A stochastic programming model for the network design of closed-loop supply chains under disruptions: A case study of glass supply chain

KEYWORDS
Supply chain management, Network design, Closed-loop supply chain, disruption.

ABSTRACT
This paper presents an optimization model for the design of a closed-loop supply chain network consisting of suppliers, production facilities, recovery centers, disposal centers, and markets. The proposed model is capable of accounting for risks of disruption and investigating the lateral transshipment strategy to reduce such risks. The objective is to minimize the total supply chain costs, while considering different recovery and disposal activities during normal situations and when disruptions occur. The application of the proposed model is examined in a case problem where real data is utilized to design a closed-loop network for a company involved in the production and distribution of glass. The numerical results arrive at helpful managerial insights.

1. Introduction
Fierce competition in today’s global markets, the heightened expectations of customers, and rapid improvement of information technology has led to shorter circulation of life cycles, smaller transportation capacities and more dynamic behaviors of customers in terms of choices and demands. This has forced business enterprises to invest in, and focus attention on, their supply chains and has motivated the continuous evolution of the techniques to manage them effectively ([1]. In this context, supply chain network design is of paramount importance and can dramatically impact a company’s efficiency and effectiveness. It includes strategic decisions on the number, location, and the intensity of flow among them; the aim of designing the supply chain, in addition to finding the location of facilities, is to minimize costs, i.e. costs of purchasing, production, transportation, inventories costs and etc. One important issue treated in designing the supply chain and logistic networks is designing the integrated forward and reverse supply chains. Integrating the forward and reverse supply chain results in a closed loop supply chain (CLSC). In other words both channels of forward and reverse are available in the closed loop supply chain networks (CLSCN). In recent decades due to the increase in environmental concerns, governmental legislations, and limitations in natural resources, the closed loop supply chain has attracted lots of attentions, so considering these requirements and the extent of influence that is expected from designing the integrated networks on reducing the current costs in supply chain, it seems necessary to study the closed loop supply chain networks [2, 3]. Closed-loop supply chain design generally explores the best set of inventory, transportation, and production decisions while exploring ways of reducing the amount of resource needed for the production, consumption and disposal. [4, 5].

Nowadays the various kinds of systems from the simplest one to the most complicated have become integrated parts of man’s life. Failure of systems that could lead to chaos and huge and irreparable disruptions is considered as a serious threat for the community as well as for the environment. Supply chain also as a complicated system comprising of many different organizations of different identities is no exception to this rule [6, 7]. Disruption risks may result in negative financial effects and serious operational consequences (e.g., larger transportation costs, order delays, inventory shortages, loss of market shares, and, etc.) [8, 9]. Thus, it is crucial to prudentely take disruption risks into consideration in supply chain design phase and develop strategies to reduce such risks.
While closed-loop supply chain design has been the focus of researchers and practitioners during the recent years, most of the existing models in the literature overlook disruption
risks when configuring closed-loop supply chain networks (see Section 2). Motivated by a real-word case study faced by Hamadan Glass Company, the present paper aims to address the aforementioned research gap. We formulate an optimization model to design a closed-loop supply chain network which is capable of considering risks of disruption. The proposed model also can be distinguished from the literature by incorporating lateral transshipment (i.e. the redistribution of products from facilities with stock on hand to centers that face losses due to disruptions [10]), as a practical strategy to reduce the impacts of disruptions. The objective is to minimize the total supply chain costs (including fixed costs of establishing facilities, transportation costs, inventory costs and penalty costs for non-satisfied demands), while accounting for recovery and disposal activities. The rest of the paper is organized as follows. The relevant literature is reviewed in the next section. In sections 3, the concerned problem is discussed and the optimization model for the problem is formulated. The application of the developed model in a real world case is presented in Section 4 including the practical and managerial insights obtained from the numerical results. Finally, Section 5 conclude the article and present directions for future research.

2. Literature Review

This section presents a brief review on the most relevant models for the closed-loop supply chain network design. More comprehensive review of published papers in reverse logistic and closed-loop supply chain can be found in Pokharel and Mutha [11] and Govindan et al. [12].

