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A facility location model for global closed-loop supply chain network design

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ABSTRACT

Forward and reverse supply chains form a closed-loop supply chain. In this paper, a mathematical model is proposed for a closed-loop supply chain network by considering global factors, including exchange rates and customs duties. The model is a multi-objective mixed-integer linear programming model under uncertain demand. A solution approach based on fuzzy programming is developed for solving the optimization problem. The model is then applied in a network, which is located in Southwestern Ontario, Canada. A sensitivity analysis is provided to validate the model. This model considers global factors, multi-objectives, and uncertainty simultaneously in a closed-loop supply chain network.

1. Introduction

In a forward (traditional) supply chain, products are carried from suppliers to customers. On the other hand, some products may be returned from customers; this is called a reverse supply chain. Returned products are valuable from both a cost and an environmental perspective [1,2]. A closed-loop supply chain (CLSC) exists when there are both forward and reverse supply chains [3]. The integration of forward and reverse supply chains increases the complexity of networks by adding elements (e.g., some elements in CLSCs, such as recovery and disassembly locations) [4]. CLSC facility location models usually determine the number of products that are sent from one facility to another.

Some literature review papers have been published about CLSCs and reverse logistics (e.g., [2–8]). Fleischmann et al. [5] reviewed quantitative models in reverse logistics, and they mentioned that uncertainty is an important issue in this field. Guide and Van Wassenhove [6] introduced CLSC and discussed the trends in related research. They concluded that it is necessary to apply theoretical models in practice, even though it is hard to work within the industry. Akcali and Cetinkaya [7] classified the CLSC papers to deterministic and stochastic demand and return models. They stated that interactions between multiple items should be considered.

Several papers have been published in the field of CLSC network configuration. Fleischmann et al. [9] developed an optimization model for a network including multiple plants, warehouses, customers, and disassembly locations. They showed the application of the model using two examples: copier remanufacturing and paper recycling. However, they did not consider uncertainty. Selim and Ozkarahan [10] applied fuzzy goal programming to a CLSC network. They considered minimization

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0307-904X/

Table 1
Some of closed-loop supply chain network publications.

Authors	Global factors	Multi-objective	Uncertainty	Real locations	Dynamic
Fleischmann et al. [9]				*	
Salema et al. [22]			*	*	
Selim and Ozkarahan [10]		*	*		
Lee and Dong [23]			*		*
Pishvaee and Torabi [24]		*	*		*
Pishvaee et al. [25]		*			
Salema et al. [11]				*	*
Georgiadis et al. [26]			*	*	*
Shi et al. [27]			*		
Amin and Zhang [28]		*	*		
Assavapokee and Wongthatsanekorn [29]				*	*
Vahdani et al. [30]		*	*		
Zeballos et al. [12]			*	*	*
Amin and Zhang [20]		*	*		
Amin and Zhang [31]		*	*		
Cardoso et al. [19]	*		*	*	*
Ozkir and Basligil [13]		*	*		*
Ramezani et al. [32]		*	*		
Demirel et al. [33]		*	*		*
Hatefi and Jolai [34]			*		
Mirakhorli [14]		*	*		
Ozceylan and Paksoy [35]		*	*		*
Jindal and Sangwan [36]			*		
Soleimani and Kannan [37]					*
Subulan and Tasan [38]		*	*	*	*
Zhalechian et al. [39]		*	*	*	*
Our model	*	*	*	*	*

of costs and investments and maximization of service level. Salema et al. [11] applied a graph approach and mathematical programming to a CLSC, with an objective function of minimization of costs, to a Portuguese company. Zeballos et al. [12] developed an optimization model with profit maximization functions. They considered uncertainty in quality and quantity of products. Ozkir and Basligil [13] applied fuzzy logic in a CLSC configuration. They proposed a model with three objectives (maximizing satisfaction level, fill rate, and total profit). They showed the application of the model using a numerical example. Mirakhorli [14] applied interactive fuzzy multi-objective linear programming in a forward and reverse supply chain network and developed a heuristics algorithm to solve the model.

Elements of a supply chain network (such as suppliers, manufacturers, and retailers) can be located in different countries. Global shipping is an important part of the global economy [15], and networks of domestic and international locations present some challenges, such as selection of facilities in international locations and other globalization factors [16,17]. Exchange rates (between currencies) and customs duties (tariffs on products when they are transported between countries) are two important global factors. Meixell and Gargeya [16] reviewed operations management models in global supply chains. They concluded that a few models have considered practical issues in the design of global supply chain models. They classified papers based on global considerations, such as tariffs/duties, non-tariff trade barriers, currency exchange rates, and corporate income tax. In an important study, Huchzermeier and Cohen [18] developed a stochastic mathematical model for a global supply chain. They considered exchange and corporate tax rates in the model, and the network included multiple suppliers, plants, demand markets, and countries. To the best of our knowledge, very few papers related to global CLSCs have been published. However, Cardoso et al. [19] developed a mixed-integer linear program for a European CLSC network, and tax rate was one of the factors in the model.

Amin and Zhang [20] examined a CLSC network with multiple plants, products, demand markets, and collection centres. However, they did not consider global supply chain parameters. Another issue is the location of facilities in their examples. They generated the locations by random variables. We can observe this issue in most of the CLSC network papers; however, it is ideal to examine the effects of mathematical models based on geography. Geographical dimensions of supply chains include flows (such as transportation), networks, and nodes in the logistics system [21]. Some of the CLSC network models are classified in Table 1 based on the consideration of global factors, multi-objective models, models under uncertainty, applying the models with real locations, and dynamic models. To the best of our knowledge, there is no integrated model in the literature that takes all of these factors into account within a CLSC configuration.

In this research, a CLSC network—including multiple suppliers, plants, distribution centres, demand markets, collection centres, and products—is examined. The variables are flows of products between different facilities (for example, from plants to distribution centres). In addition, owners of plants decide to open facilities (plants, distribution centres, and collections centres). We propose a multi-objective mixed integer linear programming model for the network. The first objective function maximizes on-time delivery from suppliers. The second objective function maximizes the total profit of the network. As a result, not only do we configure the CLSC network, but we also select the best suppliers based on on-time delivery

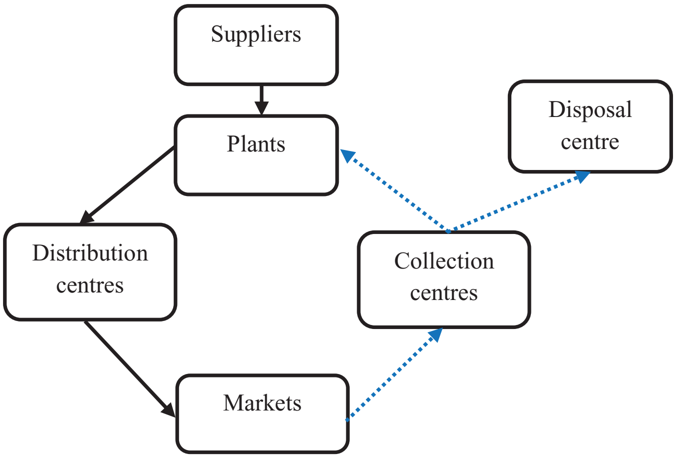

Fig. 1. A closed-loop supply chain (⟶ forward supply chain, ⋯▸ reverse supply chain).

and profit. In addition, we consider uncertainty in the model by assuming uncertain demand. Global factors (i.e., exchange rates and customs duties) are also considered in the model because there are both domestic and international suppliers in the CLSC network. We develop a solution approach according to the type of model (multi-objective and uncertain model), which entails the use of Corley and fuzzy programming methods. The proposed model is applied to a CLSC network in Southwestern Ontario, Canada.

