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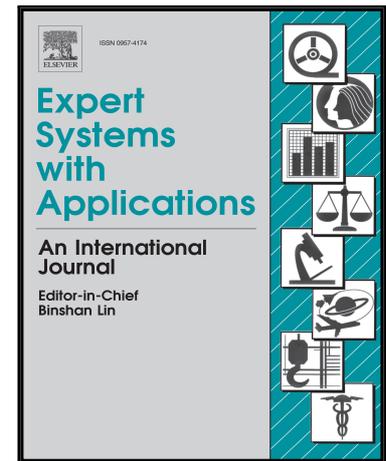
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**Highlights**

- Introducing closed-loop supply chain (CLSC) concept.
- Investigating the recovery options and CLSC network of tires in Toronto, Canada.
- Considering effects of uncertainty in CLSC network using decision tree.
- Considering cash flow in the analysis of the multi-period model.
- Utilizing real locations with real distances between the facilities using maps.

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# Effects of uncertainty on a tire closed-loop supply chain network

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# Effects of uncertainty on a tire closed-loop supply chain network

## Abstract

In a closed-loop supply chain (CLSC) network, there are both forward and reverse supply chains. In this research, a tire remanufacturing CLSC network is designed and optimized based on tire recovery options. The objective of the optimization model is to maximize the total profit. The optimization model includes multiple products, suppliers, plants, retailers, demand markets, and drop-off depots. The application of the model is discussed based on a realistic network in Toronto, Canada using map. In addition, a new decision tree-based methodology is provided to calculate the net present value of the problem in multiple periods under different sources of uncertainty such as demand and returns. Furthermore, the discount cash flow is considered in the methodology as a novel innovative approach. This methodology can be applied in comparing the profitability of different design options for CLSCs.

**Keywords:** Closed-loop supply chain (CLSC); Reverse logistics (RL); Tire remanufacturing; Uncertainty; Decision tree; Cash flow analysis

## 1. Introduction

Forward supply chain management is defined as the management of activities and flows related to sending products from suppliers to manufacturers, retailers, and finally customers (Sahoo & Poria, 2014; Guo et al., 2016). A lot of researchers have studied reverse logistics (RL). RL is defined as the logistics activities all the way from used products which are returned by users to products that are again usable in a market (Fleischmann et al., 1997). The value of the returned products can be more than hundreds of millions of dollars for one retailer (Guide & Van Wassenhove, 2009). The integration of forward and reverse logistics leads to closed-loop supply chain (CLSC) networks which usually are more complex networks rather than traditional forward logistics (Melo et al., 2009). Copier remanufacturing and paper recycling are two examples of CLSCs (Fleischmann et al., 2001).

### 1.1. CLSC literature

Some literature review papers have been published about CLSC networks and reverse logistics such as Rubio et al., 2008; Pokharel & Mutha, 2009; Guide & Van Wassenhove, 2009; Melo et al., 2009; Souza, 2013; Govindan et al., 2015; Govindan & Soleimani, 2017.

Retreated tires are examples of commonly remanufactured products. They can be used in different vehicles such as cars and trucks. The tires can be treated several times. However, "retreated tires accounted for only about 3 percent of total sales by U.S. firms within the tire sector between 2009 and 2011" (Chopra & Meindl, 2015). Without recovery of used tires, they may end up in a landfill (e.g. Fig. 1) and harm the environment. Ferrer (1997) described typical supply chains of tires. In addition, he reviewed the value-adding operations and tire retreading process. He provided recommendations for selecting the number of times a tire should be retreaded. Sasikumar et al. (2010) examined a truck tire remanufacturing case by an optimization model. Recently, Subulan et al. (2015) have published a paper about a tire remanufacturing case study in Turkey.



Fig. 1. Used tires may end up in a landfill

Some of the CLSCs papers have been categorized in Table 1 based on uncertainty, sources of uncertainty, financial factors, multi-period, multi-product, type of product, and real locations (maps). Some authors have considered uncertainty in CLSC networks. Francas & Minner (2009) considered demand and return sources of uncertainty in a CLSC network. They examined two situations including sending the products to the same market or the secondary one. The proposed model by Demirel et al. (2014) consists of a genetic algorithm approach with crisp and fuzzy

objectives. Subulan et al. (2015) took into account more sources of uncertainty in the models including demand, return, and disposal rate. We observe that a few of authors have considered more than three sources of uncertainty at the same time in CLSCs.

A few of authors have considered financial factors in CLSC network configuration. Cardoso et al. (2016) developed a mixed-integer linear programming model that integrates financial risk measures in a CLSC. They used  $\varepsilon$ -constraint method to solve the optimization problem. Ramezani et al. (2014) presented a financial approach to model a CLSC network. They included current and fixed assets and liabilities, and a set of budgetary constraints in the model. However, uncertainty has not been considered in the model. According to Chopra and Meindle (2015), “uncertainty in demand and economic factors should be included in the financial evaluation of supply chain design decisions”.

Table 1  
Some of the CLSC papers

Authors	Uncertainty	Sources of uncertainty	Financial factors	Multi-period	Multi-product	Type of product	Real locations (maps)
Fleischmann et al. (1997)						Copier, Paper	✓
Francas & Minner (2009)	✓	Demand, Return			✓		
Kannan et al. (2009)				✓		Tire	
Sasikumar et al. (2010)				✓		Tire	
Shi et al. (2010)	✓	Demand, Return			✓		
Amin & Zhang (2012)					✓	Computer	
Amin & Zhang (2013)	✓	Demand, Return			✓	Copier	
Demirel et al. (2014)	✓	Cost		✓	✓		
Mirakhorli (2014)	✓	Demand, Return				Bread	
Ramezani et al. (2014)			✓	✓			
Zeballos et al. (2014)	✓	Demand, Supply		✓	✓		
Subulan et al. (2015)				✓	✓	Tire	✓
Accorsi et al.					✓		✓

