IJE TRANSACTIONS A: Basics Vol. 31, No. 4, (April 2018) 648-658

International Journal of Engineering

Journal Homepage: www.ije.ir

A Robust Reliable Closed Loop Supply Chain Network Design under Uncertainty: A Case Study in Equipment Training Centers

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PAPER INFO

Paper history:
Received 14 April 2017
Received in revised form 27 May 2017
Accepted 07 July 2017

Keywords:
Closed Loop Supply Chain
Responsiveness
Robust Optimization
P-Robust
Uncertainty
Training Center

ABSTRACT

The aim of this paper is to propose a robust reliable bi-objective supply chain network design (SCND) model that is capable of controlling different kinds of uncertainties, concurrently. In this regard, stochastic bi-level scenario based programming approach which is used to model various scenarios related to strike of disruptions. The well-known method helps to overcome adverse effects of disruptions and extend a network that is less vulnerable regarding disruptions strike. Also, scenario-based modeling approach enables decision makers (DMs) to the model uncertainty of model parameters regarding different scenarios that are disregarded in reliable SCND research scope. An effective robust programming method is employed to control the risk-aversion level of output decisions that helps company managers to adjust long-term effects of their decisions via determining uncertainty level of model parameters. Notably, extended bi-objective programming model minimizes total costs of network design aside with maximization of responsiveness of supply chain network. Agile and fast performing networks could be regarded as a long-term competitive advantage for companies that are modeled in the extended form as a different objective besides cost minimization. Finally, the extended robust reliable network model is implemented and evaluated based on real case study of a national project and output results demonstrates efficiency and applicability of proposed reliable network.

***doi**: 10.5829/ije.2018.31.04a.17*

1. INTRODUCTION

The importance of major changes in the business environment such as customer demand, variable costs of operations, products processing, transportation and facilities construction leads to designing reliable supply chain networks. SCND could be performed in both forward and reverse orientations of networks [1, 2]. Forward supply chain networks consist of different echelons that add value to raw materials and turn them into final products to satisfy demand of customers [3]. On the other hand, owing to importance of environmental issues and efforts of companies to effectively and efficiently use End-of-life products, design of backward and closed-loop supply chain networks became an important issue for company managers and DMs[3-5]. In this regard, defective and used goods recycling and recovery with the aim of preventing waste of resources, reducing environmental pollution and achieving profitability are taken into consideration [6, 7]. Since aforementioned types of networks regarding some network echelons are interdependent and have effect on each other's performance, so many researchers have strived to design integrated forward and reverse networks called as closed-loop supply chains[8, 9]. Noted matter leads to optimize direct and reverse networks simultaneously and prevents sub-optimality of decisions [10, 11]. Important point is dynamic nature of supply chains that affect effectiveness, structure and supply chain coordination[12, 13]. The most important sign of complexity of the supply chain networks is uncertainty of network parameters regarding complex interaction between chain facilities that heightens necessity of dealing with the various sources of supply chain risks inevitable. Thus, according to the high impact of

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Please cite this article as: A. Hamidieh, A. Arshadikhamseh, M. Fazli-Khalaf, A Robust Reliable Closed Loop Supply Chain Network Design under Uncertainty: A Case Study in Training Centers Equipment,International Journal of Engineering (IJE),IJE TRANSACTIONS A: Basics Vol. 31, No. 4, (April 2018) 648-658

uncertainty on supply chain performance, efficient management of risk sources is an important issue. Risk sources could be generally divided into two groups. First group is associated with differences and contradictions between supply and demand and second group is related to risks caused by disruptions. Disruptions are unpredictable events such as natural disasters, floods, earthquakes, hurricanes, economic disturbances and terrorism. The second group of risks is derived from three sources, namely (1) operating possibilities (2) natural hazards (3) terrorism and political instability [12, 14]. In fact, occurrence of the second group can cause lost capacity of facilities, increasing the cost of product transport and lowering organizations market share. Thus, attention to the reliable network design problem, not only can make decisions more reliable, but also will prevent possible losses [15, 16]. Such an approach is called reliable SCND under disruptions strike. Notably, the design of sustainable supply chain networks is related to the researchers' orientation and companies commitment to corporate social responsibilities (CSR) [17, 18]. In fact, CSR is a concept that recently has been considered in the design of supply chain networks. Social Responsibility of companies is defined as impact of corporate activities on various social groups that includes environmental protection, employees and citizens' rights and also workplace safety [19, 20].

This study aims to design a reliable closed-loop supply chain network based on case study of training centers of an Iranian national project that presents the concept of CSR in a new perspective. Equipping smart training centers for the start of each school year is essential and reducing the delivery speed of needed electronic appliances to educational centers could be regarded as governments' social responsibility toward E-learning centers. Therefore, shortening the timely delivery of manufacturing levels, technical support levels, and pole centers could be considered as an essential social commitment factor in SCND scope. Another important feature of this study is taking into account various capacity levels for network facilities. Also, component base recycling and recovery of End-of-Life products could be regarded as novel and significant feature of the proposed model. In the present study, an efficient robust programming approach with discrete scenario is applied to control uncertainty of parameters. It is worthy to mention that it is the first time that noted robust optimization method with P-Robust restriction was employed to cope with the facilities disruption and uncertainty of parameters, concurrently. In other words, the mentioned model is a responsive network design model that controls the speed of transportation between facilities and speed of processing products at different facilities aside from cost minimization regarding different disruption scenarios. About enumerated matters, main contributions of this paper are listed as follows.

- Presenting a bi-objective reliable model that minimizes costs of network besides maximization of responsiveness system regarding processing of products between echelons of network
- Suggesting a bi-level scenario base programming model that is capable of modeling uncertain parameters and disruption scenarios concurrently and also controlling adverse effects of disruptions via designing less disruption vulnerable network
- Extending a reliable model that enables DMs to model partial and complete disruption of capacity of facilities
- Extending a robust stochastic programming model that is capable of controlling risk-aversion level of output decisions of proposed model based on preference of company managers and DMs
- Extending a SCND model based on case study of equipping Iranian national training centers that is a general model and is applicable in industries such as electronic appliances manufacturing and plastic instruments manufacturing with minor modifications
- Extending a closed-loop model that its reverse direction is capable of component base recycling and efficient production planning regarding components used in products produced in the forward direction of the network.