This research is among the first investigations to simultaneously consider global factors, uncertainty, and multi-objectives in real locations in the CLSC network configuration. Unlike most of the previous investigations in this field, the real distances between the locations have been measured using Google Maps.

In the next section, the problem is stated. In Section 3, a mathematical model is proposed to solve the problem. Then in Section 4, a solution approach is developed. In Section 5, the application of the model is illustrated. Then, a sensitivity analysis is conducted to validate the model in Section 6. The results of proposed model are compared to another method in Section 7. Finally, conclusions are provided in Section 8.

2. Problem statement

Fig. 1 illustrates a CLSC network including multiple suppliers, plants, distribution centres, markets, and collection centres. In addition, there is a disposal centre. We examine the geographical problem from economic aspect (not social and political aspects). Products are sent from plants to distribution centres. In the next part of the network, they are carried to demand markets. Some of the products are returned by customers and are collected in collection centres. Then, they are separated and most of them are sent to plants to be remanufactured. Plants produce products based on retuned and new products which are purchased from suppliers. One objective is maximization of profit in the network. Besides, delivery time of products from suppliers to plants is an important factor. The profit function ensures to select efficient suppliers. On the other hand, delivery time function is helpful to select responsive suppliers. It is assumed that plants, distribution centres, collection centres, and disposal centre are located in a same country. However, there are both domestic and international suppliers. Therefore, global factors (exchange rate and customs duty) should be taken into account in the network configuration. Another assumption is uncertainty in demand of markets. Furthermore, we assume that the network is managed by owner of plants. She is interested to know the flows of products in each part of the network (e.g. between markets and collection centres). In addition, the owner would like to know which facilities (e.g. plants) should be opened based on total profit.

3. Mathematical model

In this section, a multi-objective mixed-integer linear programming model is developed to configure the CLSC network. Sets, parameters, and decision variables are as follows:

Sets

S	set of suppliers $(1 \ldots s \ldots S)$
J	set of products $(1 \ldots j \ldots J)$
I	set of potential plants locations $(1 \ldots i \ldots I)$
R	set of potential distribution centres locations $(1 \ldots r \ldots R)$
K	set of demand markets locations $(1 \ldots k \ldots K)$

L set of potential collection centres locations ($1 \ldots l \ldots L$)
N set of countries in which suppliers are located ($1 \ldots n \ldots N$)
$\hat{C}$ set of time periods ($1 \ldots \hat{c} \ldots \hat{C}$)
$\bar{A}$ set of disposal centres locations ($1 \ldots \bar{a} \ldots \bar{A}$)

Parameters
c_{sij} on-time delivery (percentage) for product j sent from supplier s to plant i
t_j selling price of product j
A_i fixed cost for opening plant i
B_r fixed cost for opening distribution centre r
C_l fixed cost for opening collection centre l
p_{sjn} purchasing cost of product j from supplier s in country n
v_{sjn} customs duty rate of product j from supplier s in country n
D_{jn} transportation cost of product j per km between suppliers and plants in country n
E_{sin} the distance between locations s and i in country n
$E_{l\bar{a}}$ the distance between collection centre l and disposal centre $\bar{a}$
F_j production cost of product j
G_j transportation cost of product j per km between plants and distribution centres
H_j transportation cost of product j per km between distribution centres and demand markets
M_j transportation cost of product j per km between demand markets and collection centres
q_j disposal cost of product j
O_j transportation cost of product j per km between collection centres and disposal centre
a_j cost saving of product j (because of product recovery)
b_j transportation cost of product j per km between collection centres and plants
$\tilde{d}_{kj\hat{c}}$ uncertain demand of market k for product j in period $\hat{c}$
e_j minimum disposal fraction of product j
$f_{kj\hat{c}}$ returned product j of customer k in period $\hat{c}$
m_{ij} capacity of plant i for product j
o_{rj} capacity of distribution centre r for product j
g_{lj} capacity of collection centre l for product j
h_n exchange rate of currency of country n with numeraire currency

Decision variables
$P_{sij\hat{c}}$ quantity of product j purchased for plant i from supplier s in period $\hat{c}$
$Q_{irj\hat{c}}$ quantity of product j produced by plant i for distribution centre r in period $\hat{c}$
$T_{rkj\hat{c}}$ quantity of product j distributed by distribution centre r for demand market k in period $\hat{c}$
$U_{klj\hat{c}}$ quantity of returned product j from demand market k to collection centre l in period $\hat{c}$
$V_{lij\hat{c}}$ quantity of returned product j from collection centre l to plant i in period $\hat{c}$
$W_{l\bar{a}j\hat{c}}$ quantity of returned product j from collection centre l to disposal centre $\bar{a}$ in period $\hat{c}$
X_i 1, if a plant is located and set up at potential site i, 0, otherwise
Y_r 1, if a distribution centre is located and set up at potential site r, 0, otherwise
Z_l 1, if a collection centre is located and set up at potential site l, 0, otherwise

$$Max\ z_1 = \sum_{\hat{c}} \sum_{s} \sum_{i} \sum_{j} c_{sij} P_{sij\hat{c}}$$

$$\begin{aligned} Max\ z_2 = {} & \sum_{\hat{c}} \sum_{r} \sum_{k} \sum_{j} (t_j - H_j E_{rk}) T_{rkj\hat{c}} - \Bigg[\sum_{i} A_i X_i + \sum_{r} B_r Y_r \\ & + \sum_{l} C_l Z_l + \sum_{\hat{c}} \sum_{n} \sum_{s} \sum_{i} \sum_{j} h_n ((1 + v_{sjn}) p_{sjn} + D_{jn} E_{sin}) P_{sij\hat{c}} + \sum_{\hat{c}} \sum_{i} \sum_{r} \sum_{j} (F_j + G_j E_{ir}) Q_{irj\hat{c}} \\ & + \sum_{\hat{c}} \sum_{k} \sum_{l} \sum_{j} M_j E_{kl} U_{klj\hat{c}} + \sum_{\hat{c}} \sum_{l} \sum_{\bar{a}} \sum_{j} (q_j + O_j E_{l\bar{a}}) W_{l\bar{a}j\hat{c}} + \sum_{\hat{c}} \sum_{l} \sum_{i} \sum_{j} (-a_j + b_j E_{li}) V_{lij\hat{c}} \Bigg] \end{aligned}$$

s.t.

$$\sum_{s} P_{sij\hat{c}} + \sum_{l} V_{lij\hat{c}} = \sum_{r} Q_{irj\hat{c}} \qquad \forall i, j, \hat{c}, \tag{1}$$

$$\sum_{i} Q_{irj\hat{c}} \geq \sum_{k} T_{rkj\hat{c}} \qquad \forall r, j, \hat{c}, \tag{2}$$

$$\sum_r T_{rkj\hat{c}} \le \tilde{d}_{kj\hat{c}} \qquad \forall k, j, \hat{c}, \tag{3}$$

$$\sum_r T_{rkj\hat{c}} \ge \sum_l U_{klj\hat{c}} \qquad \forall k,\ j,\ \hat{c}, \tag{4}$$

$$\sum_l U_{klj\hat{c}} = f_{kj\hat{c}} \qquad \forall k,\ j, \hat{c}, \tag{5}$$

$$e_j \sum_k U_{klj\hat{c}} \le \sum_{\bar{a}} W_{l\bar{a}j\hat{c}} \qquad \forall l, j, \hat{c}, \tag{6}$$

$$\sum_k U_{klj\hat{c}} = \sum_i V_{lij\hat{c}} + \sum_{\bar{a}} W_{l\bar{a}j\hat{c}} \qquad \forall l, j, \hat{c}, \tag{7}$$

$$\sum_s \sum_j P_{sij\hat{c}} + \sum_l \sum_j V_{lij\hat{c}} \le X_i \sum_j m_{ij} \qquad \forall i, \hat{c}, \tag{8}$$

$$\sum_i \sum_j Q_{irj\hat{c}} \le Y_r \sum_j o_{rj} \qquad \forall r, \hat{c}, \tag{9}$$

$$\sum_k \sum_j U_{klj\hat{c}} \le Z_l \sum_j g_{lj} \qquad \forall l, \hat{c}, \tag{10}$$

$$X_i, Y_r, Z_l \in \{0,\ 1\} \qquad \forall i, r, l, \tag{11}$$

$$P_{sij\hat{c}}, Q_{irj\hat{c}}, T_{rkj\hat{c}}, U_{klj\hat{c}}, W_{l\bar{a}j\hat{c}}, V_{lij\hat{c}} \ge 0 \qquad \forall s, i, j, r, k, \bar{a}, l, \hat{c}, \tag{12}$$

