,3)
Minimum of chromosome lifetime	✓		(8,9,10)
Fraction of full designed factorial experiments in Taguchi-based crossover	✓		(1/4,1/2,1)
Percent of best solutions transferred from previous generation to the next generation	✓	✓	(0.05,0.1,0.15)
Orthogonal array	$L_{27}(3^8)$	$L_{27}(3^6)$	

Note: The selected values are highlighted in gray

5.1- Determining the effective order of NS selection

To determine the effective order of neighborhood structures selection, a fitness landscape analysis approach discussed in section 4.3 is used. First, *Dmm* is calculated for each combination of repair and destroy neighborhood structure via applying a hill climbing algorithm that incorporates one combination to improve a population [39]. For this matter, the proposed test problems discussed in the previous section are used for 5 times with an initial similar population of size 100. The obtained results of *Dmm* computation are outlined in Figure 2. These results indicate that all of the applied neighborhood structures have a significant positive impact on concentrating examined populations. The neighborhood structures with a smaller *Dmm* value have a more focused concentration. The order of neighborhood structure selection is determined based on the ascending order of *Dmm* values (see Figure 2). The results indicate that the neighborhood structures

(DNS1-RNS1, DNS1-RNS4, and DNS2-RNS1) are selected sequentially in each iteration of the proposed ALNS. The others combinations are selected via the systematic selection procedure based on their performance during the local search process due to tackle the conflict of selection order.

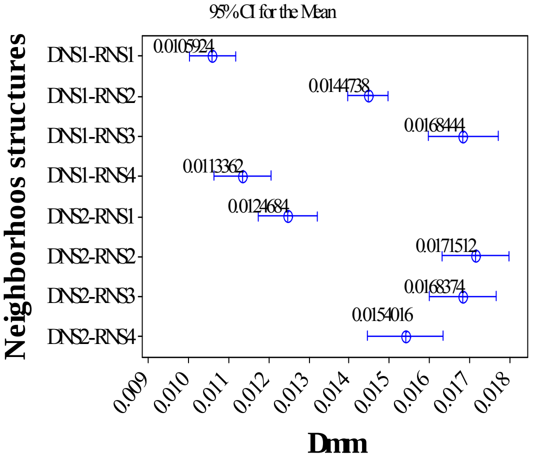


Figure 2. Interval plot of obtained *Dmm* via applying different neighborhood structures

5.2- Evaluation of TMe-ALNS efficiency

The quality of the best solutions obtained by TMe-ALNS is examined via comparing them with solutions obtained from the LINDOGLOBAL. The results indicate that the superiority of the proposed TMe-ALNS algorithm (see Table 3). The average gap between solutions obtained by TMe-ALNS and LINDOGLOBAL for medium-sized (5 scenarios) and large-sized (10 scenarios) instances are 22.214% and 27.88%, respectively. The maximum allowed CPU time for LINDOGLOBAL was limited to 100 hours. Due to the solution algorithm restrictions and capabilities, LINDOGLOBAL was not able to proving optimality of its best-found solutions for all instances, even after the permitted run time limitation. In addition, the efficiency of the proposed TMe-ALNS is investigated via comparing its performance with a general systematic NS selection in the ALNS, namely TMe-GALNS, for solving large instances (i.e., instances with 10 scenarios). The obtained results indicate the superiority of the proposed TMe-ALNS in terms of time efficiency and solution quality over TMe-GALNS (see Table 4). This superiority indicates the effectiveness of the proposed improved adaptive large neighborhood search.

5.3- Computational results and managerial insights

The Performance of the proposed GSC network configuration highly depends on the disruption occurrence in a competitive business environment. The utilities of distributors' facilities are affected by disruption. Hence, in this section, the effect of the strategies to deal with disruption on the performance of the proposed network is investigated in terms of net after-tax profit, captured market share, and inventory cost of GSC. Due to the computational complexity and saving running time, fractional factorial design of experiment is adopted (i.e., half of the treatments of the full factorial design are done). All of the statistical analysis is done with statistical software, named as Minitab 16.