(2015)							
Subulan et al. (2015)	✓	Demand, Return, Disposal			✓	Battery	✓
Al-Salem et al. (2016)							
Keyvanshokoo et al. (2016)	✓	Cost		✓			
Cardoso et al. (2016)	✓	Demand	✓	✓	✓		✓
Kaya & Urek (2016)							✓
Gaur et al. (2017)			✓	✓		Battery	
Our paper	✓	Demand, Return	✓	✓	✓	Tire	✓

Several papers have been published about CLSC networks configuration recently (e.g. Hashemi et al., 2014; Ozceylan et al., 2014; Abbey et al., 2015; Alimoradi et al., 2015; Bottani et al., 2015; Das & Posinasetti, 2015; Moghaddam, 2015a, 2015b; Ma et al., 2016; Zohal & Soleimani, 2016; Mohajeri et al., 2016; Amin & Baki, In press). Most of the publications in CLSC field have focused on general networks (not specific products), and locations based on random numbers (not real locations in maps). Another issue is using Euclidean distance (i.e. straight-line distance) to calculate the distances between facilities in the networks. However, the actual roads should be utilized to calculate the distances (for example with the help of Google Maps).

## 1.2. Aim and research contributions

In this paper, a tire remanufacturing CLSC network is designed and optimized. The objective of the optimization model is to maximize the total profit. The optimization model includes multiple products, suppliers, plants, retailers, demand markets, and drop-off depots. The application of the model is examined in a realistic network in Toronto, Canada. The distances between the facilities are calculated by Google Maps. To our knowledge, this research is the first investigation that considers tire remanufacturing CLSC network configuration in Toronto area. A decision tree-based methodology is also provided to calculate the total profit of the optimization model in multiple periods under different sources of uncertainty such as demand and return. The discount cash flow is also considered in the methodology. The proposed methodology can be

used to develop an expert system that helps the decision-makers to select the best design option of CLSCs based on profitability of networks. The expert system (computer software) can be designed to handle large decision trees, including several branches. Therefore, several sources of uncertainty can be handled by the decision trees in the expert system.

The main research contributions of this paper are as follows:

- Introducing and investigating the recovery options and CLSC network of tires with focus on the related organizations in Canada and a network in Toronto.
- Considering effects of uncertainty in CLSC network configuration by a decision tree-based methodology.
- Considering cash flow in the analysis of the multi-period model.
- Utilizing real locations with real distances between the facilities using Google Maps.

The structure of the paper is as follows: In Section 2, the problem is described. In Section 3, the problem is formulated by a mathematical model and it is solved and analyzed. Section 4 discusses multi-period analysis under uncertainty. Then, discussions are provided in Section 5. Finally, Section 6 is devoted to the conclusions.

## 2. Problem statement

There are some recovery options for tires including reusing, remanufacturing, and recycling ones. Tire remanufacturing is popular because of both price and using environmentally responsible parts. In terms of cost, the price of a remanufactured tire is 40% to 50% of the brand new tires. The quality of remanufactured tire is almost equal to the quality of the new one.

Tires are manufactured, remanufactured, or imported for sale in Canada. The Tire and Rubber Association of Canada (TRAC) collects tire shipment data from its members. The daily operations of the TRAC include three main areas: government relations, industry data, and consumer education. The Canadian Association of Tire Recycling Agencies (CATRA) is responsible for tire recycling. Provincial and national data and statistics related to tires are available in their website. CATRA is made up of tire recycling agencies in the provinces and territories of Canada. In Ontario, Ontario Tire Stewardship (OTS) works with the network of Ontario stewards, collectors, haulers, processors, and innovative recycled product manufacturers to ensure a more sustainable future. The OTS manages tire recycling activities in Ontario

including Toronto. There are some drop-off depots in Toronto. Several items can be dropped including rubber tires, excluding heavy truck, forklift and large off-road tires.

Fig. 2 shows a closed-loop supply chain network of tire remanufacturing. Suppliers provide tire casing for the manufacturer. Tire casing is the main body of the tire exclusive of the tread, tube, etc. The manufacturer can manufacture and remanufacture the tires. The tires are sent to retailers by the manufacturer. Then, customers purchase the tires. Some of the tires are returned to drop-off depots after use. Some of the returned tires are recycled after sorting and inspecting (e.g. thickness inspection). Others are sent to the manufacturer to be remanufactured. Tire casing of the returned tires is utilized to build tires.

There are both strategic and planning decisions in this problem. Strategic decisions include: Which supplier(s) should be selected? Which location(s) should be selected for the plant(s)? Which retailers should be selected to sell the products? Which drop-off depot(s) should be the source(s) of used tires? On the other hand, planning decisions consist of: How many products are purchased from each supplier? How many products exist in each part on the network?

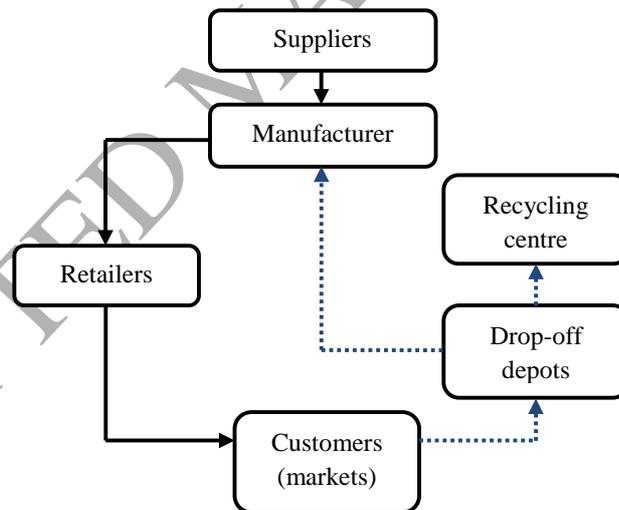


Fig. 2. Closed-loop supply chain of tire remanufacturing (  $\longrightarrow$  forward supply chain,  $\cdots\cdots\longrightarrow$  reverse supply chain)

### 3. Mathematical model

A mixed-integer linear programming model is developed to optimise the network. Sets, parameters, and decision variables are as follows:

## Sets

$J$  = set of products (1 ...  $j$  ...  $J$ )

$S$  = set of suppliers (1 ...  $s$  ...  $S$ )

$I$  = set of potential plants locations of the manufacturer (1 ...  $i$  ...  $I$ )

$R$  = set of potential retailers locations (1 ...  $r$  ...  $R$ )

$K$  = set of customers locations (1 ...  $k$  ...  $K$ )

$L$  = set of potential drop-off depots locations (1 ...  $l$  ...  $L$ )

## Parameters

$N_s$  = fixed-cost associated with supplier  $s$

$p_{sj}$  = purchasing cost of product  $j$  from supplier  $s$

$t_j$  = selling price of product  $j$

$A_i$  = fixed-cost for opening plant  $i$  by the manufacturer

$B_r$  = fixed-cost for selling products through the retailer  $r$

$C_l$  = fixed-cost associated with the drop-off depot  $l$

$D_j$  = transportation cost of product  $j$  per km between suppliers and plants

$E_{si}$  = the distance between locations  $s$  and  $i$

$F_j$  = production cost of product  $j$

$G_j$  = transportation cost of product  $j$  per km between plants and retailers

$H_j$  = transportation cost of product  $j$  per km between retailers and customers

$M_j$  = transportation cost of product  $j$  per km between customers and drop-off depots

$a_j$  = cost saving of product  $j$  (because of product recovery)

$b_j$  = transportation cost of product  $j$  per km between drop-off depots and plants

$d_{kj}$  = demand of customer (market)  $k$  for product  $j$

$e_j$  = percentage of the product  $j$  that is recoverable

$f_{kj}$  = returned product  $j$  of customer  $k$

$m_{ij}$  = capacity of plant  $i$  for product  $j$

$o_{rj}$  = capacity of retailer  $r$  for product  $j$

$g_{lj}$  = capacity of drop-off depot  $l$  for product  $j$

$x_{sj}$  = capacity of supplier  $s$  for product  $j$

## Decision Variables

$P_{sij}$  = quantity of product  $j$  purchased for plant  $i$  from supplier  $s$

$Q_{irj}$  = quantity of product  $j$  produced by plant  $i$  for retailer  $r$

$T_{rkj}$  = quantity of product  $j$  sold by retailer  $r$  to customer  $k$

$U_{klj}$  = quantity of returned product  $j$  from customer  $k$  to drop-off depot  $l$

$V_{lij}$  = quantity of returned product  $j$  from drop-off depot  $l$  to plant  $i$

$X_i = 1$ , if a plant of the manufacturer is located and set up at potential site  $i$ , 0, otherwise

$Y_r = 1$ , if the retailer which is located in site  $r$  is utilized to sell the products, 0, otherwise

$Z_l = 1$ , if the drop-off depot which is located in site  $l$  is utilized to supply used products, 0, otherwise

$W_s = 1$ , if the supplier  $s$  is selected, 0, otherwise

$$\begin{aligned} \text{Max } z = & \sum_r \sum_k \sum_j (t_j - H_j E_{rk}) T_{rkj} - [\sum_s \sum_i \sum_j (p_{sj} + D_j E_{si}) P_{sij} + \sum_i \sum_r \sum_j (F_j + G_j E_{ir}) Q_{irj} \\ & + \sum_k \sum_l \sum_j M_j E_{kl} U_{klj} + \sum_l \sum_i \sum_j (-a_j + b_j E_{li}) V_{lij} + \sum_s N_s W_s + \sum_i A_i X_i + \sum_r B_r Y_r + \sum_l C_l Z_l] \end{aligned}$$

s.t.

$$\sum_s P_{sij} + \sum_l V_{lij} = \sum_r Q_{irj} \quad \forall i, j, \quad (1)$$

$$\sum_i Q_{irj} \geq \sum_k T_{rkj} \quad \forall r, j, \quad (2)$$

$$\sum_r T_{rkj} \leq d_{kj} \quad \forall k, j, \quad (3)$$

$$\sum_r T_{rkj} \geq \sum_l U_{klj} \quad \forall k, j, \quad (4)$$

$$\sum_l U_{klj} = f_{kj} \quad \forall k, j, \quad (5)$$

$$\sum_i V_{lij} \leq e_j \sum_k U_{klj} \quad \forall l, j, \quad (6)$$

$$\sum_s \sum_j P_{sij} + \sum_l \sum_j V_{lij} \leq X_i \sum_j m_{ij} \quad \forall i, \quad (7)$$

$$\sum_i \sum_j Q_{ij} \leq Y_r \sum_j o_{rj} \quad \forall r, \quad (8)$$

$$\sum_k \sum_j U_{klj} \leq Z_l \sum_j g_{lj} \quad \forall l, \quad (9)$$

$$\sum_i \sum_j P_{sij} \leq W_s \sum_j x_{sj} \quad \forall s, \quad (10)$$

$$X_i, Y_r, Z_l, W_s \in \{0, 1\} \quad \forall i, r, l, s, \quad (11)$$

$$P_{sij}, Q_{ij}, T_{rkj}, U_{klj}, V_{lij} \geq 0 \quad \forall j, s, i, r, k, l, \quad (12)$$

The objective function maximizes the total profit in the CLSC network. The first part is related to the profit of selling products to the customers. The next part considers the purchasing and transportation costs of products sending from suppliers to the plants. The costs of production and transportation of products between the plants and retailers are considered in the third part of the objective function. The fourth part includes the transportation cost of sending products from customers to the drop-off depots. The next section in the objective function includes the costs associated with carrying products from drop-off depots to the plants of the manufacturer. In addition, the total fixed-costs associated with suppliers, plants, retailers, and drop-off depots are considered in the objective function.

The first constraint shows the relation between the number of products that is sent to the manufacturer and the number of products that leaves the plants. Constraint (2) illustrates the number of products that is sent from the manufacturer to the retailers is greater than the quantity of products that is sent to the customers. Constraint (3) is related to the demand. Constraint (4) is a network constraint. Besides, Constraint (5) is related to the returned products. Constraint (6) also is a network constraint. Constraints (7), (8), (9), (10) show the limitations in the capacities of plants, retailers, drop-off depots, and suppliers. Constraints (11) and (12) are related to the binary and non-negative types of decision variables, respectively.