The first objective function maximizes the on-time delivery of purchased products from suppliers. The second objective function maximizes the total profit (difference between total price and total cost) in the CLSC network. The first part of it is related to the profit of selling products in markets. The parts 2, 3, 4 show the costs of opening facilities (plants, distribution centres, collection centres). The fifth part, illustrated the purchased and transportation costs and customs duty of products. Because there are both domestic and international suppliers, index of countries is applied in this section of the model. The sixth part of the second objective function includes production and transportation costs of products from plants to distribution centres. The next part of the objective function shows transportation costs of returned products. The eights part of it illustrates disposal and transportation costs of products in the model. Cost saving of returned products and transportation costs of sending products from collection centres to plants are shown in the next part of the second objective function.

The first constraint shows numbers of products that are sent from plants are equal to the numbers of products from collection centres and suppliers. The second constraint is again a network constraint. Constraint (3) shows that numbers of products that are sent to markets should be equal or less than demands. The fourth constraint is a network constraint. Constraint (5) illustrates that the numbers of products from demand markets are equal to returns. Constraint (6) states that a fraction of returned products is disposed. Constraint (7) shows numbers of products that are carried to collection centres are equal to numbers of products sent to disposal centre and plants. Constraints ((8), (9), (10)) are related to the capacities of facilities (plants, distribution centres, collection centres, respectively). The binary variables are illustrated in Constraint (11). Finally, Constraint (12) shows non-negative variables.

4. Solution approach

The proposed model is a multi-objective one under uncertainty. The appropriate solution approach should handle the two issues. The approach is described in the following sections.

4.1. Multi-objective method

Multi-objective models provide flexibility in optimization process that cannot be achieved by mono-objective models. However, the degree of freedom leads to a set of solutions which are called Pareto solutions. The collection of the solutions builds a trade-off surface [40]. There are several methods in the literature to solve multi-objective models (e.g. scalar and interactive methods). In this paper, Corley method is applied which is a hybrid method [40]. The method combines weighted-sums method and compromise method. In weighted-sums method, weights are assigned to objective functions and a new objective function is constructed. The weights show the importance of objective functions. The method is very efficient but cannot find some solutions in concavities. Compromise method (or ε-constraint method) can transfer multi-objective model to a mono-objective one by introducing additional constraints. Computational time for large problems with several objective functions is weakness of the method. The Corley method is selected to solve the model because it has advantages of both weighted-sums and compromise methods.

4.2. Fuzzy programming method

Fuzzy logic and fuzzy programming are effective tools to deal with problems under uncertainty. Membership functions are defined in these problems. A membership function (μ) can be between zero and one [41,42].

Verdegay [43] proposed a fuzzy programming method to solve problems with uncertain resources (right-hand-side parameters). The general mathematical programming problem with fuzzy resource ($\tilde{\varphi}$) is shown in (13).

$$\begin{aligned} & Max\, z = \delta x \\ & s.t. \\ & (\lambda x)_\gamma \le \tilde{\varphi}_\gamma \qquad \forall \gamma. \\ & x \ge 0 \end{aligned} \tag{13}$$

Verdegay [43] showed that problem (13) can be transformed to the crisp problem (14), and it is equivalent to a parametric programming with $\theta = 1 - \alpha$. Parameter y is defined as maximum tolerance from φ, and it is determined by decision makers.

$$\begin{aligned} & Max\ z = \delta x \\ & s.t. \\ & (\lambda x)_\gamma \le \varphi_\gamma + (1-\alpha) y_\gamma \qquad \forall \gamma, \\ & x \ge 0 \\ & \alpha \in [0,\ 1] \\ & \mu_\gamma(x) = \begin{cases} 1 & (\lambda x)_\gamma < \varphi_\gamma, \\ 1 - \dfrac{[(\lambda x)_\gamma - \varphi_\gamma]}{y_\gamma} & \varphi_\gamma \le (\lambda x)_\gamma \le \varphi_\gamma + y_\gamma, \\ 0 & (\lambda x)_\gamma > \varphi_\gamma + y_\gamma. \end{cases} \end{aligned} \tag{14}$$

4.3. Proposed solution approach

To solve the problem, we apply Corley method and the fuzzy programming method, simultaneously. Fuzzy programming method is applied because there is not enough information to determine the probabilities of different decision-making options and using stochastic programming. Suppose that u represents set of objective functions ($u = 1$, 2 in this case). w_u is weight of objective function u. Weights are assigned based on importance of objective functions. In addition, z_u represents objective function u. To consider uncertainty in demand, $y_{kj\hat{c}}$ is defined as maximum tolerance from $d_{kj\hat{c}}$. Furthermore, ε_u represents non-negative parameter and it is defined for each objective function. The formula is shown in (15)–(21). The objective function (15) combines the previous objective functions and their weights. It is maximization because both of previous objective functions were maximization objective functions. There is no change in Constraints ((1), (2), (4)–(12)). Constraint (17) is added because of uncertainty in demand (right-hand-side parameter in this model). It shows that the actual demand depends on the maximum tolerance from the estimated demand ($y_{kj\hat{c}}$) and parameter α (determined by decision-maker). Constraint (18) shows that the objective functions must be equal or greater than ε. We restrict the search space by considering this constraint. Constraint (19) illustrates that the summation of weights is equal to 1. Constraint (20) is related to non-negativity of the new parameters. Constraint (21) shows the membership function.

$$Max\ z_3 = \sum_u w_u z_u \tag{15}$$

s.t.

$$\text{Eqs. } (1)-(2),\ (4)-(12), \tag{16}$$

$$\sum_r T_{rkj\hat{c}} \le d_{kj\hat{c}} + (1-\alpha) y_{kj\hat{c}} \qquad \forall k, j, \hat{c}, \tag{17}$$

$$z_u \ge \varepsilon_u \qquad \forall u, \tag{18}$$

$$\sum_u w_u = 1, \tag{19}$$

$$w_u,\ \varepsilon_u \ge 0 \qquad \forall u, \tag{20}$$

$$\mu(T_{rkj\hat{c}}) = \begin{cases} 1 & \sum_r T_{rkj\hat{c}} < d_{kj\hat{c}}, \\ 1 - \dfrac{\left[\sum_r T_{rkj\hat{c}} - d_{kj\hat{c}}\right]}{y_{kj\hat{c}}} & d_{kj\hat{c}} \le \sum_r T_{rkj\hat{c}} \le d_{kj\hat{c}} + y_{kj\hat{c}}, \\ 0 & \sum_r T_{rkj\hat{c}} > d_{kj\hat{c}} + y_{kj\hat{c}}. \end{cases} \tag{21}$$

The steps of the proposed solution approach are as follows:

Step 1. Determine the values of w_u and ε_u ($u = 1$, 2), and $y_{kj\hat{c}}$. Decision makers may determine them based on their experiences.
Step 2. Solve the problem (15–21), and calculate a Pareto solution.
Step 3. Change the values of w_u and repeat Step 2.
Step 4. Draw the trade-off surface.