Table 3. Results of investigating the efficiency of TMe-ALNS

Fitness function value of best solution			
Test problem (Medium-sized)	*TMe-ALNS*	*LINDOGLOBAL*	*Gap$_{\text{TMe-ALNS}}$ (%)*
1	1.58E+13	1.22E+13	29.41
2	1.60E+13	1.27E+13	25.71
3	1.64E+13	1.43E+13	14.4
4	1.81E+13	1.50E+13	20.67
5	1.81E+13	1.59E+13	14.07
6	1.87E+13	9.64E+12	29.64
7	1.25E+13	1.06E+13	23.77
8	1.31E+13	1.20E+13	12.88
9	1.36E+13	1.32E+13	16.65
10	1.54E+13	1.18E+13	31.02
11	1.55E+13	1.15E+13	16.61
12	1.62E+13	1.05E+13	30.63
13	1.34E+13	1.16E+13	23.18
14	1.37E+13	1.27E+13	25.54
15	1.43E+13	1.24E+13	29.06
16	1.59E+13	9.12E+12	17.32
17	1.60E+13	9.00E+12	24.49
18	1.66E+13	1.00E+13	17.82
19	1.07E+13	1.22E+13	13.56
20	1.12E+13	1.09E+13	27.85

Average gap (%)	22.21

Test problem (Large-sized)	*TMe-ALNS*	*LINDOGLOBAL*	*Gap$_{\text{TMe-ALNS}}$ (%)*
21	1.00E+13	7.74E+12	29.21
22	1.07E+13	8.59E+12	24.62
23	1.08E+13	8.35E+12	29.4
24	1.13E+13	9.02E+12	25.31
25	1.19E+13	9.69E+12	22.82
26	1.28E+13	6.51E+12	20.28
27	7.83E+12	6.51E+12	27.79
28	8.32E+12	6.80E+12	24.25
29	8.45E+12	7.04E+12	29.17
30	9.10E+12	7.88E+12	29.51
31	1.02E+13	6.82E+12	20.89
32	1.10E+13	7.13E+12	23.93
33	8.25E+12	7.18E+12	25.74
34	8.84E+12	7.17E+12	34.4
35	9.03E+12	8.20E+12	25.64
36	9.64E+12	5.44E+12	21.88
37	1.03E+13	5.16E+12	40.76
38	1.11E+13	5.73E+12	30.63
39	6.63E+12	5.82E+12	37.35
40	7.27E+12	6.71E+12	34.05
Average gap (%)			27.88

Figure 3 indicates that three strategies, including facility reinforcement, facility dispersion, and multiple sourcing have the most significant positive effects on the net after-tax profit of considered GSC. In addition, Figure 3 demonstrates that all of the six proposed strategies have a positive effect on the net after-tax profit. However, only three of them are most important based on their large positive significant effects. Applying these three strategies at the same time improved competition condition of distributors' facilities efficiently compared with the other combination of the proposed strategies. These strategies could decrease the disruption effects across at all the tiers of GSC efficiently. Therefore, utilities of distributors' facilities are less affected via disruption occurrence.

Table 4. Evaluation of performance of the proposed ALNS with fitness landscape analysis