Fleischmann et al. [13] are among the first researchers that attempted to design integrated models for reverse and closed-loop supply chain network planning. Salema et al. [14] tried to modify the work of Fleischmann et al. [13] by presenting a model for the design of a generic reverse logistics network under uncertainty. Using stochastic mixed-integer programming approach, the authors tried to consider capacity limitations, multi-product management and uncertainty on product demands and returns. Lu and Bostel [15] studied a bi-level location problem with three types of facilities that must be located in a remanufacturing network. They formulated a mixed-integer programming model accounting for both forward and reverse flows and their interactions at the same time. To solve the proposed model, a lagrangian-based heuristic was developed. Listes [16] presented a scenario-based stochastic programming model for the design of integrated forward/reverse supply chain network. They develop a decomposition method based on the branch-and-cut procedure to solve the model in large-sized instances. Özcyylan et al. [13] formulated an integrated model that jointly optimizes the strategic and tactical decisions of a closed-loop supply chain. The objective of their problem is to minimize costs including transportations, purchasing, refurbishing and operating the disassembly workstations costs.

Qiang et al. [17] investigated a closed-loop supply chain network with decentralized decision-makers consisting of raw material suppliers, retail outlets, and the manufacturers that collect the recycled product directly from the demand market. Pishvaee et al. [18] developed a bi-objective mixed-integer linear programming model which seeks to maximize the network responsiveness and minimize the total costs in a closed-loop supply chain network. Likewise, Pishvaee et al. [19] presented a bi-objective possibilistic mixed integer programming model that deals with uncertainty. The proposed model integrates the network design decisions in both forward and reverse supply chain networks, and also incorporates the strategic network design decisions along with tactical material flow ones to avoid the sub-optimality. Another bi-objective model for the design of a closed-loop supply chains developed by Amin et al. [20]. Their model tries to simultaneously minimize total costs and maximize the utilization of environmental friendly materials.

A limited number of multi-period models can be found in the literature of closed-loop supply chain network design. Keyvanshokoo et al. [21] formulated a multi-echelon, multi-period and multi commodity model for forward/reverse logistics network design that the returned products are categorized with respect to their quality levels. The objective of the proposed model is to minimize the total costs. Demirel et al. [23] proposed a mixed integer programming model for a closed-loop supply chain network with multi-periods. They assumed two policies in model, secondary market pricing and incremental incentive policies. To solve the model in real size a genetic algorithm approach was developed. Ramezani et al. [22] also addressed the application of fuzzy sets to design a multi-product, multi-period, closed-loop supply chain network. Their model includes three objective functions: maximization of profit, minimization of delivery time and maximization of quality.

There are scanty models in the literature considering disruptions in closed-loop supply chains network. Hatemi et al. [24] developed a reliable model for design of an integrated forward-reverse logistics network and used reliability concepts to deal with facility disruptions. Unreliable hybrid facilities were allowed to be partially disrupted but they could still serve their customers with their remaining capacities. Vahdani et al. [25] presented a model for designing a reliable network of facilities in closed-loop supply chain under uncertainty. To this aim, a bi-objective mathematical programming formulation was developed which minimizes the total costs and the expected transportation costs after failure of facilities of the logistics network. More recently, Hasanzadeh Amin et al. [26] developed a robust and reliable model for a forward-reverse logistics network design that takes uncertain parameters and facility disruptions into account simultaneously. The proposed network was single-period, single-product and multi-echelon which includes production and distribution centers in the forward flow and collection, recovery and disposal centers in the reverse flow. Devika et al. [26] considered the three pillars of sustainability in the design of closed-loop supply chain network problem simultaneously. For this purpose, a mixed integer programming model was developed. In order to solve the model, three hybrid metaheuristic methods were developed. Hasanzadeh Amin et al. [26] worked on a multi-objective model for CLSCN. They investigated a CLSCN consisting of plants, collection centers, demand points, and products. They proposed a linear programming model which its purpose is to minimize the costs.

As it can be concluded from reviewing the literature the present paper differs from the existing studies in the area of closed-loop supply chain design by considering risks of disruption and investigating the lateral transshipment. More specifically, our model takes into account the risks of disruption in the design of closed-loop supply chain networks. While there are some papers in the realm of closed-loop supply chain network design accounting for random disruptions, none of them incorporate lateral
transshipment into the problem. Moreover, unlike the presented model in this study, the existing models in the literature typically overlook multiple-period nature of the problem. The application of our model in an actual closed-loop supply chain involved in the production and distribution of glass also distinguishes our research from the earlier works in the literature.