5. Application of the model

The model has been applied for designing a CLSC network in Southwestern Ontario, Canada in a single period. The potential locations of facilities have been illustrated in Fig. 2. Major cities in the area are selected as markets (London, Brantford, Cambridge, Kitchener, Owen Sound, Sarnia, St. Thomas, Stratford, Waterloo, Windsor, Woodstock). Ingersoll, Chattam-Kent, Leamington are potential plants locations. There are four potential distribution centres (Kitchener, London, Sarnia, Windsor). In addition, collection centres can be located in Waterloo, Brantford, Woodstock, Chattam-Kent. There is a disposal centre in Arva. Furthermore, there are two potential international suppliers (Dearborn, Ypsilanti) located in Michigan, United States and two domestic suppliers (St. Thomas, Cambridge). The population density is not high in Southwestern Ontario and some cities are far from each other (e.g. Owen Sound to London, 203 km). Therefore, transportation costs play an important role. Transportation mode in this research is road because approximately 74% of goods are transported through the border by trucks [44]. It is noticeable that highway 401 is the major highway in the province of Ontario. The Ambassador bridge and a tunnel connect Windsor (Canada) to Detroit (United States). Interested readers can refer to Anderson [44,45] for more information about the business and geographical aspects of the border between Windsor and Detroit. The distances between locations (suppliers, plants, distribution centres, markets, collection centres, disposal centre) are calculated by Google Maps.

The products are electrical and electronic equipments. It is supposed that demand of market k for product j is 0.01 of population of the market (city). The population of the cities can be found in 2011 census of Canada. The return is 0.1 of market demand. Canadian dollar is considered as numeraire currency. We apply exchange rate (US dollar to Canadian dollar). The customs duty in Canada depends on province of residency (Ontario in this case), product category (Electronics & Media in the case), and where the product was manufactured (NAFTA or elsewhere). Based on the factors, 13% is assigned to customs duty rate (v_{sjn}). Other parameters have been written in Table 2. Fixed costs for opening facilities, transportation and disposal costs, minimum disposal fraction have been obtained from Fleischmann et al. [9].

It is assumed that weights of objective functions are equal (0.5). In addition, $\alpha = 0.5$. Besides, $\varepsilon_1 = \varepsilon_2 = 10{,}000$, and $y_{kj} = 0.1 d_{kj}$. General Algebraic Modeling System (GAMS) is utilized to solve the mathematical model. The model is solved

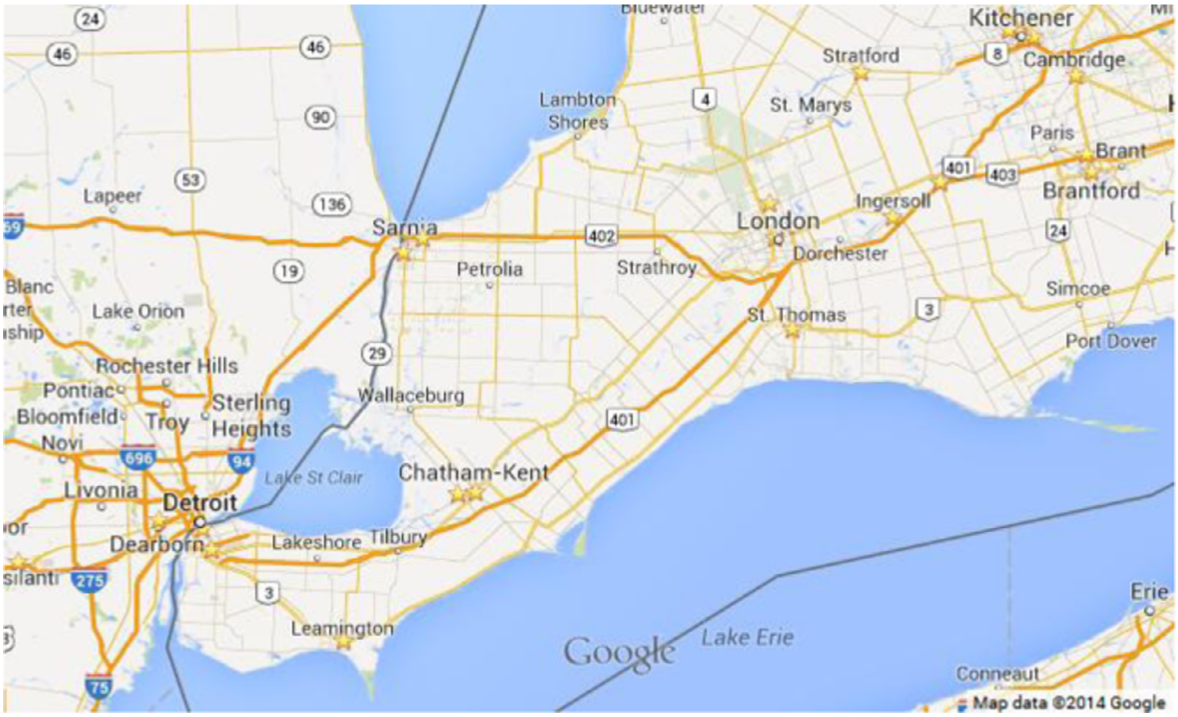

Fig. 2. Locations of facilities, suppliers, and markets in the CLSC network are illustrated with (because of scale, Owen Sound is not shown in this map).

Table 2
Values of some parameters in the CLSC network.

$t_j = 3000$	$C_l = 500{,}000$	$q_j = 2.5$	$m_{ij} = 100{,}000$
$A_i = 5{,}000{,}000$	$F_j = 500$	$a_j = 10$	$o_{rj} = 50{,}000$
$B_r = 1{,}500{,}000$	$O_j = 0.0030$	$e_j = 0.5$	$g_{lj} = 50{,}000$
$M_j = 0.0050$	$b_j = 0.0030$	$G_j = 0.0045$	$H_j = 0.0100$
$D_{j1} = 0.0035$	$D_{j2} = 0.0040$	$c_{1ij} = 80$	$c_{2ij} = 90$
$p_{1j1} = 1180$	$p_{2j1} = 1200$	$c_{3ij} = 70$	$c_{4ij} = 60$
$p_{3j2} = 1600$	$p_{4j2} = 1700$		