2. METHODOLOGY

2.1. The Reliable Counterpart Model

Reliable supply chain network models perform efficiently while disruptions occur. In fact, the primary concern of SCND models that deals with adverse effects of disruptionsare flexibility [3, 21, 22] that leads to consistently and efficiently meet customers demand [23]. In this regard, various reliable models are presented. Snyder and Daskin [24] introduced p-Robust criteria for establishing reliability in the SCND models. For this purpose, assuming that some scenarios have been impaired,so that s = 0 represents that no disruption scenarios are available. In this model, the flow decision variables depend on defined scenarios and location variables are fixed regarding all scenario that could regard as first level decision variables. Furthermore, decision variables X and Y correspond to location and flow variables. Moreover, Fs(X, Y) is the target value of (X, Y) in scenario S. So P-robust criteria can be applied as follows.

$$\frac{F_s(X,Y)-F_s^*}{F_s^*} \leq p \ \rightarrow \ F_s(X,Y) \leq (1+p)F_s^* \quad (1)$$

Parameter $p \geq 0$ represents the Robustness level of scenarios S. The right hand side of inequality (1) demonstrates relative regret value of scenario S. P-

Robust criteria to heighten reliability of supply chain network is used by few researches [8, 15, 25]. In present study, a robust and reliable mixed integer linear programming model for the closed-loop SCND of smart training centres is offered and the P-Robustness criteria is used to create output results of the proposed model reliable.

2. 2. Scenario-based Robust Optimization A practical approach for dealing with the uncertainty of the parameters is robust optimization. This approach seeks to find near-optimal solutions which can be named feasibility robustness, and it strives to retain objective function value near optimal regarding different scenarios that could be called as optimality robustness [26]. Mulvey et al. [27] proposed model robustness considering solution and optimality robustness based on cost-benefit analysis. They regarded as robust programming model to create a framework to define robustness concept in objective function and constraints. Now, consider following the compact model.

$$\boldsymbol{min\ \mathbf{Z} = c^T x + d^T y} \tag{2}$$

$$\boldsymbol{s.t.} \qquad Ax = b \tag{3}$$

$$Bx + Cy = e \tag{4}$$

$$x, y \geq 0 \tag{5}$$

where, Ax=b is a design or structural constraint and Bx+Cy=e is a control constraint. Uncertainty parameters in this approach is defined by scenarios that set S is representative of scenarios and probability of each scenario is determined by parameter P_s. Based on the presented model and robust programming model extended by Mulvey et al. [27], hybrid robust programming model is formulated as follows:

$$Min\sigma(x, y_1, y_2, \dots, y_s) + \gamma\rho(\mathrm{z}_1, \mathrm{z}_2, \dots, \mathrm{z}_\mathrm{s}) \tag{6}$$

$$s.t. \qquad Ax = B \tag{7}$$

$$B_s x + C_s y_s = e_s, \qquad \forall s \in \Omega \tag{8}$$

$$x \geq 0, \qquad y_s \geq 0, \qquad \forall s \in \Omega \tag{9}$$

where, x is a design variable and y is a control variable. Parameters B, A and C are coefficients, and e and b are parameters of the model (right-hand side values). A and B are specified parameters. While B, C, and e are uncertain parameters and uncertain coefficients could be formulated as B_s, C_s, $e_s$regarding scenario $s \in \Omega$.

There are two terms in the objective function. The first phrase is representative of solution robustness and the second one demonstrates the robustness of objective function via application of weight γ. Symbol ξ is a function of the costs and benefits used for each scenario (i.e., $\xi_\mathrm{s} = \mathrm{f}(\mathrm{x}, \mathrm{y}_s)$). High variance for $\xi_s = f(x, y_s)$ indicates that the outcome decisions include high risks for company. Objective function in this method can minimize the total cost of all possible scenarios. Notably, Mulvey et al. [27] offered mean-variance approach as a technique to cope with deviations of objective function. Revised cost function seeks to minimize expected valued of objective function aside with its deviations. Mulvey et al. [27] used following method to find a robust solution and dedicated weight of δ to control variance of solutions.

$$\sigma(0) = \textstyle\sum_{s\in\Omega} p_s \xi_\mathrm{s} + \delta \sum_{s\in\Omega} p_s \left[\xi_\mathrm{s} - \sum_{s\in\Omega} p'_s \xi'_\mathrm{s}\right]^2 \tag{10}$$

In a presented phrase, there is a quadratic term that makes model nonlinear. Leung et al. [28] provided the following modeling method to change the model into a linear form.

$$min \textstyle\sum_{s\in\Omega} p_s \xi_\mathrm{s} + \delta \sum_{s\in\Omega} p_s \left[(\xi_\mathrm{s} - \sum_{s'} p_{s'} \xi_{\mathrm{s}'}) + 2\theta_s\right] + \gamma\rho(\mathrm{z}_1, \mathrm{z}_2, \dots, \mathrm{z}_\mathrm{s}) \tag{11}$$

$$s.t. \qquad Ax = B \tag{12}$$

$$B_s x + C_s y_s = e_s, \qquad \forall s \in \Omega \tag{13}$$

$$\xi_s - \textstyle\sum_{s\in\Omega} p_s \xi_s + \theta_s \geq 0\ ; \tag{14}$$

$$x \geq 0, y_s \geq 0, \theta_s \geq 0 \qquad \forall s \in \Omega \tag{15}$$

Recently, scenario-based robust optimization approach in supply chain planning scope has attracted researchers’ attention. This approach enables decision-makers to control uncertainty of parameters in constraints and objective function based on their level of risk-aversion [29]. This path leads to creation of a series of solutions that are less sensitive to uncertainties of input data [30]. Thus, robust optimization approach via applying different defined scenarios strives to find reliable output decisions for company DMs [28, 30]. In fact, scenario-based robust optimization method considers a range of values for uncertain parameters by defining different scenarios and seeks to achieve risk-averse output decisions [31]. Azaron presented a stochastic multi-objective mixed integer nonlinear programming model to minimize total costs of network design and cost variance [32]. Pishvaee et al. [1]offered a mixed integer linear programming model for closed-loop SCND. Haun and Kuhn developed a framework for value-based performance optimization and supply chain risk management [33]. Ramezani et al. [5] offered closed-loop supply chain network in a multi-product and multi-stage network and suggested a robust optimization approach to handle the uncertainty of demand and the rate recycled End-of-Life products. Salehi et al. [34]expanded a possibilistic Scenario-based robust approach to design flexible retailing network.