3. Illustrations

3.1. Problem statement

We examine the network design of a closed-loop supply chain that is multi-echelon, multi-product, and multi-period. The network under investigation includes different markets, collection/inspection centers, production facilities, disposal centers and suppliers. There are two flows of items within the supply chain: forward and reverse flows. Associated with forward flows of products, production centers receive raw materials from suppliers to produce the products. Then, the products are shipped to the customers at the first markets. Conversely, the reverse flow of products aim to satisfy the demand of customers through recovering the returned products from the second markets. More specifically, the returned products are delivered to collection/inspection centers serving as responsible for collecting/testing the items. Next, the recoverable items are transported to production/recovery centers, and the scrapped products are shipped to disposal centers. The recovered products are then transported to customers at the first markets. Fig. 1 illustrates the structure of the supply chain network.

![Fig. 1: Structure of supply chain network](image)

The key point is that production/recovery centers are vulnerable to random disruptions due to different reasons such as natural disasters, machine failures, air pressure drop, power outage and etc. If a disruption occurs at a production/recovery center, the facility lose a percentage of its capacity. In this context, the unaffected production/recovery centers can transship the products to the disrupted facilities to compensate their lost capacities.

The following assumptions are made in the network configuration:

- The model is designed for multiple products and multiple periods,
- The unsatisfied demands of customers are lost,
- Locations of suppliers, customers and disposal centers are known in advance,
- Capacity of facilities are limited, and
- The lateral transshipments between facilities are allowed.

To formulate the problem, we develop a stochastic optimization model which minimizes the total supply chain cost, while incorporating different scenarios of disruptions. Our model is based on two-stage programming approach and simultaneously determines the following decisions:

- Number and location of production/recovery centers,
- Number and location of hybrid collection/inspection centers,
- Flows of raw materials and products within the supply chain network,
- Quantity of transshipment between facilities in case of disruptions, and
- Amounts of lost sales in markets.

3.2. Notations

The model uses the following sets, parameters and decision variables.

Sets:

- $J$ Set of suppliers $j = 1,...,J$
- $l$ Set of potential locations for production/recovery centers $i = 1,...,L$
- $K$ Set of potential locations for collection/inspection centers $k = 1,...,K$
- $M$ Set of first market zones $m = 1,...,M$
- $N$ Set of second market zones $n = 1,...,N$
- $L$ Set of disposal centers $l = 1,...,L$
- $S$ Set of disruption scenarios $s = 1,...,S$
- $T$ Set of time periods $t = 1,...,T$
- $P$ Set of product types $p = 1,...,P$
- $Mat$ Set of raw materials in the forward flow $mat = 1,...,Mat$
- $RMat$ Set of raw materials in the reverse flow $rmat = 1,...,RMat$

Parameters:

- $d_{nt}^{opt}$ Demand of customer $n$ for product $p$ in period $t$
- $r_{nt}^{opt}$ Amounts of product type $p$ which are returned from customer $m$ in period $t$
- $\alpha_k$ Average disposal fraction
- $cc_k$ Capacity of returned products at collection/inspection center $k$
$c_{ri}$ Capacity of recovered products at production/recovery center $i$

$cr_{ri}$ Capacity of raw materials at production/recovery center $i$

$crp_{ri}$ Production capacity of production/recovery center $i$

\[ \text{parameter} \]

$cd_{li}$ Capacity of scrapped products at disposal center $l$

$oc_{ki}$ Fixed cost of opening collection/inspection center $k$

$or_{ri}$ Fixed cost of opening production/recovery center $i$

$c_{nkpi}$ Unit transportation cost of returned product $p$ from customer zone $m$ to collection/inspection center $k$ in period $t$

 =>$a_{kpi}$ Unit transportation cost of recovered product $p$ from collection/inspection center $k$ to production/recovery center $i$ in period $t$

 =>$V_{kpi}$ Unit transportation cost of scrapped product $p$ from collection/inspection center $k$ to disposal center $l$ in period $t$

 =>$ctr_{ki}$ Unit transportation cost of product $p$ from production/recovery center $i$ to production/recovery center $e$ in period $t$

 =>$citi_{kpi}$ Unit transportation cost of recovered product $p$ from production/recovery center $i$ to customer zone $n$ in period $t$

 =>$ic_{pi}$ Unit cost of handling product $p$ at production/recovery center $i$ in period $t$

 =>$ic_{pi}$ Penalty cost of not satisfying a unit of demand type $p$ at market $n$ in period $t$