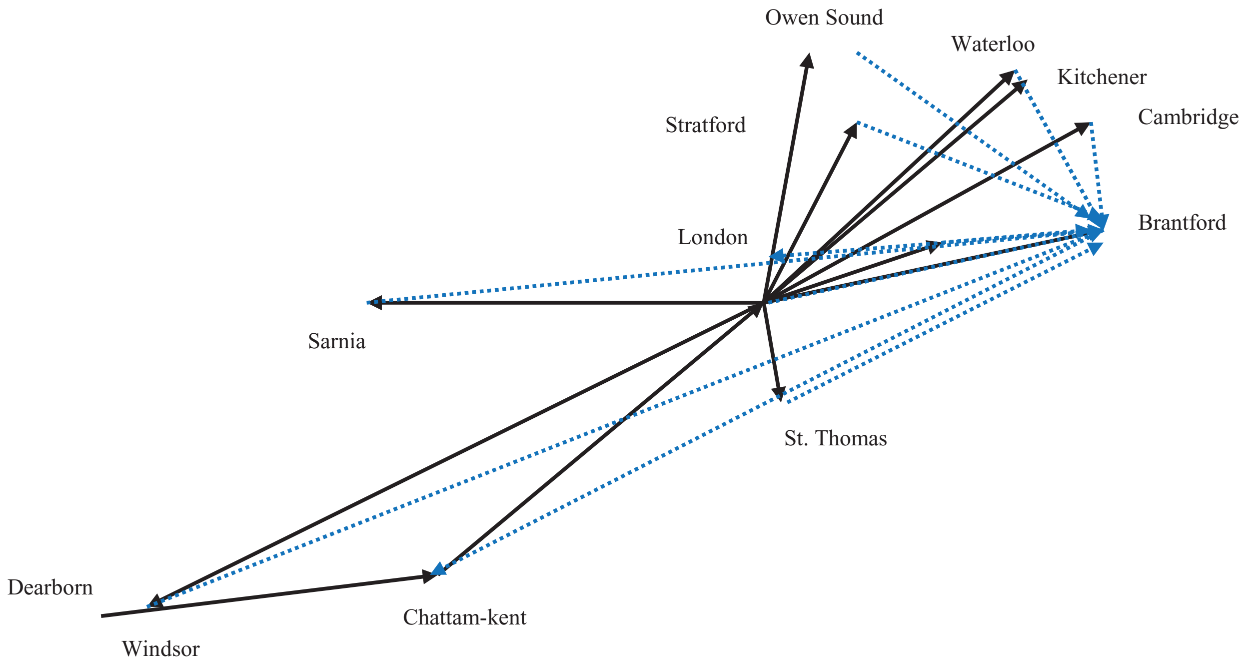

Fig. 3. The optimal CLSC network for Product 1 (⟶ forward supply chain, ⋯▸ reverse supply chain).

in 0.031 s. There are 112 single equations, 270 single variables, 11 discrete variables, and 1510 non-zero elements. The optimal CLSC network (for Product 1) is shown in Fig. 3. We focus on Product 1 to avoid complexity in the figure. Some products are purchased from Supplier 1 (Dearborn) that has the lowest purchasing cost. The Plant 2 (Chattam-Kent) and Distribution centre 2 (London) are open. It is noticeable that London is central city of Southwestern Ontario. The returned products are collected in Collection centre 2 (Brantford).

Decision makers usually determine the weights of objective functions based on their experiences. Fig. 4 illustrates the trade-off surface which is obtained by changing the values of w_u. Each point on the trade-off surface represents a solution. For example, $w_1 = 0.9$ and $w_2 = 0.1$ lead to $z_1 = 2.3687\text{E}+6$ and $z_2 = 1.8640\text{E}+7$. The shape of the trade-off surface is a classic shape for two maximization objective functions. The method is effective because there are two objective functions in this problem (not several objective functions). In addition, the method can be applied for convex or not convex optimization problems.

In the previous paragraphs, the application of the mathematical model in a single period was discussed. The general multi-period mathematical model presented in Section 3 can be applied to design and optimize the CLSC network in multiple periods. The model was applied for 4 periods (quarters). We observed that the same facilities (plants, distribution centres, and collection centres) are open. One of the issues in multiple-period model is ignoring the rate of return. As a future research, it is valuable to calculate the actual profit considering rate of return and cash flow analysis.

6. Sensitivity analysis

In this section, sensitivity analysis is provided to examine the proposed model.

6.1. Global factors

Sensitivity analysis of exchange rate is provided in Fig. 5a. Vertical axis shows the value of objective function. The horizontal axis represents the value of exchange rate. By increasing the exchange rate, the value of objective function decreases

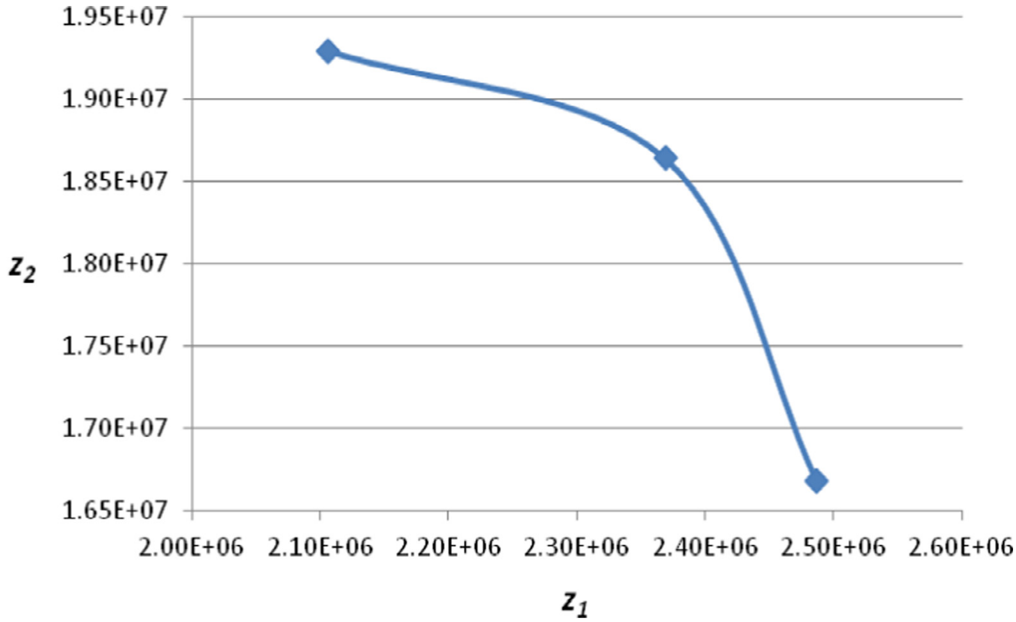

Fig. 4. The trade-off surface.

because the costs will increase and the objective function is maximization of profit. However, for the exchange rate equal or more than 1.308, the value of objective function is fixed because for that value and more, domestic supplier (St. Thomas) is selected (not Dearborn that is an international supplier). The result shows that the model is sensitive to the exchange rate, and sourcing decision of countries with unstable economy (exchange rate) is risky in global CLSC network. Fig. 5b illustrates the historical data of Canadian dollar exchange rate to US dollar. It is noticeable that at the beginning of 2016, the exchange rate was higher than 1.308 which is an important point in Fig. 5a.

Fig. 6 shows sensitivity analysis of customs duty. Increasing the customs duty leads to more costs and less profit. But for customs duty equal or more than 0.26, the value of objective function is not altered. In those cases, domestic supplier (St. Thomas) is selected and the customs duty is not effective on the value of objective function. As a managerial insight, decisions of countries about customs duty may affect the sourcing decisions of companies in global closed-loop supply chain.

It is worthwhile to compare the optimal CLSC network (Fig. 3) with the case that there is no global supplier, and as result no global factor. The network is shown in Fig. 7. The supplier is located in St. Thomas. The plant in Ingersoll sends products to distribution centre in London. The collection centre in Woodstock is open. We observe that global suppliers and factors have significant influence on the results of the problem. Considering global factors is one of the contributions of this research.

6.2. Uncertain demand

To deal with uncertainty, fuzzy programming has been applied. Fig. 8a shows the sensitivity analysis of α. By increasing α, right-hand side of Constraint (17) is decreased. Therefore, number of products sent to markets decreases and the profit (value of objective function) becomes smaller.