The model has been applied for design and optimization of a CLSC network in Toronto, Canada. The Toronto wards have been illustrated in Fig. 3. There are 44 wards in Toronto. They have been classified to 11 groups (demand markets) in this research. Thus, there are 4 wards in each group. In this case, 2 types of tires are considered. In addition, there are 3 potential

suppliers located in Waterloo, Hamilton, and Oshawa. 2 potential plant locations are in Brampton and Ajax. 5 big retailers are potential retailers located in different parts of Toronto. Besides, there are 5 drop-off depots. The transportation mode is truck in this research. The distances between the locations (suppliers, plants, retailers, markets, drop-off depots) are calculated by Google Maps. It is assumed that the demand of market  $k$  for product  $j$  ( $d_{kj}$ ) is 0.01 of population of the market (group). The population of the Toronto wards can be found in 2011 census of Canada. The return ( $f_{kj}$ ) is 0.1 of market demand. Table 2 includes other parameters.

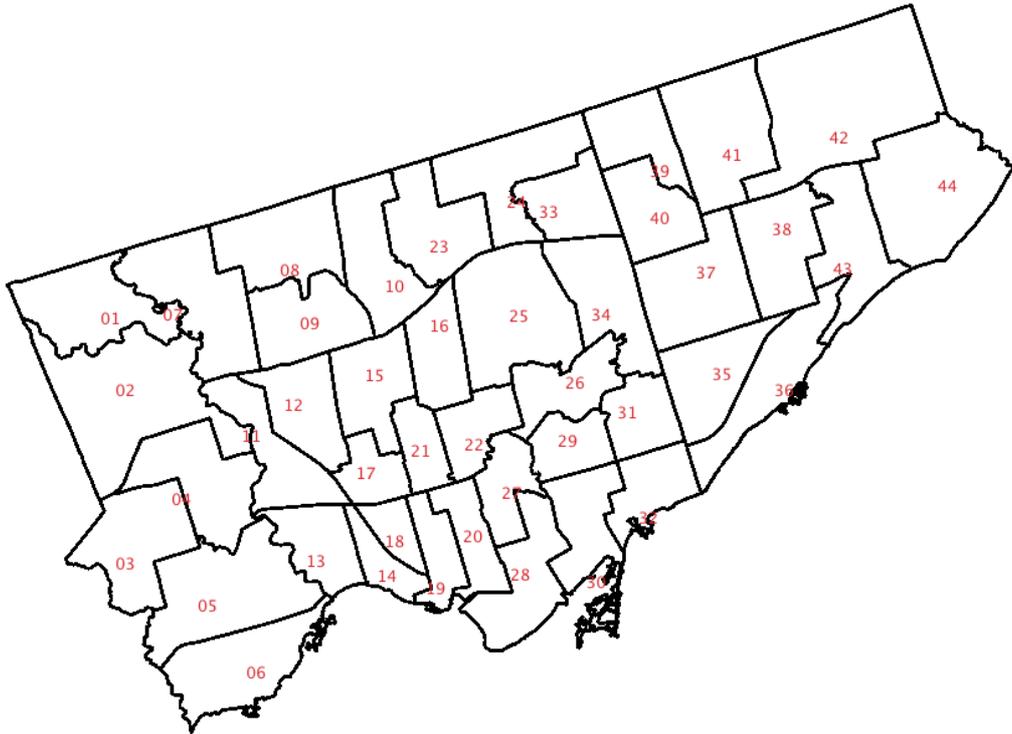
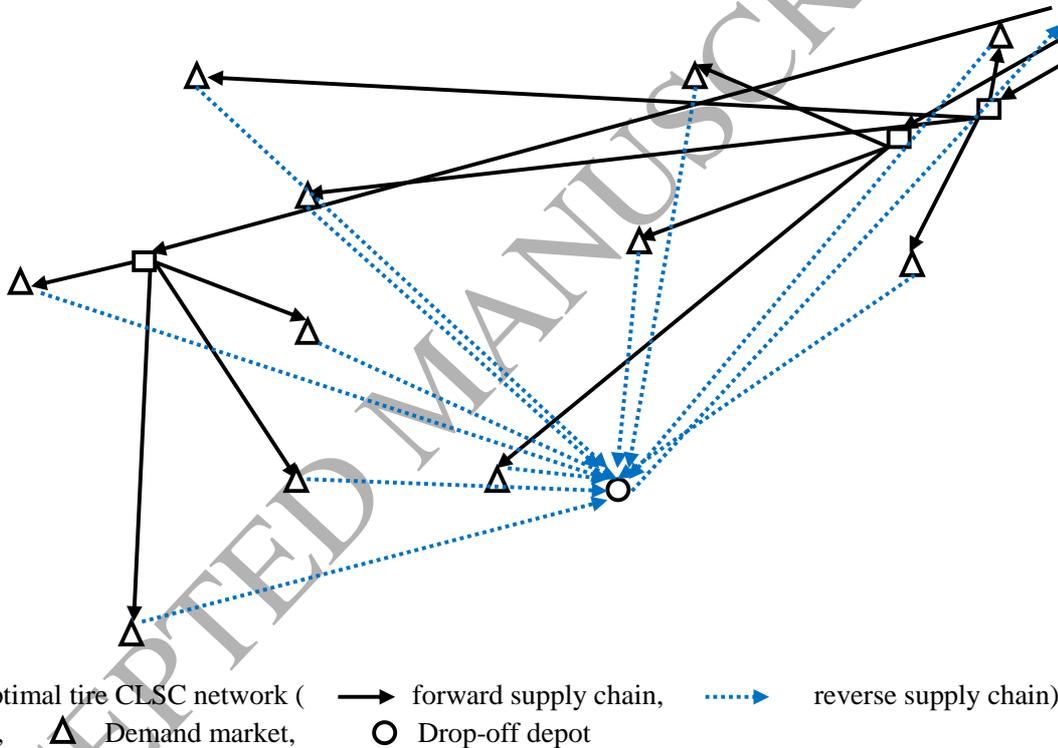