 $\text{weight}_{m,p}$ Weight of raw material used in product $p$

 $rweight_{m,p}$ Weight of recycled raw material used in product $p$

 $\text{weight}_{m,p}$ Weight of recycled material obtained from product $p$

 $\text{cm}_{pi}$ Unit production cost of product $p$ from raw materials at production/recovery center $i$

 =>$cpr_{p}$ Unit production cost of product $p$ from returned products at production/recovery center $i$

 =>$\%_{i}$ Percentage of disruption at production/recovery center $i$ in period $t$ in scenario $s$ (it is takes value from the interval $[0,1]$)

 $\text{probs}$ Probability occurrence of scenario $s$

**Decision Variables:**

$STI'_{n, j, z, s}$ Quantity of raw materials shipped from supplier $j$ to production/recovery center $i$ in period $t$ in scenario $s$

 =>$ITN'_{n, p, s}$ Quantity of recovered product $p$ shipped from production/recovery center $i$ to market zone $n$ in period $t$ in scenario $s$

 =>$X'_{m, s, k, p, i}$ Quantity of returned product $p$ shipped from market zone $m$ to collection/inspection center $k$ in period $t$ in scenario $s$

 =>$U'_{k, p, s}$ Quantity of scrapped product $p$ shipped from collection/inspection center $k$ to production/recovery center $i$ in period $t$ in scenario $s$

 =>$G'_{k, s, l}$ Quantity of scrapped product $p$ shipped from collection/inspection center $k$ to disposal center $l$ in period $t$ in scenario $s$

 =>$TR'_{k, p, s}$ Quantity of product $p$ shipped from production/recovery center $i$ to production/recovery center $e$ in period $t$ in scenario $s$

 =>$PM'_{p, s}$ Quantity of product $p$ produced from raw materials at production/recovery center $i$ in period $t$ in scenario $s$

 =>$PR'_{p, s}$ Quantity of product $p$ produced from returned products at production/recovery center $i$ in period $t$ in scenario $s$

 =>$\delta_{n, p, s}$ Quantity of unsatisfied demand of product type $p$ at market zone $n$ in period $t$ in scenario $s$

 =>$IN'_{p, s}$ Quantity of inventory of product type $p$ at production/recovery center $i$ in period $t$ in scenario $s$

 =>$Y_{k}$ A binary variable equal to 1 if collection/inspection center $k$ is established; 0, otherwise

 =>$Z_{i}$ A binary variable equal to 1 if production/recovery center $i$ is established; 0, otherwise

**3.2. Model formulation**

In terms of the above notation, the integrated model for market to market closed-loop supply chain network design problem can be formulated as follows:
\[
\begin{align*}
\min \quad & Z = \sum_{s} oc_s Y_s + \sum_{i} or_i Z_i \\
& + \sum_{m,k,p,s,\alpha} \sum_{i} \left( \text{probs}_{\alpha} \right) c_{\alpha} Y_{s,i} X_{s,i}^* \\
& + \sum_{i} \sum_{k} \sum_{p,s} \left( \text{probs} \right) a_{\alpha} U_{s,i}^* \\
& + \sum_{i} \sum_{k} \sum_{p,s} \left( \text{probs} \right) c_{\alpha} ITN_{s,i}^* \\
& + \sum_{i} \sum_{k} \sum_{p,s} \left( \text{probs} \right) c_{\alpha} STI_{s,i}^* \\
& + \sum_{i} \sum_{k} \sum_{p,s} \left( \text{probs} \right) w_{\alpha} G_{s,i}^* \\
& + \sum_{i} \sum_{k} \sum_{p,\alpha} \left( \text{probs} \right) b_{\alpha} TR_{s,i}^* \\
& + \sum_{i} \sum_{k} \sum_{p,\alpha} \left( \text{probs} \right) c_{\alpha} PM_{s,i}^* \\
& + \sum_{i} \sum_{k} \sum_{p,\alpha} \left( \text{probs} \right) c_{\alpha} PR_{s,i}^* \\
& + \sum_{i} \sum_{k} \sum_{p,\alpha} \left( \text{probs} \right) \sigma_{\alpha} \delta_{s,i}^* \\
& + \sum_{s} \sum_{p,\alpha} \left( \text{probs} \right) i_{\alpha} \sigma_{s,i}^* 
\end{align*}
\]