	TMe-ALNS	
Large instances	*Best fitness function value*	*Average CPU time*
21	1.00E+13	26939.35665
22	1.07E+13	28272.09816
23	1.08E+13	25052.59936
24	1.13E+13	27317.55096
25	1.19E+13	24715.6533
26	7.83E+12	26118.2696
27	8.32E+12	24539.37216
28	8.45E+12	25471.48329
29	9.10E+12	28498.54074
30	1.02E+13	23566.85415
31	8.25E+12	26078.4922
32	8.84E+12	24969.21699
33	9.03E+12	24940.4722
34	9.64E+12	27398.06363
35	1.03E+13	27488.23012
36	6.63E+12	22924.40304
37	7.27E+12	24323.8304
38	7.49E+12	29507.32049
39	8.00E+12	30889.61474
40	8.99E+12	31733.93771
	TMe-GALNS	
	Best fitness function value	*Average CPU time*
21	9.30E+12	31478.56584
22	1.03E+13	32043.63387
23	1.03E+13	28212.38667
24	1.13E+13	30454.3489
25	1.16E+13	29799.4373
26	7.43E+12	30124.87843
27	7.91E+12	28109.24646
28	8.11E+12	29959.40166
29	9.10E+12	34253.05377
30	9.96E+12	26267.11341
31	7.67E+12	29557.39794
32	8.37E+12	30306.12573
33	8.48E+12	28467.60895
34	9.20E+12	32044.51887
35	9.87E+12	32747.47453
36	6.59E+12	27378.9598
37	6.99E+12	28419.0097
38	7.12E+12	35792.47998
39	8.00E+12	36153.57531
40	8.76E+12	37986.51869
	Gap analysis (%)	
	Best fitness function value	*Average CPU time*
	Max (%)	
	7.54	17.61
	Min (%)	
	0	10.28
	Average (%)	
	3.861	14.22

Figure 4 indicates that there is an interaction between some of the strategies to deal with disruption. For instance, strategy of keeping an inventory has an interaction with other strategies, including the adoption of alternative BOM, production of semi-manufactured products, and facility dispersion. The reason is that adoption of alternative BOM and production of semi-manufactured products is not applied when there is a sufficient supplement of required material. The performance of mentioned significant strategies in terms of net after-tax profit and captured market share of test problems (20-40) is depicted in Figure 5. These three strategies will have the most impact on maintaining a competitive position of considered GSC. In addition, results indicate the positive association between the gained profit and market share in the presence of inelastic demand under the considered static competition. By increasing the sensitivity of customers to distance, the importance of access cost in attraction functions increases. Therefore, closer distributors with cheaper access cost can capture more market share. Hence, there is a need to establish closer facilities to demand points.

The above approach leads to increase of the total cost of GSC via increasing the number of established facilities. Figure 5 demonstrates the decrease of GSC profit with increasing of the sensitivity to distance (i.e., access cost). Obtained results indicate that applying three significant strategies concurrently has the best performance between the others strategies combinations. Employing these strategies guarantees the considered GSC network against disruptions in a highly volatile and competitive business environment. In addition, net after-tax profit and captured market share decrease as the uncertainty level (budget) increases due to the rising of costs of coping with uncertainty. In other words, the higher budget values result in more conservative GSC configurations, which in turn result in less profit. Minimum budget values represent a nominal deterministic model without disruption occurrence (e.g., see test problems 25, 30, 35, and 40). However, instances with maximum budget values represent full uncertainty (e.g., see test problem 21, 26, 31, and 36). Furthermore, inventory cost decreases as the uncertainty level increases (see Figure 6). This event demonstrates an agile paradigm behavior of the proposed robust model under uncertainty. Proposed model has a good performance in the considered static competition condition under uncertainty and disruption (see Figure 6). Due to applying efficient strategies to deal with disruptions, desired demand satisfaction level is satisfied. In addition, competitive advantage of MDX Company will be improved via preserving market share under normal and disruption situation at the same time.

Finally, the following implications can be inferred from the mathematical model and computational results from an applied point of view as useful managerial insights for decision makers and managers of global supply chains:

- The proposed comprehensive mathematical model tries to capture characteristics of the decision-making environment of the global supply chains for medical devices under uncertainty and static competition via considering a set of resilience strategies.
- Using the set of resilience strategies includes facility dispersion, facility fortification, production of semi-manufactured products, multiple sourcing, keeping an inventory, and using primary and alternative BOM provides a realistic tool to design an efficient global supply chain network (GSCN) under disruptions. However, each strategy has a specific impact in performance of the GSCN as well as an interdiction effect with others strategies as a consequence of its role in designing a resilience structure. Consequently, the decision makers should determine the impact of each strategy to design an efficient GSCN which resilience under disruption. All of the six considered resilience strategies have a positive impact on performance of GSC under disruption. However, three strategies including facility fortification, facility dispersion and multiple sourcing strategy have most important positive impact on performance of GSC under disruption which are affect the supply chain facility capacity in each region differently.