Fig. 3. Toronto Wards

Table 2  
Values of the parameters in the network

$N_s = 1,000$	$G_j = 0.005$	$o_{rj} = 10,000$
$t_j = 100$	$H_j = 0.005$	$g_{lj} = 10,000$
$A_i = 1,000,000$	$M_j = 0.005$	$x_{sj} = 150,000$
$B_r = 1,500$	$a_j = 10$	$p_{1j} = 30$
$C_l = 1,500$	$b_j = 0.005$	$p_{2j} = 35$
$D_j = 0.005$	$e_j = 0.1$	$p_{3j} = 37$
$F_j = 15$	$m_{ij} = 500,000$	

General Algebraic Modeling System (GAMS) is applied to solve the mathematical model. The model is solved in 0.219 seconds. There are 109 single equations, 288 single variables, 15 discrete variables, and 1,229 non-zero elements. Fig. 4 illustrates the optimal tire CLSC network (for Product 1). We focus on Product 1 to prevent any difficulty in the Figure. Some products are purchased from Supplier 1 located in Waterloo. The main reason is the low price. The Ajax is selected for the location of the plant. Retailers 3, 4, and 5 are selected (out of 5 retailers). In addition, the first drop-off depot is chosen.



We examine the changes in some parameters and related results. Fig. 5 shows the changes in demand of Market 1 (for Product 1) and the effects on the profit (objective function). By the increase in demand of the Market 1, the profit will be increased.

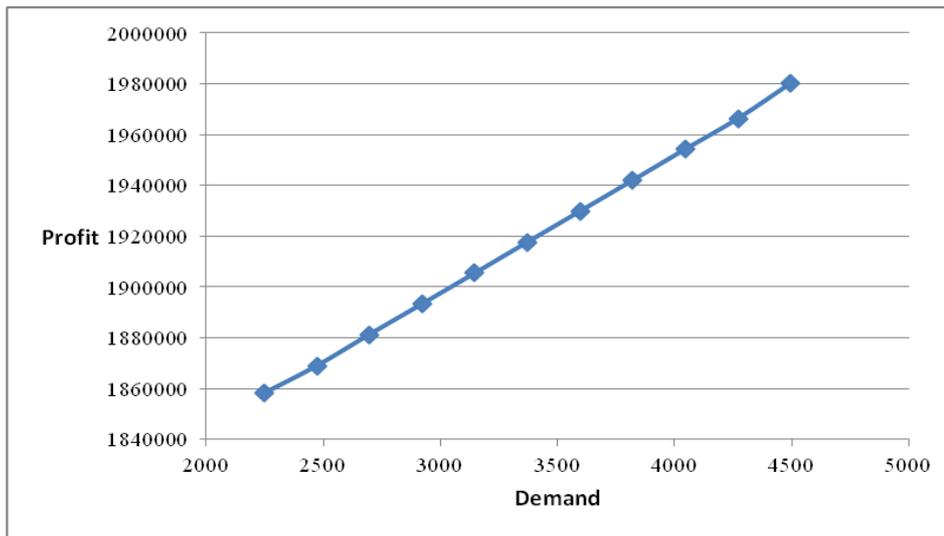


Fig. 5. The effects of demand of Market 1 on the total profit (for Product 1)

In the Section 3, the Drop-off depot 1 has been selected. We examine the effects of 10% increase in the fixed-cost associated with the Drop-off depot 1 on the network configuration. Fig. 6 illustrates the new tire CLSC network. Because of the increase in the cost of the Drop-off depot 1, Drop-off depot 5 will be selected. Therefore, major changes will be applied in the network. This analysis shows that fixed-costs associated with the drop-off depots are sensitive parameters.

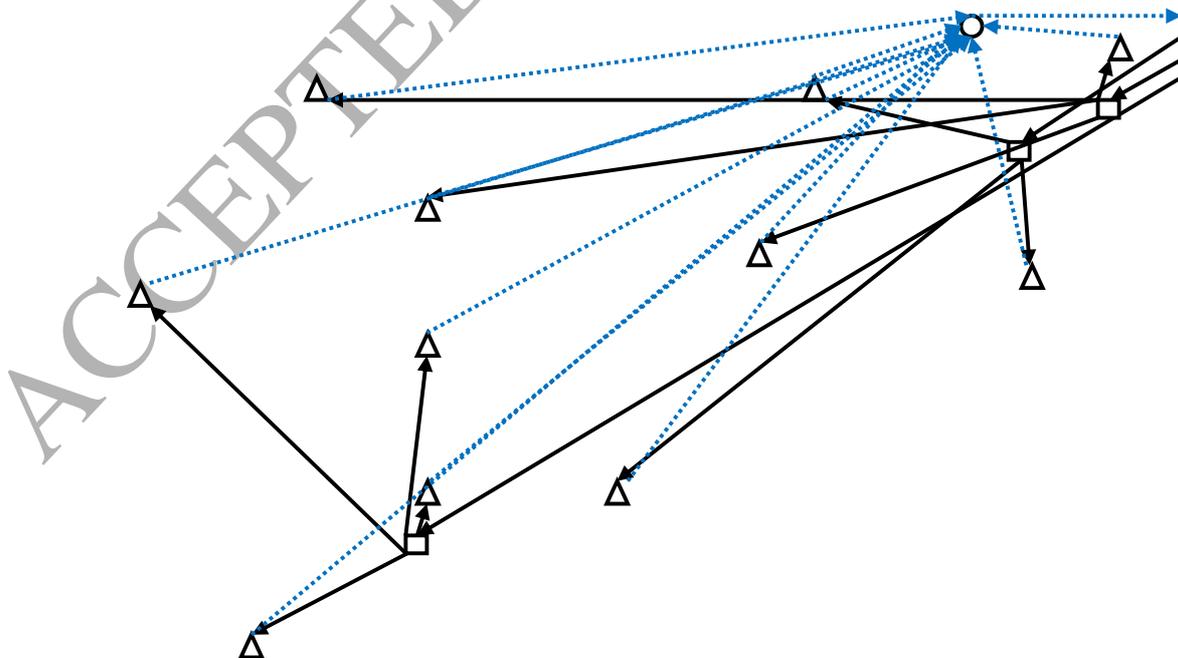


Fig. 6. The new optimal tire CLSC network (  $\longrightarrow$  forward supply chain,  $\cdots\cdots\longrightarrow$  reverse supply chain)  
 $\square$  Retailer,  $\triangle$  Demand market,  $\circ$  Drop-off depot