Niknamfar et al. [35] developed an optimization model regarding a multi-level supply chain network including production facilities, distribution and customer zones to efficiently manage production-distribution master plan. Most of the above studies are based on the approach extended by Mulvey et al. [27]. This review is also a closed-loop SCND model proposing two objective functions, multi-capacity levels with different production technologies in production, support and pole centers. The extended model controls the flow of components and final products aside with increasing speed of product flow between different echelons of supply chain network.

3. PROBLEM DESCRIPTION AND MODELING

3. 1. Model Definition

This study was conductedby an Iranian national project and real data derived from the noted actual case study. The purpose of this case study was to design a supply chain network for delivering notebook laptops to intelligent training centers that are located across the country. These products were assembled by three components including the body with keyboard and LCD monitor attached to component I, main board and module power supply connected to component II) and main memory or hard drive attached to component III. The forward direction of supply chain network consists of suppliers that provide three noted components for manufacturers' assembly process. Assembly process is performed at manufacturing plants. Final products are sent to pole centers and then distributed in educational centers. In reverse network, defective and End-of-Life products of training centers are sent to national support centers. In any situation that software or hardware of products had limited problems, they would be sent to support centers for repair process, and they will then be returned to pole centers. In a situation that a defective hardware component is non-repairable, it would be entered into the recycling process. Then, recycled components aside with other components coming from suppliers could enter into the production cycle.

To specify the study scope, assumptions are postulated in the proposed model formulation as follows.

- The model covers tactical and strategic planning horizons for one product. Nevertheless, multiple products can be modeled by a small modification.
- The capacity of manufacturers, support centers,and pole centers are restricted.
- Location of suppliers, training centers,and disposal centers are fixed and predefined.
- Flow is only permitted between consecutive stages of the network. Also, there are no flows between facilities at the same stage.
- The quantity of demands, percent of correct and defective components and repairable products, transportation costs and return rates are uncertain and could be described by the set of discrete scenarios.
- Minimization of total costs and maximization of processing and transportation flow speed are regarded as objective functions of the proposed model.

3. 2. Model Formulation

The following notations are used to formulate the P-Robust reliable bi-objective closed loop supply chain model (see Figure 1).

Indices:

s	index of potential locations for suppliers
K	index of potential locations for the manufacturer
P	index of potential locations for national pole centers
E	index of fixed locations of customers
F	index of potential locations for support centers
m	index of potential locations for disposal centers
c	index of components
h	index of scenario
o	index of production technology of manufacturer
u	index of the capacity level of manufacturer
w	index of the capacity level of pole centers
r	index of the capacity level of support centers

Parameters:

*Processing = (operation and isolation)

TFP_{fp}	Shipping cost per product from support center *f* to pole center *p*
TEF_{ef}	Shipping cost per product from training center *e* to support center *f*
TPE_{pe}	Shipping cost per product from pole center *p* to training center *e*
VP_p	Storage cost of pole center *p*
TKP_{kp}	Shipping cost per product from manufacturer *k* to pole center *p*
VK_{ko}	Production cost of manufacturer *k* with production technology *o*
FK_{kuo}	Fixed cost of opening the manufacturer *k* with capacity level *u* and production technology *o*
FP_{pw}	Fixed cost of pole center *p* with capacity *w*
TSK_{skc}	Shipping cost per component *c* unit from supplier *s* to manufacturer *k*
FF_{frt}	Fixed cost of support center *f* with technology t and capacity level *r*
VS_{sc}	Purchase cost per component *c* from supplier *s*
VFP_f	Repairing cost of software per product at support center f
$VHFP_f$	Repairing cost of hardware per product at support center f