The objective function of this problem is to minimize the total supply chain costs which includes fixed costs of opening facilities, transportation costs, production cost, inventory costs and penalty costs for non-satisfied demands. Eq. (2), represents the flow balance constraints in market locations. Eq. (3) ensures the returned products from the first market are collected. Eq. (4) requires the quantities of non-satisfied demand are less than the amounts of total demand. Eq. (5) and Eq. (6), indicate the flow balance constraints in collection/inspection centers. Eq. (7)-(9), are the capacity constraints in collection/inspection centers. Eq. (10), represents the inventory balance constraint in production/recovery centers. Eq. (11) and Eq. (12), guarantee a lateral transshipment between two production/recovery centers is possible only in the situation that the both facilities are open and the amounts of transshipment is less than the capacities of the centers. Eq. (13), stipulates the inventory level at each production/recovery center is less than the capacity of the center. Eq. (14), and Eq. (15), ensure the amounts of raw materials in the forward and reverse flows are sufficient for producing the products. Eq. (16), enforces the limited capacity of production/recovery centers under each disruption scenario. Eq. (17), and Eq. (18), enforce the binary and non-negativity restrictions on corresponding decision variables.

4. Implementation and evaluation

4.1. Case problem

Hamadan Glass Company (HGC) is an Iranian corporation involved in the production and distribution of glass. The company was established in 1354 with the participation of Bank of Industry and Mine (formerly Industrial Credit Bank) in Hamadan. Currently, HGC not only is a pioneer glass production company in Iran, but also does serve as one of the largest companies across the neighbor countries. The company’s products include a variety of glass bottles and jars in different sizes for different products such as lemon juice, syrup, alcohol, beverages, liquid oil, soda, milk, sauce, jam, pickles, tomato and etc.

We applied the proposed approach in this study to
redirect the HGC’s supply chain network. The main reasons which have motivated HGC to redesign its supply chain network are as follows. First, HGC aims to enter new markets requiring new infrastructures. Moreover, high risks of disruption in the region (e.g. the risks of earthquakes) has persuaded HGC to seek more reliable supply chain network. Another reason is related to lower costs of producing glass items through returned products justifying the redesign of supply chain network for more efficient reverse logistics.

HGC identified 6 potential locations for establishing new plants, 10 candidate sites for locating collection centers, and 5 locations for establishing disposal centers around the country. Fig. 2 implies these sites. The markets each include 15 customers whose demands are presented in Table 1. The capacity and fixed opening costs of potential production/recovery centers and collection/inspection centers are given in Table 2. And Table 3.

### Table 1. Demand of products in different markets

<table>
<thead>
<tr>
<th>Markets</th>
<th>135gr Jar</th>
<th>190gr Jar</th>
<th>250gr Jar</th>
<th>280gr Jar</th>
<th>290gr Jar</th>
<th>500gr Jar</th>
<th>750gr Jar</th>
<th>1050gr Jar</th>
<th>1500gr Jar</th>
<th>1700gr Jar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Javenh 4 Fasl Co.</td>
<td>186000</td>
<td>198300</td>
<td>143000</td>
<td>189000</td>
<td>180000</td>
<td>45000</td>
<td>16000</td>
<td>750</td>
<td>10000</td>
<td>12000</td>
</tr>
<tr>
<td>Limondis Co.</td>
<td>34000</td>
<td>160000</td>
<td>123000</td>
<td>0</td>
<td>41000</td>
<td>121000</td>
<td>0</td>
<td>63000</td>
<td>45000</td>
<td>0</td>
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<tr>
<td>Tak Miveh Co.</td>
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<td>56000</td>
<td>156000</td>
<td>83000</td>
<td>158000</td>
<td>36000</td>
<td>53000</td>
<td>40000</td>
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<td>184000</td>
<td>164000</td>
<td>260000</td>
<td>17000</td>
<td>150000</td>
<td>171000</td>
<td>148000</td>
<td>153000</td>
</tr>
<tr>
<td>Mahram Co.</td>
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<td>189000</td>
<td>12000</td>
<td>91500</td>
<td>153000</td>
<td>163000</td>
<td>169000</td>
<td>164000</td>
<td>175000</td>
<td>53000</td>
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<td>Etko Co.</td>
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<td>240000</td>
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<td>315000</td>
<td>120000</td>
<td>165000</td>
<td>148000</td>
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<td>Kalleh Co.</td>
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<td>163000</td>
<td>180000</td>
<td>146000</td>
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<td>211000</td>
<td>211000</td>
<td>193000</td>
<td>21000</td>
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Table 2. Capacities (million unit) and fixed opening costs (million Rial) of production centers