- This competition condition is affected by the disruption occurrence because of the dependency of attractiveness of the GSC facilities on their available capacities. In such a situation, effect of disruption occurrence in the upper tiers of GSC could be seen in the lower tiers such as distributors. Therefore, a competitive advantage of GSC is tied with the performance of GSC under disruption. To deal with the disruption efficiently, six practical strategies are considered at the same time in the design of GSCN. Using the concept of robust budget based uncertainty provides a realistic as well as useful tool to handle uncertainty via considering different decision maker's degree of conservativeness. The computational results indicate that the higher budget values result in more conservative GSC configurations, which in turn result in less profit. In addition, inventory cost decreases as the uncertainty level increases that demonstrates an agile paradigm behavior of the proposed robust model under uncertainty.

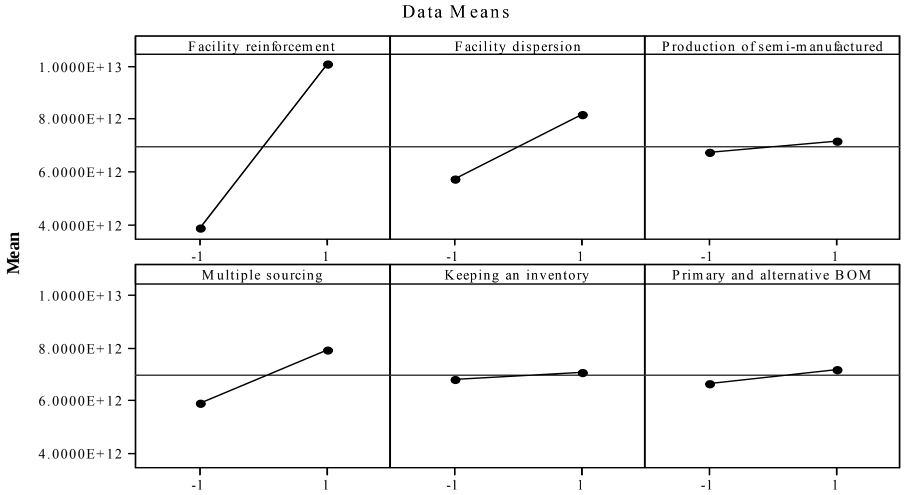


Figure 3. Main Effects Plot of proposed strategies for net after-tax profit

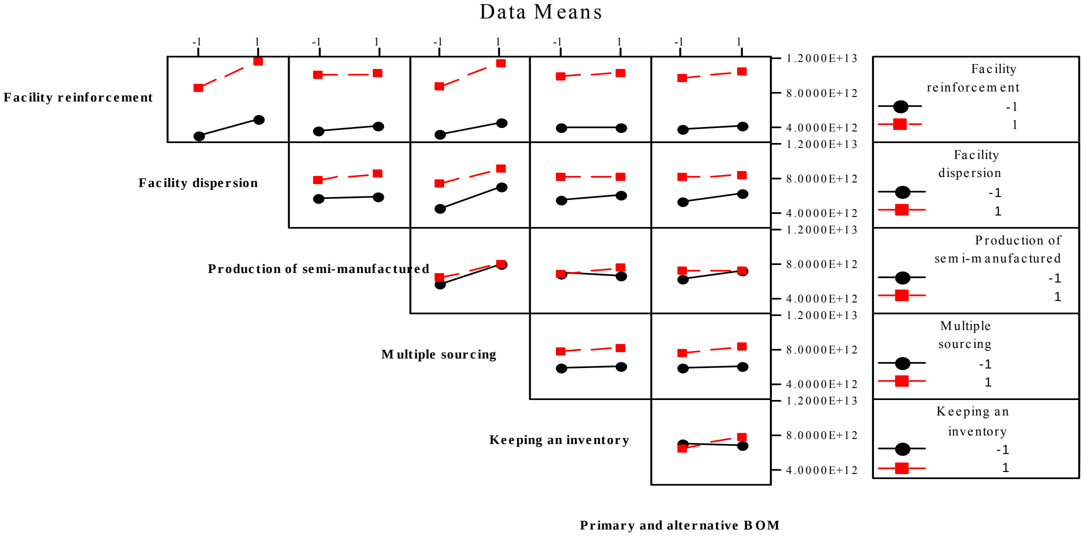


Figure 4. Interaction plot of proposed strategies for net after-tax profit

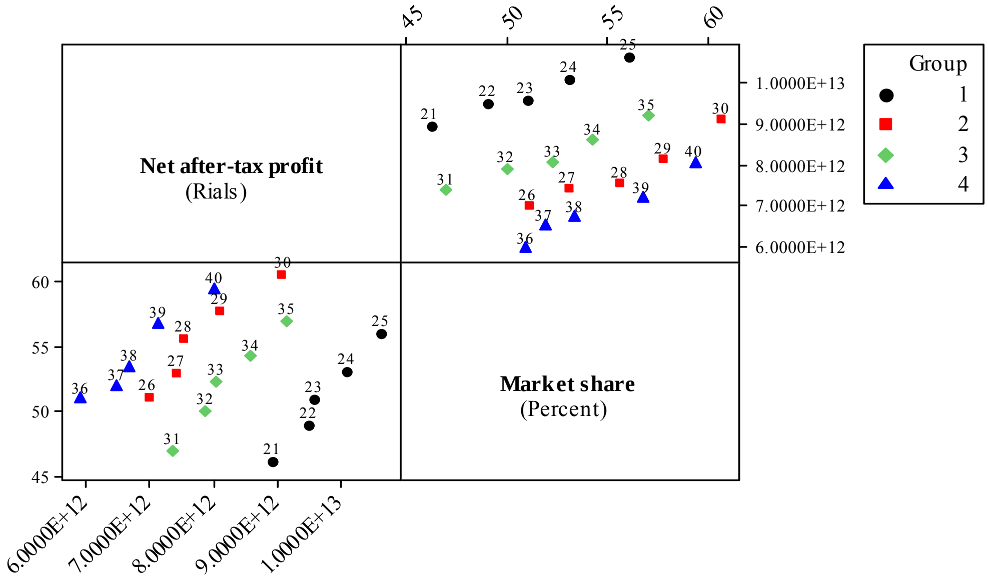


Figure 5. The matrix plot of impact of the most significant strategies on net after-tax profit and market share (i.e., test problems 21-40)