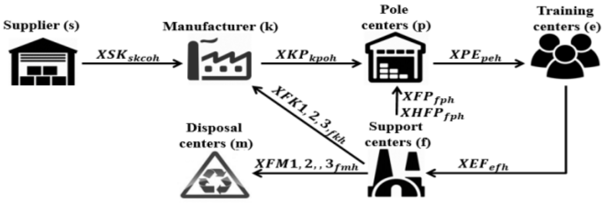

Figure 1. Closedloop supply chain network structure

$THFP_{fp}$	Shipping cost of hardware repaired product from support center *f* to pole center *p*
VFF_f	Processing cost for products with disposal requirements at support center *f*
$STSK_{skc}$	Transportation speed of component *c* between supplier s and manufacturer *k*
SK_{ko}	Production speed with production technology *o* at manufacturer *k*
$STKP_{kp}$	Transportation speed of product between manufacturer *k* and pole center *p*
$STPE_{pe}$	Transportation speed of product between pole center *p* and training center *e*
$STEF_{ef}$	Transportation speed of product between training center *e* and support center *f*
SFF_f	Processing* speed of component with disposal requirements at support center *f*
SFP_f	Repairing speed of software per product at support center *f*
$STFP_{fp}$	Transportation speed of product between support center *f* and pole center *p*
$SHFP_f$	Repairing speed of hardware per product at support center *f*
$KAPK_{ouk}$	Capacity of manufacturer*k* with capacity level *u* and production technology *o*
$CAPP_{pw}$	Capacity of pole center *p* with capacity level *w*
$CAPF_{fr}$	Capacity of support center *f* with capacity level *r*
N_h	Probability of scenario *h*
NP_{kh}	Percentage of the disruptive capacity of manufacturer *k* in scenario *h*
DE_{eh}	Demand for training centers *e* over scenario *h*
σ_{eh}	Percentage of returned products of training center *e* over scenario *h*
PSR	Percentage of the returned product for software repairing
PHR	Percentage of the returned products for hardware repairing
q_{dis}	Percentage of the returned product with disposal conditions
$\gamma, \bar{\gamma}$	Weighting factors for model robustness & objective functions
δ_1, δ_2	Weighting factor for solution robustness part in objective functions *1,2*
q_1, q_2, q_3	Percentage of the returned product with correct components *1,2,3*
q_{12}, q_{13}, q_{2}	Percentage of the returned products with correct components (*1,2;1,3;2,3)*
$VF1_f,$ $VF2_f,$ $VF3_f$	Processing cost of defective components *1,2,3* at support center *f*
$TFM1_{fm},$ $TFM2_{fm},$ $TFM3_{fm}$	Packaging cost of components *1,2,3* from support center *f* to disposal center *m*
$TFK1_{fk},$ $TFK2_{fk},$ $TFK3_{fk}$	Shipping cost of components *1,2,3* from support center *f* to manufacturer *k*
$TFK12_{fk},$ $TFK13_{fk},$ $TFK23_{fk}$	Shipping cost of components(*1,2;1,3;2,3)* from support center *f* to manufacturer *k*
$VFK1_f,$ $VFK2_f,$ $VFK3_f$	Processing cost of components *1,2,3* at support center *f*
$VFK12_f,$ $VFK13_f,$ $VFK23_f$	Processing cost of components(*1,2;1,3;2,3)* at support center *f*
$SFM1_f,$ $SFM2_f,$ $SFM3_f$	Processing* speed of components *1,2,3* with disposal requirements at support center *f*
$STFM1_{fm},$ $STFM2_{fm},$ $STFM3_{fm}$	Transportation speed of components *1,2,3* with disposal requirements between support center *f* and disposal center *m*
$SFK1_f,$ $SFK2_f,$ $SFK3_f$	Processing* speed of correct component *1,2,3* at support center *f*
$SFK12_f,$ $SFK13_f,$ $SFK23_f$	Processing* speed of correct components (*1,2;1,3;2,3)*at support center *f*
$STFK1_{fk},$ $STFK2_{fk},$ $STFK3_{fk}$	Transportation speed of correct components *1,2,3* between support center *f* and manufacturer *k*
$STFK12_{fk,}$ $STFK13_{fk,}$ $STFK23_{fk}$	Transportation speed of correct components (*1,2;1,3;2,3)* between support center *f* and manufacturer *k*

Variables:

XSK_{skcoh}	Quantity of shipped components *c* from supplier *s* to manufacturer *k* with technology *o* over scenario *h*
XKP_{kpoh}	Quantity of shipped products from manufacturer *k* to pole center *p* with production technology *o* over scenario *h*
XPE_{peh}	Quantity of shipped products from pole center *p* to training center *e* over scenario *h*
YK_{kuo}	Quantity of produced products at manufacturer*k* with capacity level u and production technology *o*
XEF_{efh}	Quantity of produced products at training center *e* shipped to support center *f* over scenario *h*
XFF_{fh}	Quantity of products with disposal conditions at support center f over scenario h
XFP_{fph}	Quantity of repaired products (software repairing) shipped from support center *f* to pole center *p* over scenario *h*
$XHFP_{fph}$	Quantity of repaired products (hardware repairing) shipped from support center *f* to pole center *p* over scenario *h*
DEM^{-}_{eh}	Amount of not meeting demand of training center *e* over scenario *h*
θ_{1h}, θ_{2h}	Deviation for violations of the mean of total costs and speeds in scenario *h*
YK_{kuo}	1: If a factory *k* is established with capacity level *u* and production technology *o*; 0: otherwise
YP_{pw}	1: If a pole center *p*is established with capacity level *w*; 0: otherwise
YF_{fr}	1: If support center *f*is established with capacity level *r*; 0: otherwise
$XFK1_{fkh},$ $XFK2_{fkh},$ $XFK3_{fkh}$	Quantity of correct components *1,2,3* isolated at support center *f* shipped to manufacturer *k* in scenario *h*
$XFK12_{fkh},$ $XFK13_{fkh},$ $XFK23_{fkh}$	Quantity of correct components (*1,2;1,3;2,3)* isolated at support center *f* shipped to manufacturer *k* in scenario *h*
$XFM1_{fmh},$ $XFM2_{fmh},$ $XFM3_{fmh}$	Quantity of defective components *1,2,3*isolated at support center *f* shipped to disposal center *m*

$$\boldsymbol{Min\ Z_1} = \sum_o \sum_u \sum_k FK_{kuo} YK_{kuo} + \sum_{\boldsymbol{p}} \sum_{\boldsymbol{w}} FP_{pw}\, YP_{pw} + \sum_f \sum_r FF_{fr}\, YF_{fr} + \sum_h N_h . [\sum_s \sum_k \sum_c (VS_{sc} + TSK_{skc}) . XSK_{skch} + \sum_k \sum_p \sum_o \left(VK_{ko} + TKP_{kp}\right) . XKP_{kpoh} + \sum_p \sum_e \left(VP_p + TPE_{pe}\right) . XPE_{peh} + \sum_e \sum_f TEF_{ef} . XEF_{efh} + \sum_f \sum_m \left(VF1_f + TFM1_{fm}\right) . XFM1_{fmh} + \sum_f \sum_m \left(VF2_f + TFM2_{fm}\right) . XFM2_{fmh} + \sum_f \sum_m \left(VF3_f + TFM3_{fm}\right) . XFM3_{fmh} + \sum_f \sum_k \left(VFK1_f + TFK1_{fk}\right) . XFK1_{fkh} + \sum_f \sum_k \left(VFK2_f + TFK2_{fk}\right) . XFK2_{fkh} + \sum_f \sum_k \left(VFK3_f + TFK3_{fk}\right) . XFK3_{fkh} + \sum_f \sum_k \left(VFK12_f + TFK12_{fk}\right) . XFK12_{fkh} + \sum_f \sum_k \left(VFK13_f + TFK13_{fk}\right) . XFK13_{fkh} + \sum_f \sum_k \left(VFK23_f + TFK23_{fk}\right) . XFK23_{fkh} + \sum_f \sum_p \left(VFP_f + TFP_{fp}\right) . XFP_{fph} \tag{16}$$