When $\alpha = 0.1$, the quantity of Product 1 purchased from supplier (P_{121}) is 13,686, and quantity of Product 1 produced by plant (Q_{221}) is 14,344. However, with $\alpha = 0.9$, the values are $P_{121} = 12{,}633$ and $Q_{221} = 13{,}291$. It is noticeable that although the selected supplier and open plant are as same as before, the values of variables are different. This observation is straightforward because α has effect on a constraint.

Fig. 8b illustrates the sensitivity analysis of y_{kj}. By increasing y_{kj}, the right-hand side of Constraint (17) is increased. As a result, the profit (value of objective function) will increase.

6.3. On-time delivery

Both costs (transportation and purchasing costs) and on-time delivery are effective in selection of the supplier in the multi-objective model. The degree of effects depends on the weights (w_1 and w_2). We noticed that for $0 \leq w_1 \leq 0.71$, Supplier 1 (Dearborn) is selected due to the costs. However, for $0.71 < w_1 < 1$, Supplier 2 (Ypsilanti) is chosen because on-time delivery of the supplier is the highest one between the four suppliers (it is 90).

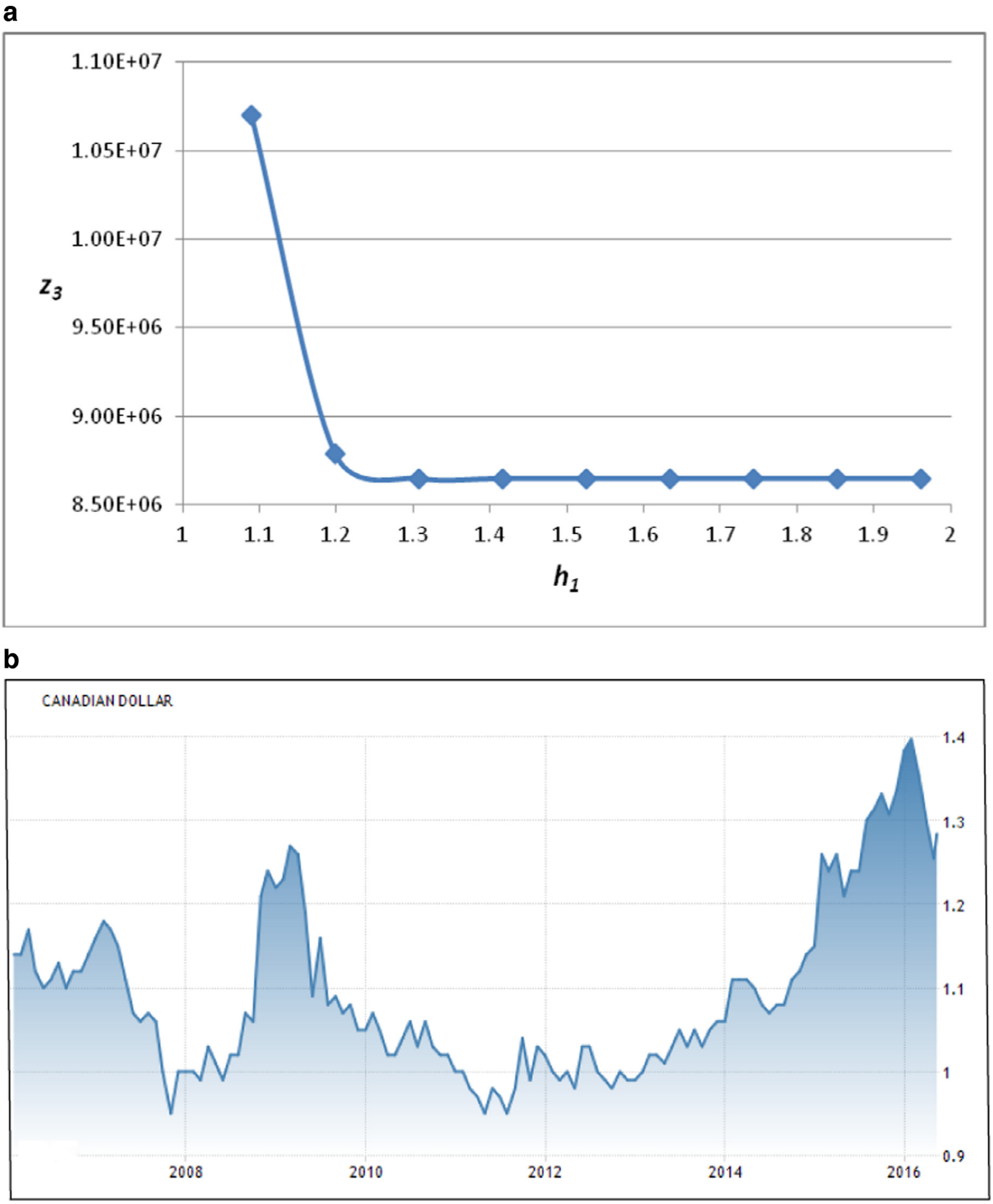

Fig. 5. (a) Sensitivity analysis of exchange rate. (b) Exchange rate of Canadian dollar (*Source:* http://www.tradingeconomics.com/canada/currency).

6.4. Capacity of facilities

The parameters have been introduced in Table 2. Capacities of distribution and collection centres are both 50,000. The capacities are enough to open one distribution centre and one collection centre in the optimal solution. In other words, the behaviour of the model under the parameters is like an uncapacitated model. Suppose $o_{rj} = 5000$ and $g_{lj} = 1000$. In this case, Supplier 1 (Dearborn), Plant 2 (Chattam-Kent), Distribution centres 1, 2, 4 (Kitchener, London, Windsor), Collection centres 1 and 4 (Waterloo, Chattam-Kent) are active. Fig. 9 shows the optimal CLSC network with new parameters.

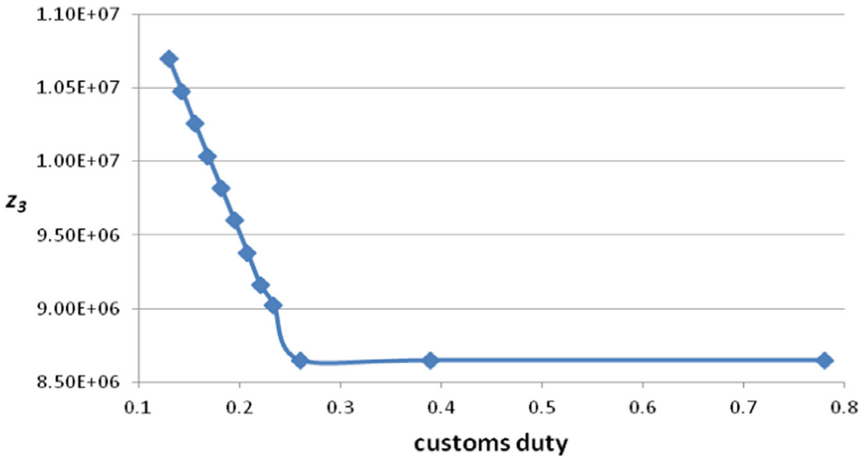

Fig. 6. Sensitivity analysis of customs duty.