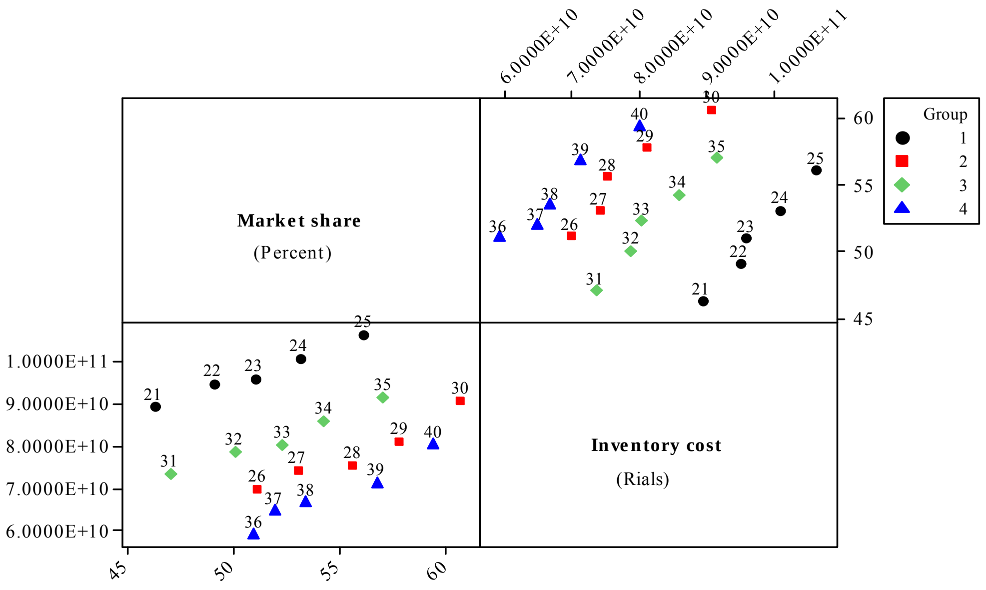


Figure 6. The matrix plot of impact of the most significant strategies on market share and inventory cost (i.e., test problems 21-40)

6. Conclusion

In this study, the robust competitive design of GSC network for medical device industries under the ECOTA is presented. Due to the characteristics of the considered market and pre-existing competitors, a static competition is considered in the design of GSCN. This competition condition is affected by disruption occurrence because of the dependency of attractiveness of the GSC facilities on their available capacities. In such a situation, effect of disruption occurrence in the upper tiers of GSC could be seen in the lower tiers such as distributors. Therefore, a competitive advantage of GSC is tied with the performance of GSC under disruption. To deal with the disruption efficiently, six practical strategies are considered at the same time in the design of GSCN. Disruption occurrence is considered via defining the disruption scenarios with a pre-determined occurrence probability. In addition, the uncertainty of the business environment is handled via robust optimization technique based on the uncertainty budget concept. The aim of the proposed model is to maximize the net after-tax profit of the proposed GSC network under disruption and normal situation at the same time. The obtained results indicate the efficiency of the proposed model to well compete with pre-existing competitors for selling a product, which has an inelastic demand, in a highly volatile and disruptive business environment. To improve the competitive advantage of GSC under abnormal condition, six strategies are considered at the same time. Three strategies, including facility reinforcement, facility dispersion, and multiple sourcing have a most positive significant effect on the studied GSC performance among the six considered strategies. Applying these strategies efficiently guarantees competitive advantages of GSC in terms of a captured market share and gained profit in a highly volatile and competitive conditions. In addition, results indicate the agile behavior of the proposed model via observing the decrease of the inventory cost of GSC in the presence of high level of uncertainty despite of the maintaining captured market share under uncertainty.

To tackle the proposed MINLP model, a hybrid MA incorporating Taguchi-based GA with adaptive population size and ALNS was designed to solve a real-world case study. A fitness landscape analysis is used to improve the systematic procedure of neighborhood selection in the proposed ALNS. In addition, customized repair and destroy neighborhood structures are used in the proposed ALNS. Obtained results indicate the significant superiority of the improved ALNS via the fitness landscape analysis compared with general ALNS in terms of solution time and quality. Furthermore, the superiority of the proposed hybrid MA is investigated via comparing its performance with the other hybrid MA.

For further research, considering the other competition condition including foresight and dynamic in the strategic design of GSC according to the characteristics of studied market and business environment could be applicable to many others real-world situations. While the effects of disruption on facility capacity were considered in this study, the other important ones such as a disruptive capacity of global transportation routes and system could be considered. These considerations can improve the competitive advantages of GSC in normal and disruptive situations simultaneously. Therefore, developing a mathematical model and appropriate efficient solution algorithm to tackle such complex problems could be interest of both the practitioners and researchers.

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