$$+ \sum_f \sum_p \left(VHFP_f + THFP_{fp}\right) . XHFP_{fph} + \sum_f VFF_f . XFF_{fh}] \tag{16-1}$$

$$+ \delta_1 \sum_h N_h \left[\left(\xi_h - \sum_{h'} p_{h'} \xi_{h'}\right) + 2\theta_{1h}\right] + \gamma \sum_h N_h \sum_e DEM^-_{eh} \tag{16-2}$$

$$\boldsymbol{Max\ Z_2} = \sum_h N_h\, [\sum_k \sum_c \sum_s STSK_{skc} . XSK_{skch} + \sum_p \sum_e STPE_{pe} . XPE_{peh} + \sum_e \sum_f STEF_{ef} . XEF_{efh} + \sum_k \sum_p \sum_o \left(SK_{ko} + STKP_{kp}\right) . XKP_{kpoh} + \sum_f SFF_f . XFF_{fh} + \sum_f \sum_p \left(SFP_f + STFP_{fp}\right) . XFP_{fph} + \sum_f \sum_p \left(SHFP_f + STFP_{fp}\right) . XHFP_{fph} + \sum_f \sum_m \left(SFM1_f + STFM1_{fm}\right) . XFM1_{fmh} + \sum_f \sum_m \left(SFM2_f + STFM2_{fm}\right) . XFM2_{fmh} + \sum_f \sum_m \left(SFM3_f + STFM3_{fm}\right) . XFM3_{fmh} + \sum_f \sum_k \left(SFK1_f + STFK1_{fk}\right) . XFK1_{fkh} + \sum_f \sum_k \left(SFK2_f + STFK2_{fk}\right) . XFK2_{fkh} + \sum_f \sum_k \left(SFK3_f + STFK3_{fk}\right) . XFK3_{fkh} + \sum_f \sum_k \left(SFK12_f + STFK12_{fk}\right) . XFK12_{fkh} + \sum_f \sum_k \left(SFK13_f + STFK13_{fk}\right) . XFK13_{fkh} \tag{17}$$

$$+ \sum_f \sum_k \left(SFK23_f + STFK23_{fk}\right) . XFK23_{fkh}] \tag{17-1}$$

$$-\delta_2 \sum_{h'} N_h [(\tau_{h'} - \sum_{h'} p_{h'} \tau_{h'}) + 2\theta_{2h}] \tag{17-2}$$

$$\sum_s \sum_k \sum_c (VS_{sc} + TSK_{skcb}) . XSK_{skch} + \sum_k \sum_p \sum_o \left(VK_{ko} + TKP_{kp}\right) . XKP_{kpoh} + \sum_p \sum_e \left(VP_p + TPE_{pe}\right) . XPE_{peh} + \sum_e \sum_f TEF_{ef} . XEF_{efh} + \sum_f \sum_m \left(SFM1_f + STFM1_{fm}\right) . XFM1_{fmh} + \sum_f \sum_m \left(SFM2_f + STFM2_{fm}\right) . XFM2_{fmh} + \sum_f \sum_m \left(SFM3_f + STFM3_{fm}\right) . XFM3_{fmh} + \sum_f \sum_k \left(SFK1_f + STFK1_{fk}\right) . XFK1_{fkh} + \sum_f \sum_k \left(SFK2_f + STFK2_{fk}\right) . XFK2_{fkh} + \sum_f \sum_k \left(SFK3_f + STFK3_{fk}\right) . XFK3_{fkh} + \sum_f \sum_k \left(SFK12_f + STFK12_{fk}\right) . XFK12_{fkh} + \sum_f \sum_k \left(SFK13_f + STFK13_{fk}\right) . XFK13_{fkh} + \sum_f \sum_k \left(VFK23_f + TFK23_{fk}\right) . XFK23_{fkh} + \sum_p \sum_f \left(VFP_f + TFP_{fp}\right) . XFP_{fph} \sum_p \sum_f \left(VHFP_f + THFP_{fp}\right) . XHFP_{fph} \sum_f VFF_f . XFF_{fh} \le Z^* (1 + p) \tag{18}$$

$$\sum_p \sum_b \sum_o XKP_{kpoh} \le \sum_o \sum_u KAPK_{ouk} (1 - NP_{kh}) . YK_{ouk} \quad \forall k, h \tag{19}$$

$$\sum_o \sum_u YK_{ouk} \le 1 \qquad \forall k \tag{20}$$

$$\sum_e XPE_{peh} \le \sum_w CAPP_{pw} . YP_{pw} \quad \forall p, h \tag{21}$$

$$\sum_w YP_{pw} \le 1 \forall p \tag{22}$$

$$\sum_e XEF_{efh} \le \sum_r CAPF_{fr} . YF_{fr} \quad \forall f, h \tag{23}$$

$$\sum_r YF_{fr} \le 1\ \forall f \tag{24}$$

$$\sum_p XPE_{peh} \ge DE_{eh} \forall e, h \tag{25}$$

$$\sum_f XEF_{efh} \ge \sigma_{eh} . DE_{eh} \qquad \forall e, h \tag{26}$$

$$\sum_s XSK_{skch} + \sum_f XFK1_{fkh} + \sum_f XFK12_{fkh} + \sum_f XFK13_{fkh} = \sum_p \sum_o XKP_{kpoh} \qquad \forall c = 1, k, h \tag{27}$$

$$\sum_s XSK_{skch} + \sum_f XFK2_{fkh} + \sum_f XFK12_{fkh} + \sum_f XFK23_{fkh} = \sum_p \sum_o XKP_{kpoh} \qquad \forall c = 2, k, h \tag{28}$$

$$\sum_s XSK_{skch} + \sum_f XFK3_{fkh} + \sum_f XFK13_{fkh} + \sum_f XFK23_{fkh} = \sum_p \sum_o XKP_{kpoh} \qquad \forall c = 3, k, h \tag{29}$$