<table>
<thead>
<tr>
<th>Production center</th>
<th>Raw materials capacity (crm)</th>
<th>Recovered products capacity (crt)</th>
<th>Production capacity (crp)</th>
<th>Opening cost (or)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tehran</td>
<td>235.550</td>
<td>5569</td>
<td>195.685</td>
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<tr>
<td>Shiraz</td>
<td>220.500</td>
<td>5049</td>
<td>191.426</td>
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<td>Mashhad</td>
<td>210.890</td>
<td>5421</td>
<td>190.997</td>
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<td>Kerman</td>
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<td>4976</td>
<td>175.204</td>
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<td>Tabriz</td>
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<td>5384</td>
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<tr>
<td>Hamadan</td>
<td>240.330</td>
<td>5577</td>
<td>200.724</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3. Capacity (million unit) and fixed opening costs (million Rials) of collection/inspection centers

<table>
<thead>
<tr>
<th>Collection/inspection center</th>
<th>Capacity (cc)</th>
<th>Opening cost (oc)</th>
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</thead>
<tbody>
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<td>Ahvaz</td>
<td>209.727</td>
<td>3.80</td>
</tr>
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<td>Isfahan</td>
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4.2. Computational results

We implemented the developed model for determining optimal supply chain design decisions for the case problem described in Section 4.1 that the value of some parameters are given in Appendix. The model was solved using CPLEX solver of GAMS 24.3. In all the experiments, the model is solved within few seconds. Figure 3 shows optimal decisions for location and allocation decisions of the facilities.

Fig. 3. Optimal decisions for facility location and allocation decisions
Fig. 4. The impacts of varying the quantity of returned products on strategic and operational costs of the supply chain

Fig. 5. The impacts of varying the percentage of disruptions on strategic and operational costs of the supply chain

To derive useful managerial insights, we also investigate the effects of varying different parameters of the model on the strategic and operational costs of the supply chain. Strategic cost entails the total costs of establishing facilities, whereas the operational costs are associated with the sum of the other cost components in the model. The parameters under investigation include the quantity of returned products ($m_{rp}$), the percentage of disruptions ($\gamma'$), and production capacity of the production centers ($crp_i$).

Fig. 3, Fig. 4.

Fig. 5 and Fig. 6 illustrates the results.

Fig. 4 shows that an increase in the quantity of returned products leads to an increase in the operational costs. Conversely, it results in considerable decrease of strategic and total costs of supply chain. This means that a company can save significant costs by improving the
utilization of returned products from the customers. Fig. 5 demonstrates when the amounts of disruptions increase, the total cost of supply chain is increased significantly. To be more pellucid, supply chain cost can be 59.6% higher when disruption occurs in comparison with the situation no disruptions occur. Comparing the slopes of the curves in Fig. 5 reveals that a rise in amounts of disruptions impact operational costs more than strategic costs when the percentages of disruptions are low. However, when the percentages of disruptions are higher, a growth in the amount of disruptions affect strategic costs more than operational costs. Fig. 6 also implies both the strategic and operational costs decrease when the capacity of production increases. Though, the impacts of increasing capacity on the strategic costs seem to be linear, whilst this is not the case for the operational costs.

Fig. 6. The impacts of varying the production capacity on strategic and operational costs of the supply chain

5. Conclusions
This article studied the closed-loop supply chain design problem for a network which is vulnerable to random disruptions. We presented a mixed-integer programming model whose objective is to minimize the expected total cost of supply chain across different scenarios of disruptions. The developed model enables the supply chain to benefit from the lateral transshipment strategy for coping with risks of disruption. Real data was utilized to examine the utility of the proposed optimization model in designing an actual closed-loop supply chain involved in the production and distribution of glass. Important practical implications were drawn from the numerical results. For example, we showed a company can save significant costs by improving the utilization of returned products from the customers.

Future research can study inherent uncertainty of input data such as demand and return. To cope with this uncertainty, stochastic programming or robust optimization approach can be applied. Another direction for future research can be incorporation of social issues as an important factor of sustainability into the model. Multi-criteria decision making techniques can be promising tools for this purpose. Furthermore, dealing with larger network design problems, compared to those we examined in our real case study, may need the development of new solution methods that can reach optimal solutions within reasonable length of times.

References