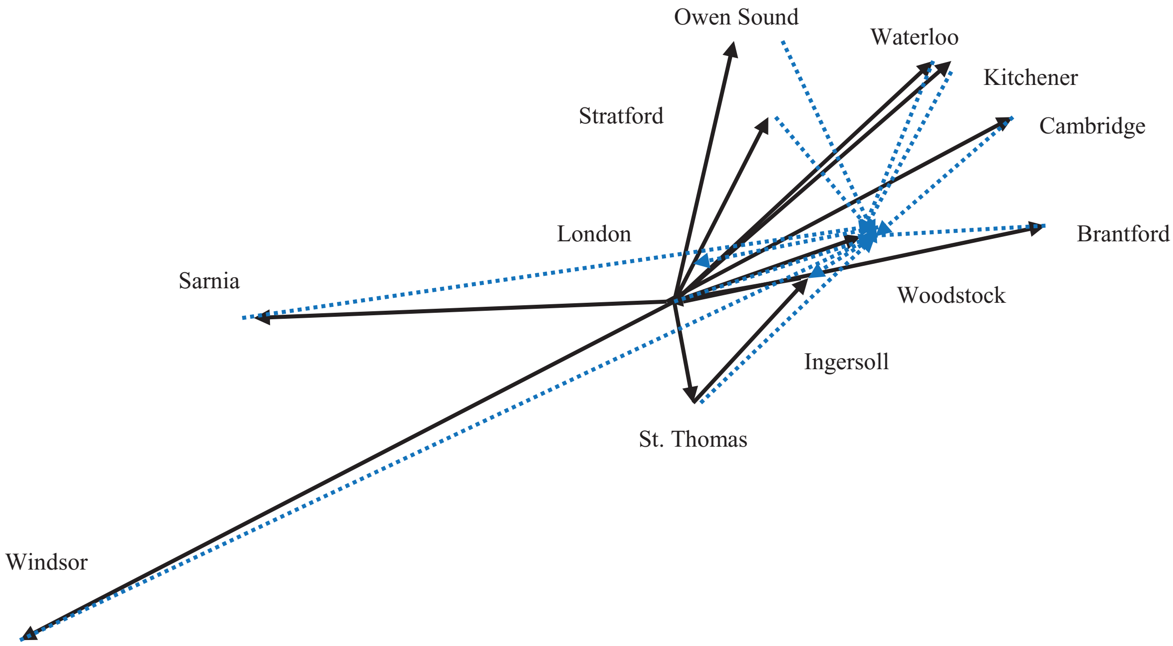

Fig. 7. The optimal CLSC network for Product 1 without global factors (⟶ forward supply chain, ⋯▸ reverse supply chain).

6.5. *More international suppliers*

In the section of application, there are two potential international suppliers located in United States, and two domestic suppliers in Canada. In this section, an international supplier from China is added to the potential suppliers and the problem is solved again. The price of the products offered by the new company is almost 50-percent of the previous selected supplier. After solving the optimization problem, the new Chinese supplier is selected instead of the international supplier in US. In this case, the on-time delivery of the new supplier is competitive. However, it is noticeable that the on-time delivery is an important and risky parameter when international suppliers from long distances provide the products. The comparison of the results between the original case and the new case with new international supplier has been provided in Table 3.

7. Discussion

In this section, a hybrid multi-objective method is developed. Then the results are compared with the proposed solution approach. Compromise programming is a multi-objective programming method that tries to find solution as close as possible to ideal solution. Ideal solution is defined as the best value for each objective function if the problem is solved by one objective function [31]. Compromise programming has been utilized in some papers such as [31]. In this section, we

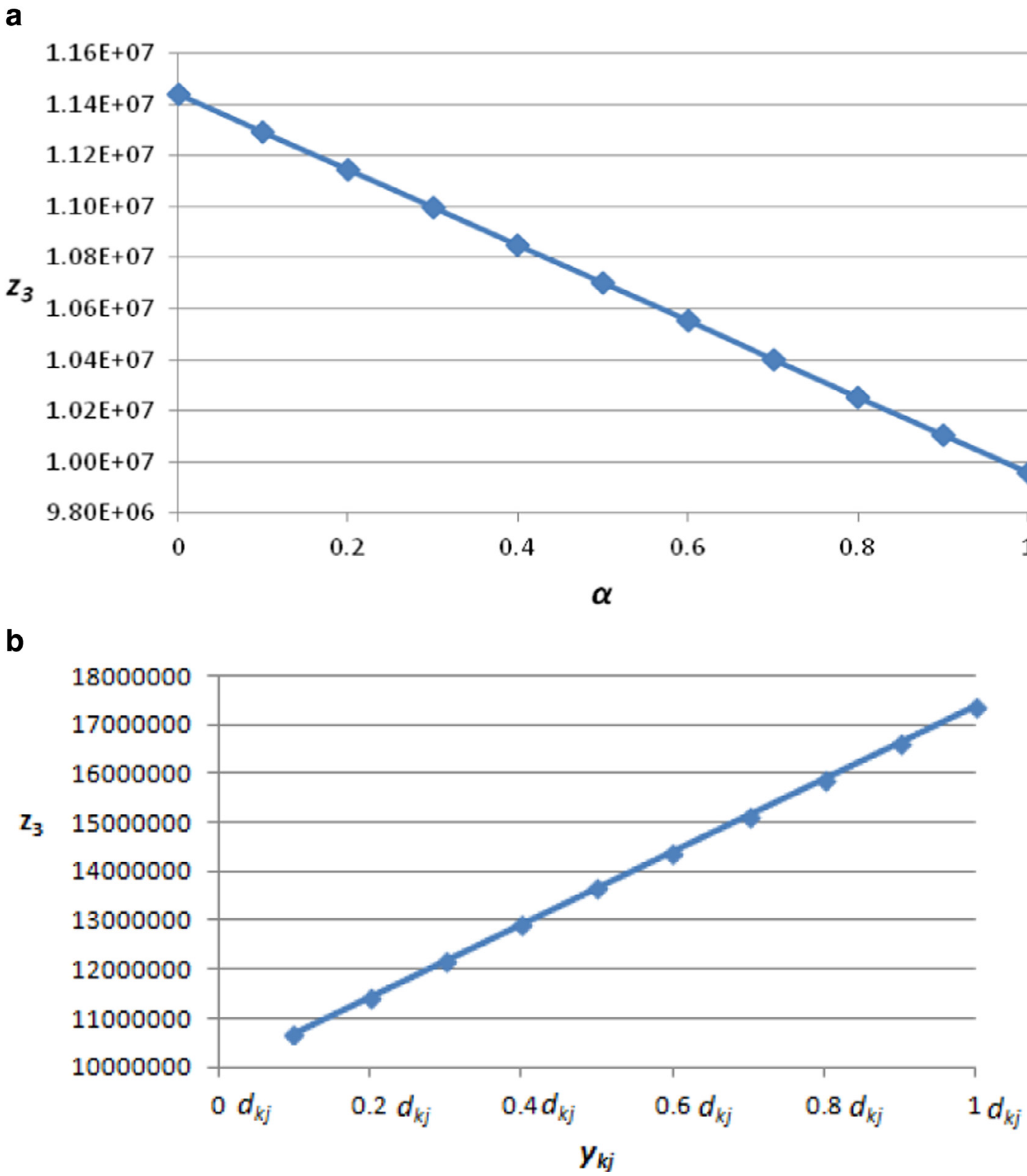

Fig. 8. (a) Sensitivity analysis of α. (b) Sensitivity analysis of y_{kj}.

formulate the problem based on that idea. Suppose that π_1 and π_2 are weights related to first and second objective functions, respectively. In addition, assume z_1^* and z_2^* are optimal values of first and second objective functions. The optimization problem is formulated as (22)–(25).

$$Max\ z_4 = \pi_1\left(\frac{z_1 - z_1^*}{z_1^*}\right) + \pi_2\left(\frac{z_2 - z_2^*}{z_2^*}\right) \tag{22}$$

s.t.