$$q_1 \sum_e XEF_{efh} = \sum_k XFK1_{fkh} \qquad \forall f, h \tag{30}$$

$$q_2 \sum_e XEF_{efh} = \sum_k XFK2_{fkh} \qquad \forall f, h \tag{31}$$

$$q_3 \sum_e XEF_{efh} = \sum_k XFK3_{fkh} \qquad \forall f, h \tag{32}$$

$$\sum_k \sum_o XKP_{kpoh} = \sum_e XPE_{peh} \qquad \forall f, h \tag{33}$$

$$PSR \sum_e XEF_{efh} = \sum_k XFP_{fkh} \qquad \forall f, h \tag{34}$$

$$q_{12} \sum_e XEF_{efh} = \sum_k XFK12_{fkh} \qquad \forall f, h \tag{35}$$

$$q_{13} \sum_e XEF_{efh} = \sum_k XFK13_{fkh} \qquad \forall f, h \tag{36}$$

$$q_{23} \sum_e XEF_{efh} = \sum_k XFK23_{fkh} \qquad \forall f, h \tag{37}$$

$$q_{dis} \sum_e XEF_{efh} = XFF_{fh} \qquad \forall f, h \tag{38}$$

$$PHR \sum_e XEF_{efh} = \sum_p XHFP_{fph} \qquad \forall f, h \tag{39}$$

$$\sum_e XEF_{efh} = \sum_k XFK1_{fkh} + \sum_k XFK2_{fkh} + \sum_k XFK3_{fkh} + \sum_p XFP_{fph} + \sum_k XFK12_{fkh} + \sum_k XFK13_{fkh} \sum_k XFK23_{fkh} + XFF_{fh} + \sum_p XHFP_{fph} \quad \forall f, h \tag{40}$$

$$q_2 \sum_e XEF_{efh} + q_3 \sum_e XEF_{efh} + q_{23} \sum_e XEF_{efh} + XFF_{fh} + PHR \sum_e XEF_{efh} = \sum_m XFM1_{fmh} \qquad \forall f, h \tag{41}$$

$$q_1 \sum_e XEF_{efh} + q_3 \sum_e XEF_{efh} + q_{13} \sum_e XEF_{efh} + XFF_{fh} + PHR \sum_e XEF_{efh} = \sum_m XFM2_{fmh} \qquad \forall f, h \tag{42}$$

$$q_1 \sum_e XEF_{efh} + q_2 \sum_e XEF_{efh} + q_{12} \sum_e XEF_{efh} + XFF_{fh} + PHR \sum_e XEF_{efh} = \sum_m XFM3_{fmh} \qquad \forall f, h \tag{43}$$

$$\xi_h - \sum_{h'} p_{h'} \xi_{h'} + \theta_{1h} \ge 0 \forall h \tag{44}$$

$$\tau_{h'} - \sum_{h'} p_{h'} \tau_{h'} + \theta_{2h} \ge 0 \forall h \tag{45}$$

$$\sum_p XPE_{peh} + DEM_{eh}^{-} = DE_{eh} \; \forall e, h \tag{46}$$

$$YK_{kuo}, YP_{pw}, YF_{fr} \in \{0,1\} \tag{47}$$

$$YK_{ouk}, YP_{pw}, YF_{frt}, XSK_{skch}, XKP_{kpoh}, XPE_{peh}, XEF_{efh},$$

$$XFM1_{fmh}, XFM2_{fmh} XFM3_{fmh}, XFK1_{fkh}, XFK2_{fkh}, XFK3_{fkth}$$

$$XFK12_{fkh}, XFK13_{fkh}, XFK23_{fkh}, XFP_{fph}, XHFP_{fph}, XHFP_{fph}$$

$$XFF_{fh}, XKP_{kpoh}, XKP_{kpoh} \geq 0 \tag{48}$$

First objective function (16) minimizes total costs of network design regarding robustness costs. The first part (16-1) minimizes thefixed cost of opening facilities at different echelons of the network. The second part of the objective function (16-2) minimizes different processing costs including cost of raw material procurement, storage and transportation costs in forwarding direction and processing and transportation costs of End-of-Life products at the reverse side of network regarding different scenarios. The second objective function (17) is related to maximization of responsiveness of supply chain network to quickly answer and immediately meet the demand of learning centres. It includes processing speed at different echelons of network and transportation speed between consecutive echelons of network. Constraint (18) presents P-Robust constraint. In this constraint, it is assumed that considered costs regarding each planning scenario should be less than or equal to$Z^*(1+p)$. Constraint (19) ensures that total number of products transferred from each factory to different pole centres should be lower than or equal to capacity of manufacturing plant. Constraint (20) ensures that at most one capacity level and production technology would be open for each potential factory. Constraint (21) assures that total number of products sent from each pole centre to training centres should be less than or equal to maximum capacity of each pole centre. Constraint (22) ensures that at most one capacity level should be opened for each pole centre. Constraint (23) ensures that the number of returned products from training centre to each support centre should be less than or equal to capacity of each support centre. Constraint (24) ensures that at most one capacity level should be opened for each support centre. Constraint (25) guarantees meeting demand of customers. Constraint (26) ensures collection of all End-of-Life products from training centres via different support centres. Constraints (27) to (29) ensure flow balance of input components and output final products at manufacturing plants. Constraints (30) to (32) determine number of recycled components at support centres based on number collected products from different training centres. Constraint (33) ensures flow balance at each pole centre. Constraint (34) ensures that number of products requiring software repair at each support centre should be equal to a predefined percentage of number of collected products different training centres. Constraints (35) to (37) assure flow balance of End-of-Life products at each support centre comprising two non-defective components. Constraint (38) ensures flow balance of useless products collected from training centres that should be sent to disposal centres. Constraint (39) assures flow balance of End-of-Life products at support centres that mean number of collected products with hardware problems should be equal to number of recovered products transferred to pole centres. Constraint (40) guarantees flow balance at each support centre. Constraint (41) to (43) ensures flow balance of components at each pole centre. Noted constraints assure that total number of usable recycled components at support centres should be equal to number of components transported to manufacturing plants. Constraints (44) and (45) are used for linearization of robust model based on equations (10) to (15). Notably, ξ_h presents value of cost objective and τ_h refers to value of objective function of delivery speed maximization regarding scenario h. Constraint (46) is a control constraint that manages flow of products from pole centres to training centres. Constraint (47) and (48) impose binary and non-negativity restrictions on decision variables.