#### 4. Multi-period analysis under uncertainty

The proposed model is a single period one. However in most of the cases, companies are interested to know the total profit in multiple periods. One option is extending the optimization model to include multiple periods, but financial factors such as interest rates and cash flows are ignored in this situation. Another issue in the proposed model is ignoring uncertainty in the parameters such as demand and return and the impacts of them on the total profit. To overcome these difficulties, a methodology is proposed based on decision tree and discounted cash flow concept.

##### 4.1. Decision tree

A decision tree is a graphic tool which can be used to assess decisions in uncertain situations. Decision trees are depicted for the identified periods (for example 3). A period can be defined as a day, a month, a quarter, or other time periods (Chopra & Meindl, 2015). Each period is a year in this paper. It is necessary to identify factors that will affect the value of the decision over time periods. The values of those factors can change in different periods. Transition probabilities between the nodes (e.g. 0.25) in different time periods are other important parts of decision trees.

##### 4.2. Discounted cash flow

Discounted cash flow analysis evaluates the present value of any stream of future cash flows considering the interest rate. It enables managers to compare different cash flow streams in terms of their financial values (Chopra & Meindl, 2015; Sasaki, 2016).

Suppose that  $y$  represents rate of return. The discount factor ( $w$ ) can be calculated by Eq. (13). Then, the Net Present Value (NPV) is obtained by Eq. (14) which  $O_0, O_1, \dots, O_c, \dots, O_n$  is stream of cash flows over  $n$  periods.

$$w = \frac{1}{1 + y} \quad (13)$$

$$NPV = O_0 + \sum_c \left(\frac{1}{1 + y}\right)^c O_c \quad (14)$$

### 4.3. Effects of uncertainty

In this section, a methodology is described to consider the effects of uncertainty and discounted cash flow on the CLSC network. The main steps are as follows:

Step 1: Determine the duration (e.g. year), and the number of periods.

Step 2: Determine the uncertain factors in the CLSC network such as demand and return.

Step 3: Draw the decision tree.

Step 4: Calculate and add the transition probabilities to the decision tree.

Step 5: Determine the rate of return ( $y$ ).

Step 6: Solve the problem backward. For the last period, solve the mathematical model presented in Section 3 and calculate the total profit for each node. Then, calculate the expected profit ( $\lambda$ ) for each branch of the decision tree. Then, compute the profit moved from the last period to the previous one considering the discount factor. It can be calculated as  $\beta = \lambda / (1 + y)$ . The total profit in that period can be calculated as the summation of  $\beta$  and the profit obtained by solving the mathematical model presented in Section 3. Continue this process to calculate the total profit in Period 0 which is the Net Present Value (NPV).

About the CLSC network in Toronto, the supply chain manager decides to calculate the NPV for three periods (years). She identifies demand and return as the sources of uncertainty. The rate of return of 0.1 is utilized to solve the problem. From one year to the next, it is expected that the demand may increase by 20 percent with the probability of 0.5, or decrease by 20 percent. For the return parameter, the values can go up or down by 10% with the probability of 0.5. Fig. 7 shows the decision tree including the transition probabilities which are  $0.5 * 0.5 = 0.25$  for each branch. [Microsoft Excel is utilized to combine the values of different periods and calculate the NPVs.](#) The results of solving the mathematical model in Period 2 have been written in Table 3. Table 4 includes the results related to Period 1. For instance,  $0.25 * (3,331,669.162882 + 3,327,024.870755 + 1,748,597.815830 + 1,743,245.039193) = 2,537,634.222$ .

The expected profit in Period 1 =  $0.25 * (4,826,555.503 + 4,801,739.332 + 2,465,660.519 + 2,457,631.382) = 3,637,896.684$ . Then, the profit from Period 1 moved to Period 0 =  $3,637,896.684 / 1.1 = 3,307,178.804$ . Finally,  $NPV = 1,858,157.293$  (profit of Period 0) +

3,307,178.804 (profit from Period 1 in Period 0) = 5,165,336.097. The NPVs can be utilized for comparing different design options and selecting the best one.

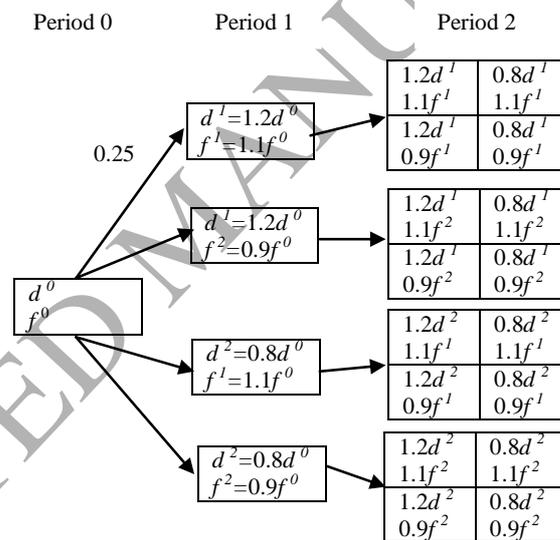


Fig. 7. The decision tree

Table 3  
Profit in Period 2

Node	Profit of Period 2
$1.2d^1, 1.1f^1$	3,331,669.162882
$1.2d^1, 0.9f^1$	3,327,024.870755
$0.8d^1, 1.1f^1$	1,748,597.815830
$0.8d^1, 0.9f^1$	1,743,245.039193