$$\text{Eqs. (16), (17), (21)} \tag{23}$$

$$\pi_1 + \pi_2 = 1, \tag{24}$$

$$\pi_1, \pi_2 \geq 0. \tag{25}$$

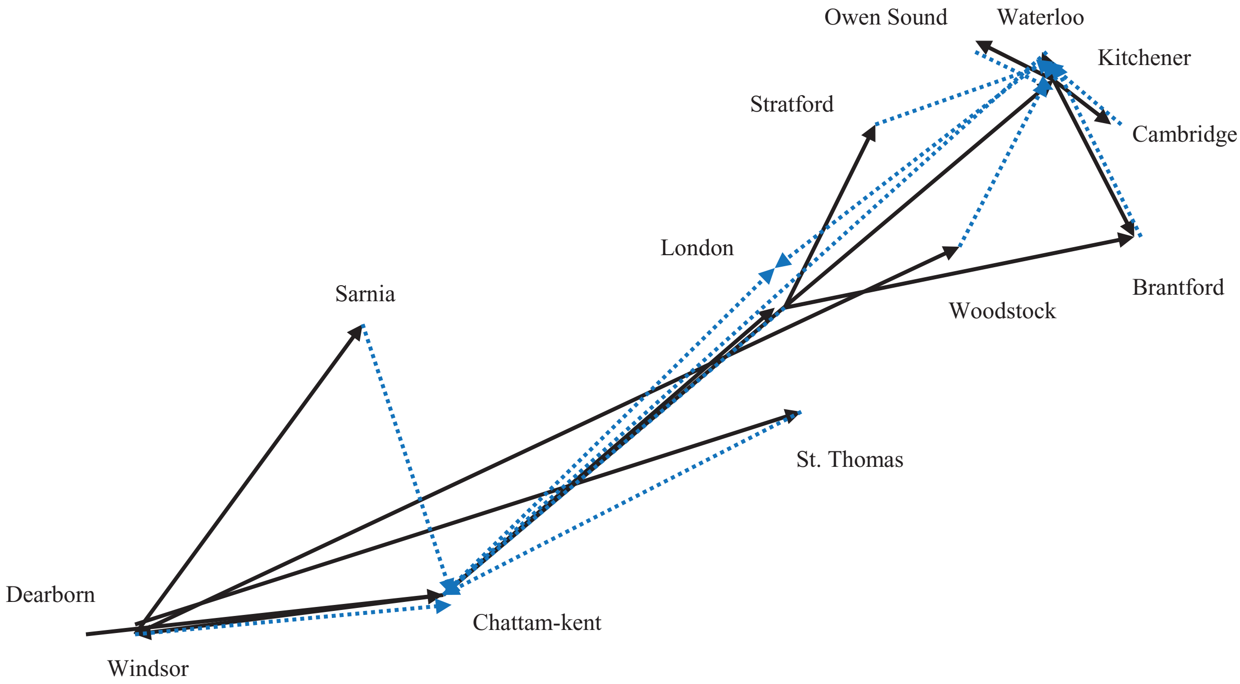

Fig. 9. The optimal CLSC network for Product 1 with new parameters (⟶ forward supply chain, ⋯▸ reverse supply chain).

Table 3
Comparison of the results.

	Original case	New case
Supplier	1 (Dearborn)	5 (New supplier)
Plant	2 (Chattam-Kent)	1 (Ingersoll)
Distribution centre	2 (London)	2 (London)
Collection centre	2 (Brantford)	3 (Woodstock)

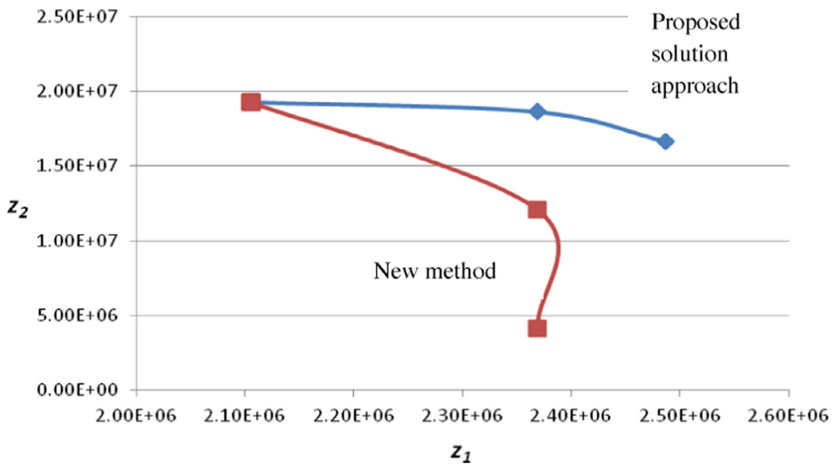

Fig. 10. The trade-off surfaces.

The optimization problem has been solved by the new method and different solutions have been calculated by changing π_1 and π_2. Fig. 10 illustrates the trade-off surfaces obtaining from the proposed solution approach (introduced in Section 4.3) and the new method. It can be seen that better solutions can be obtained by proposed solution approach than the new method. As a result, the proposed solution approach is preferred than the new method.

In this paper, global suppliers have been considered in the models. A future research can focus on developing more general models that consider international and domestic facilities such as plants, and collection centres in addition to global suppliers. Modelling the forward supply chain is not a challenging task in this case. The objective function of the model can be updated as $\sum_{\hat{c}}\sum_{n}\sum_{i}\sum_{r}\sum_{j} h_n((1+\upsilon_{jn})F_{jn} + G_{jn}E_{irn})Q_{irj\hat{c}}$ for the flows of the products between plants and distribution centres. Besides, the flows of the products between distribution centres and markets in the objective function can be revised as $\sum_{\hat{c}}\sum_{n}\sum_{r}\sum_{k}\sum_{j} h_n(t_{jn} - (1+\upsilon_{jn})\hat{g}_{jn} - H_{jn}E_{rkn})T_{rkj\hat{c}}$ that $\hat{g}_{jn}$ is the cost of product j in distribution centre in country n. About modelling the reverse supply chain (between markets, collection centres, and plants), we should make sure that the markets and related collection centres are located in the same country. Furthermore, we should answer the following questions: Is it profitable to collect the returned products in a country and send them to another country? What are the current trends?

8. Conclusions

In this paper, a multi-objective mixed-integer linear programming model has been developed for a general CLSC network, including multiple plants, distribution centres, demand markets, collection centres, and products. The global factors (exchange rates and customs duties) have been considered in the model because there are both domestic and international suppliers in the network. In addition, uncertainty of demand has been taken into account. The first objective is maximization of on-time delivery, and the second objective is maximization of total profits in the CLSC network. By considering a bi-objective model, we can select the best suppliers during network configuration based on two criteria.

A solution approach has been developed to handle multi-objectives and uncertainty in the proposed model. Then, the model has been applied for a CLSC network in Southwestern Ontario. Furthermore, some sensitivity analyses and managerial insights have been provided for the model. The results show that exchange rates and customs duties play important roles in global CLSC networks. We observed that the optimal network can be different when global factors are not considered. Because the model is sensitive to exchange rates, sourcing decisions of countries with unstable economies (exchange rates) is risky in a global CLSC network. In addition, this research has considered global factors, multiple objectives, and uncertain demand in a general CLSC network. The application of the proposed model has been shown using real locations.

The proposed mathematical model can be extended to consider other factors and barriers within international businesses, such as corporate income tax. It is also worthwhile to show the applicability of the model to larger problems, including country-wide and organization-wide problems. The model in this paper has focused on global factors and does not include inventory factors. Future research should incorporate inventory management factors into the model. Interested readers can refer to Bazan et al. [46] for more information. Concerning the solution approach, it is valuable to develop meta-heuristic algorithms (e.g., genetic algorithms) for the multi-objective model because it is difficult to solve large problems with several parameters and decision variables in a reasonable amount of time.

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