4. IMPLEMENTATION AND EVALUATION (NUMERICAL EXAMPLE: CASE STUDY)

In this section, the proposed model is solved and analysed based on the case study of an Iranian national project with the aim of equipment training centers. To evaluate the accuracy of proposed model, numerical examples of the project aboveare madewith the help of field experts. According to the importance of this research in the national dimension and uncertainty of parameters, a team of managers was arranged to design realistic scenarios. First, the effect of disruption on the supply chain network facilities by altering P-Robust criteria was reviewed. Regarding equation (18), in case that $p \geq \infty$, the P-Robust criterion is disabled and there is no protection against disruptions. On the other hand, a small p-value, may cause infeasible solutions. In fact, one of goals of extended model is to minimize maximum value of costs emanated from disruptions regarding different disruption scenarios. Snyder and Daskin proposed an approach that makes a trade-off curve between the relative maximum regret and the relative cost [24]. The model was solved regarding $p \geq \infty$ and maximum regret was found for all scenarios. Then,maximum achieved regret was subtracted 0.01 and model was resolved. Process will continue until there is no feasible solution. Analysis of objective function value based on different maximum regret values were summarized in Table 1.

According to presented results in Table 1, reducing the value of robustness parameter leads to increase in the objective function cost (i.e., a small percentage). Therefore, it was concluded that the above model is capable of efficiently producing trade-off between maximal relative regret and nominal costs.

Furthermore, to assess the performance of robust model against the deterministic model, they are solved separately, and output results are rendered in Table 2.

Also, the extended model is solved via considering fixed parameter Delta and different values of parameter Gamma. The results are provided in Table 2. While increasing the robustness coefficient of the model (i.e., gamma), unsatisfied demand is compensated in the objective function, and that results in solution robustness. The model can use more than predefined capacity regarding high rates of parameter gamma.

For $\delta = 1$ and different Gamma values indicated in Table 3. It means that by increasing the balancing coefficient of model robustness and solution robustness, unsatisfied demand values and solution robustness alter according to the expected change.Also, interactions of weighting factor$\varpi$and standard deviation values are demonstrated in the Table 4.

TABLE 1. Sensitivity analysis objective function value on the robust number

P-robust	∞	**6.13**	**6.12**	**6.11**	**6.1**	**6.09**	**6.08**
Objective function	71566842	71567448	71568133	71569081	71568752	71568752	**Infeasible**
Maximum relative regret	6.14	6.13	6.12	6.11	6.1	6.09	**6.08**

TABLE 2. Comparison of the robust and deterministic results

Probability ofscenario *h*		**Objective function values**			
		Deterministic		**Robust**	
		Z_1	Z_2	Z_1	Z_2
	0.25	76265037	35307887	75889321	35689824
1	0.6	81243672	37612811	81574227	37842733
	0.95	84351265	39051511	84825549	40028631
	0.25	84677353	39202478	84725112	39761490
2	0.6	88264715	40863293	88191149	42695138
	0.95	89403732	41390616	88923928	43782225
	0.25	87769347	40633956	88389864	43254361
3	0.6	93483547	43279419	94767375	45719436
	0.95	96805724	45012309	97353754	46164381
	0.25	95674065	44477120	96083662	46175237
4	0.6	97511236	44830814	96356219	46832145
	0.95	110348452	50191696	125475378	49047827

TABLE 3. Analysis of Robust parameters ($\delta = 1$)

γ	**Unsatisfied demand**	**Robustness solution**	**Expected cost**
8000	1650	67494.251	84725746
12000	823	3450569	85646990
18000	178	8042667	88478186
35000	0	10068783	94969652

TABLE 4. Impact of changing the objective weights on mean value and standard deviation

Weighting parameter	μ_1	μ_2	σ_1	σ_2
$\varpi = 1$	88483173.75	40825159.2	92648.63	47126.42
$\varpi = 0.8$	88483173.75	40825159.2	92648.63	47126.42
$\varpi = 0.6$	88483173.75	40825159.2	92648.63	47126.42
$\varpi = 0.4$	95432868.37	42108420.7	94546.42	46532.7
$\varpi = 0.2$	95706028.49	43794351.43	91201.6	48623.1
$\varpi = 0$	94537613.49	43885273.82	93625.2	48972.4

As shown in Table 4, standard deviation of costs and expected delivery speed does not change up to $\varpi = 0.6$. Decreasing value of weighting factor from 0.6 to zero leads to increse of average standard deviation of costs. Also, decreasing trend of weighting factor ϖ has led to increase in the expected speed standard deviation. In the weighting factor $\varpi = 0.2$, overall costs is increased with high rates (i.e., 9%) compared to initial value. In contrast, the average expected speed for the initial values is increased up to 7%.

To evaluate results, proposed robust and deterministic models are solved. Mean, and standard deviation of objective functions are computed for scenarios (Figure 2). The findings demonstrate the importance and effectiveness of robust optimization approach. Figure 2 describes the application of robust optimization approach that has been effective in offsetting the costs, controlling capacity of facilities, increasing the efficiency of reopened facilities and their effectiveness in improving the delivery speed of products to the learning centers. In other words, applying robust programming method has led to lower constraint violations and accordingly total cost are lower regarding mean and standard deviation of the objective cost function. In this regard, it could be noted that robust programming method is better performing owing to its ability to control the risk-aversion level of output decisions.

Notably, to show the efficient performance of extended model strategic output decisions of the model (i.e., number of opened plants and their corresponding capacity level and production technology) are rendered in Table 5. As can be understood from output results of the model, the best choice is chosen in this model about disruptions effect on the capacity of facilities. In other words, opened facilities are less sensitive to strike of disruptions and have lowest lost capacity regarding crisis circumstance that results in lower cost increase. Noted matter confirms that long-term plan of the extended reliable network could be trustworthy for company DMs.