$1.2d^1, 1.1f^2$	3,327,024.870755
$1.2d^1, 0.9f^2$	3,323,224.696877
$0.8d^1, 1.1f^2$	1,743,245.039193
$0.8d^1, 0.9f^2$	1,739,699.185574
$1.2d^2, 1.1f^1$	1,748,597.815830
$1.2d^2, 0.9f^1$	1,743,245.039193
$0.8d^2, 1.1f^1$	839,561.840588
$0.8d^2, 0.9f^1$	835,022.103596
$1.2d^2, 1.1f^2$	1,743,245.039193
$1.2d^2, 0.9f^2$	1,739,699.185574
$0.8d^2, 1.1f^2$	835,022.103596
$0.8d^2, 0.9f^2$	831,307.964235

Table 4  
Total profit in Period 1

Node	$\lambda^2 =$ Expected profit in Period 2	$\beta^1 =$ Profit from Period 2 in Period 1 = $\lambda^2 / (1+y)$	$\rho^1 =$ Profit of Period 1	Total profit = $\beta^1 + \rho^1$
$1.2d^0, 1.1f^0$	2,537,634.222	2,306,940.202	2,519,615.301	4,826,555.503
$1.2d^0, 0.9f^0$	2,533,298.448	2,302,998.589	2,498,740.743	4,801,739.332
$0.8d^0, 1.1f^0$	1,291,606.700	1,174,187.909	1,291,472.610	2,465,660.519
$0.8d^0, 0.9f^0$	1,287,318.573	1,170,289.612	1,287,341.770	2,457,631.382

If we solve the problem without considering the decision tree for Periods 0, 1, 2, the NPV will be 5,083,058.380. We observe that when the demand and return uncertainties are ignored, the calculated NPV will be 1.619% less than the situation with considering uncertainty. This point is particularly important if there are some design options for CLSCs and we want to select the best one based on maximum NPV. The decision of considering the uncertainty in calculating the NPVs can affect the selection of the best option.

## 5. Discussion

In this section, the changes in some of the parameters and related results are discussed.

### 5.1. Effects of transition probabilities

In Section 4, the probabilities of increase and decrease in the demand and return parameters were 0.5. We solve the problem for the situation that the probabilities of increase in demand and

return are 0.6, and 0.4 for decrease. The new transition probabilities have been illustrated in Fig. 8. After solving the problem, we observe that the NPV is 5,489,767.459. We can conclude that by adding one unit to the percentage of the increase in demand and return, the NPV will be increased by 3,244,313.62 because  $(5,489,767.459 - 5,165,336.097) / (0.6 - 0.5) = 3,244,313.62$ .

Fig. 9 illustrates the sensitivity analysis for the percentage of increase in demand and return. To draw the figure, first we calculate the transition probabilities for each rate of demand and return increase. For example for 0.1, the transition probabilities are 0.01, 0.09, 0.09, 0.81, respectively. Then, the methodology is applied to solve the problem.

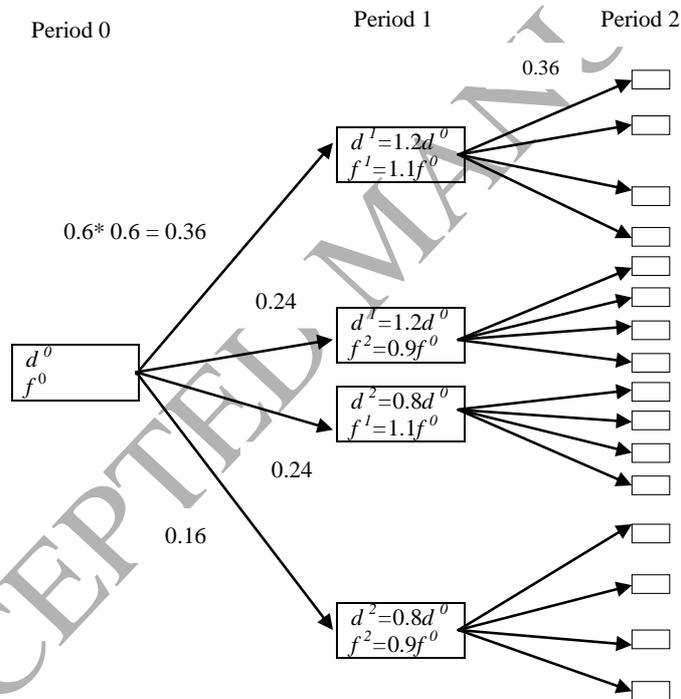


Fig. 8. The decision tree with new transition probabilities (0.36, 0.24, 0.24, 0.16)

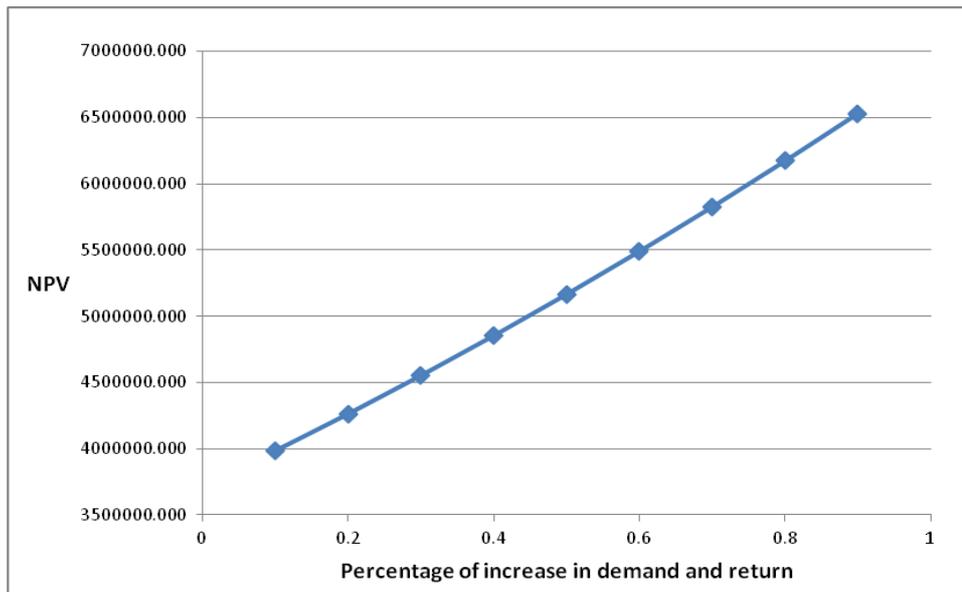
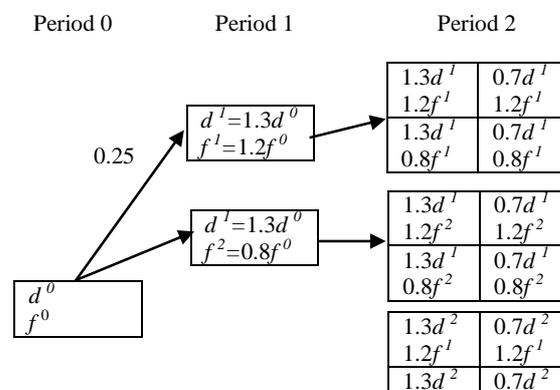


Fig. 9. Sensitivity analysis for the percentage of increase in demand and return

## 5.2. Changes in demand and return

The supply chain manager predicted that the demand can increase or decrease by 20 percent. In addition, the return can go up or down by 10 percent. In this section, we examine the effects of 30 percent changes in demand, and 20 percent changes in return. We solve the problem according to the numbers in Fig. 10. The NPV in this case is 5,554,843.787. In Section 4, the NPV of the original case was 5,165,336.097. We observe that by increasing one unit to the percentages of changes in demand and return, the NPV will be increased by 38,950.769 because  $(5,554,843.787 - 5,165,336.097) / (30 - 20) = 38,950.769$ .



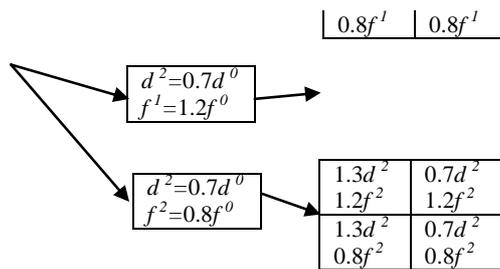


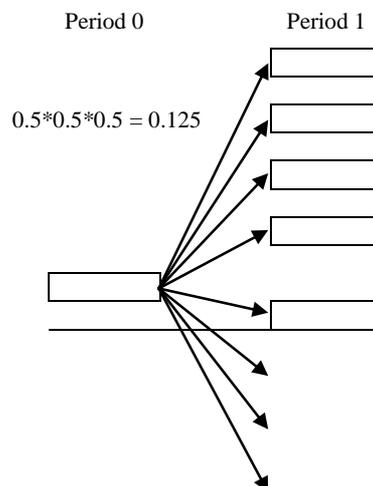
Fig. 10. The decision tree

### 5.3. Effect of rate of return

The rate of return in the original case was 0.1. In this section, the problem is solved with  $y = 0.15$  (rate of return). The NPV in this case is 4,955,813.991. It is noticeable that by increasing one unit to the rate of return, the NPV is decreased by 4,190,442.12 because  $(4,955,813.991 - 5,165,336.097) / (0.15 - 0.1) = -4,190,442.12$ .

### 5.4. More sources of uncertainty

In most of the cases in the literature, one or two sources of uncertainty have been considered. However, it is straightforward to take into account more than two sources of uncertainty in the methodology. By adding more sources of uncertainty, more branches will be added to the decision tree. For example, the supply chain manager decides to add supply uncertainty to the model that is expressed as the purchasing cost of products from suppliers ( $p$ ). The decision tree for Periods 0 and 1 has been shown in Fig. 11.



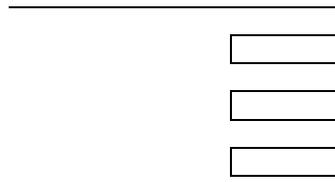


Fig. 11. The decision tree for three sources of uncertainty

## 6. Conclusions

In this paper, some important characteristics and practices of tire remanufacturing in Canada particularly in Ontario, and related associations have been introduced. In addition, a mixed-integer linear programming model has been developed to design and optimize a tire remanufacturing closed-loop supply chain network. The objective function maximizes the total profit. The optimization model consists of multiple products, suppliers, plants, retailers, demand markets, and drop-off depots. The application of the model has been shown in a network located in Toronto areas using Google maps. Unlike the most of the previous publications in this field that have used straight-line distance method, the distances between locations have been calculated by Google Maps. The results of the model have been analyzed. In Section 4, a methodology based on decision tree and discounted cash flow has been provided to consider the effects of uncertainty on the CLSC networks. Then, it has been applied for the case considering uncertainty in demand and returns. This methodology can be used to calculate the net present value of CLSCs and compare different design options. Finally, the effects of changing some parameters have been discussed.

In summary, the four main advantages of this paper are; 1) introducing and investigating the recovery options and CLSC network of tires with focus on Canada, 2) considering the effects of uncertainty in CLSC network configuration by a new decision tree-based methodology, 3) utilizing cash flow in the analysis of the model in different periods, and 4) utilizing real locations with real distances between the facilities by using Google maps.

Based on the limitations in the model, some future research opportunities can be defined. A future research is taking into account more objective functions in the model. For example, environmental and sustainable objectives such as minimization of wastes can be added to the model. Furthermore, it is valuable to develop solution approaches for large-sized problems using Metaheuristic algorithms such as Particle Swarm. Another future research area is investigating the effects of cannibalization on the CLSC network configuration and optimization. The sales

volume of the new tires can be reduced because of availability of remanufactured tires. As a result, some companies do not have strong motivation to remanufacture the used tires.

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