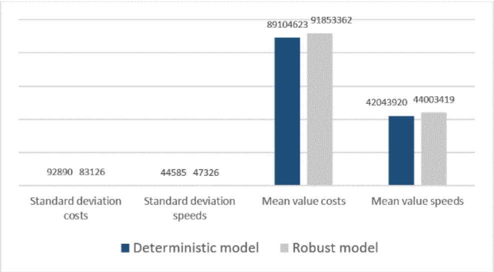

Figure 2. Comparison of the robust and deterministic results ($\varpi = 0.6$)

TABLE 5. Opened plants regarding different disruption scenarios

Manufacturing plant	Capacity level			Production technology		
	No. 1	No. 2	No. 3	No. 1	No. 2	No. 3
No. 1.		■		■		
No. 2.	■					■
No. 3.						
No. 4.						
No. 5.	■				■	
No. 6.						
No. 7.						
No. 8.			■		■	
No. 9.		■		■		
No. 10.		■				■

Output results would help DMs to cope with adverse effects of disruptions effectively. The other important point is that chosen production technologies are the best ones. As it can be seen, most of the manufacturing plants are opened with their second or third production technology that helps to deliver products to pole centers with lowest processing time and makes supply chain network responsive. Noted matter can be regarded as a long-term competitive advantage for company managers.

Finally, it should be mentioned that proposed model is a reliable, responsive closed-loop SCND model that is capable of controlling model robustness and determining the risk-aversion level of decisions. The extended robust counterpart model outperforms deterministic model regarding different performance measures.

4. CONCLUSIONS AND FUTURE RESEARCH

This article seeks to render a bi-objective optimization model with P-Robust restrictions on costs of network design regarding each scenario which is presented for the closed-loop SCND problem. Furthermore, it aims to maximize the responsiveness of supply chain by extending a new objective function. The primary goal is to increase the speed of product delivery to the training centers. Some parameters such as demand of customers, the percentage of returned products from learning centers to support centers, the amount of unsatisfied demand of e-learning centers and the percentage of disrupted capacity of manufacturers are regarded as uncertain parameters. Then, about theavailability of uncertain parameters, robust counterpart of the model should find robust solutions and control the risk-aversion level of output decisions. A feature of the extended model is minimizing the expected costs of network design including processing and operation costs in such a way that a reliable network is extended. In robust optimization, worst-case scenario would be fundamentally optimized. Also, the expected value of network design costs is minimized via different defined scenarios. In this study, the model propose to minimize the expected costs of network design; also considers a P-robustconstraint on each design scenario results in the reliability of the network. Furthermore, proposed model maximizes the flow speed of products and components in forward and reverse directions of network. It means that output decisions provided by proposed model minimizes total expected costs of network and maximizes expected product delivery speed. Notably, the model is tested via application of four scenarios; that are designed by field experts, and the impact of changing parameters on behavior and complexity of the model is analyzed. After running the model, results indicate that the quality of the output results of the extended robust model is better than deterministic model regarding mean and standard deviation measures.

Notably, output results of the extended model showed that opened facilities in disruptions strike circumstance are those facilities that are less sensitive to capacity losses and long-term operation failure. In this regard, it could be mentioned that output results achieved by solving extended bi-objective reliable SCND model are trustworthy owing to their best performance regarding disruptions strike. Also, extended model strives to open facilities and chose to transfer ways that are faster and help to heighten responsiveness of supply chain network. Output results of model confirm the accurate performance of a proposed model that could be regarded as its advantage over other extended models in the related literature based on comments of field experts and company managers.

As future research guideline, it is noted that since solving of closed-loop SCND models is an NP-HARD problem, it is better to use a meta-heuristic algorithm to reduce the time and complexity of solving the model.

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A Robust Reliable Closed Loop Supply Chain Network Design under Uncertainty: A Case Study in EquipmentTraining Centers

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PAPER INFO

Paper history:
Received 14 April 2017
Received in revised form 27 May 2017
Accepted 07 July 2017

Keywords:
Closed Loop Supply Chain
Responsiveness
Robust Optimization
P-Robust
Uncertainty
Training Center

چکیده

هدف این مقاله ارائه یک مدل P-Robust پایای دوهدفه طراحی شبکه زنجیره تامین می باشد که دارای قابلیت کنترل انواع مختلف عدم قطعیت به صورت همزمان می باشد. با توجه به این موضوع، متد دو سطحی برنامه ریزی احتمالی مورد استفاده قرار گرفته است تا سناریوهای مختلف مرتبط با وقوع اختلالات مدل شود. متد مطرح شده کمک می کند تا به اثرات منفی اختلالات غلبه گردد و شبکه ای توسعه داده شود که با توجه به وقوع اختلالات کمتر آسیب پذیر می باشد. همچنین، رویکرد مدلسازی مبتنی بر سناریو تصمیم گیرندگان را قادر می سازد تا عدم قطعیت پارامترهای مدل را با در نظر گرفتن سناریوهای مختلف مدلسازی کنند که در تحقیقات حوزه طراحی شبکه زنجیره تامین پایا مدنظر قرار داده نشده است. یک رویکرد موثر برنامه ریزی استوار به کار گرفته شده است تا سطح ریسک گریزی تصمیمات خروجی کنترل شود که به مدیران سازمان ها کمک می کند تا بتوانند اثرات بلند مدت تصمیماتشان را از طریق تعیین سطح عدم قطعیت پارامترهای مدل تنظیم کنند. لازم به ذکر است که مدل برنامه ریزی دو هدفه توسعه داده شده مجموع هزینه های طراحی شبکه را در کنار بیشینه سازی پاسخگویی شبکه زنجیره تامین، کمینه می نماید. شبکه هایی که دارای عملکرد سریع و چابک هستند می توانند به عنوان یک مزیت رقابتی بلند مدت برای سازمان ها در نظر گرفته شوند که در مدل توسعه داده شده به عنوان یک تابع هدف متضاد در کنار کمینه سازی هزینه ها مدلسازی شده است. در نهایت، مدل پایای استوار توسعه داده شده، بر اساسیک مطالعه موردی واقعی مربوط به یک پروژه ملی پیاده سازی و ارزیابی شده است و نتایج خروجی کارایی و قابلیت استفاده شبکه پایایی پیشنهادی را نشان می دهد.

doi*: 10.5829/ije.2018.31.04a.17*