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Reverse logistics network redesign under uncertainty for wood waste in the CRD industry

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ABSTRACT

This paper addresses the reverse logistics network (RLN) design problem under environmental policies targeting recycled wood materials from the construction, renovation and demolition (CRD) industry. The main objective is to determine the location and the capacities of the sorting facilities to ensure compliance with the new regulation and prevent the wood from being massively landfilled. We formulated the problem as a mixed-integer linear programming model (MILP) to minimise the total cost of the wood recycling process collected from CRD sites. The main contribution lies in the consideration of important uncertain factors such as supply sources locations, the available quantity of recycled wood at the collection sites, and the various quality grades of the collected wood. A scenario-based analysis is conducted to evaluate the impact of uncertainties on the RLN design. In addition, the proposed MILP model has been applied for a case study in the CRD industry within the province of Quebec, Canada. The results of this study show the adjustment of the reverse logistics network leads to the reduction of wood recycling cost due to the improved efficiency of sorting facilities and the economy of scale achieved under the new policy. Moreover, sorting facilities are now located near the CRD collection points and not close to landfilling site as for the actual situation. Finally, the study demonstrates that efforts to obtain accurate information about the supply sources locations and the expected wood quantity recovered from sorting facilities will guarantee a more efficient RLN redesign.

1. Introduction

Nowadays, environmental regulations are emerging in many countries worldwide. The European Union Waste Framework Directive (EU-WFD) imposes a minimum of 70% collection of material waste in the construction industry (Supino et al., 2016). Turkey has recently seen the enforcement of the Waste on Electrical and Electronics Equipment (WEEE) regulation on its territory (Amin et al., 2017) and India is facing an increasing number of air and water pollution legislations (Greenstone and Hanna, 2014). Indeed, this is probably the most efficient solution to achieve more sustainable operations and force managers to take action to reduce the damage to the environment and avoid social problems caused by supply chain activities (Seuring and Müller, 2008). Waste management and recycling activities are usually connected with environmental regulations and many countries are putting a lot of effort into improving their efficiency in this area. Thus, we notice the emergence of many closed-loop supply chains (CLSC) in the past few years. The objective of CLSC is to combine the classical forward logistics flows with reverse logistics (RL) activities which are becoming very popular fields among practitioners and academics, both of whom are trying to find better strategies to be in compliance with waste management policies.

This research addresses the specific problem of the management of wood waste by the construction, renovation, and demolition (CRD) industry. CRD is the first industrial waste generator in Canada, being responsible for a third of the total national waste generation (RECYQ-QUEBEC, 2012). Wood is frequently used as a building material in many countries, and more specifically in cold environments due to the advantages that are provided such as modularity, energy efficiency, etc. This is why countries such as Sweden, Denmark or Canada present a very high rate of usage of wood materials in their buildings (Sathre and González-García, 2014). In addition, with a very large territory and a lot of forest land, Canada is one of the countries with the highest rate of wood material inside its buildings (Yeheyis et al., 2013). Thus, wood is the first building material in terms of waste generated during the construction, renovation and demolition processes, often exceeding 30% of the total debris collected (Yeheyis et al., 2013). The recycled wood sector is facing some important challenges in Quebec. Today, more than 60% of wood generated at CRD sites is landfilled, partly because the recycling process is more expensive than the landfilling

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cost (RECYQ-QUEBEC, 2012).

Efficient RL networks have a major role to play in increasing the recovery rate of the recycled wood from the CRD industry. Indeed, in order to manage the wood recycling process in an efficient manner, we should be able to adequately locate the sorting facilities and decide on their annual treatment capacity. Dealing with transportation activities and building material flow between the collection sites and sorting facilities is usually a difficult task. It is even more complex in the CRD industry because of uncertainties in the reverse supply chain network. First, the location of the supply sources is variable over time, which means that they are different from one year to another making it complicated to locate the sorting facilities to minimise transportation distances. Secondly, the amount of wood material collected is highly unpredictable. Thus, the treatment capacity decision that must be allocated to each sorting facility to process the recycled wood is also a concern. Finally, according to the construction decisions that were made decades ago during the design stage of the buildings, the quality level of the collected wood on the CRD sites is highly unpredictable. The uncertainty of the location, quantity and quality level of wood generated in the CRD industry makes the recycled wood RL network design problem challenging.

Thus, the main objective of this research is to build a quantitative model for RL network redesign under an environmental policy that targets the recycled wood material from the CRD industry. To the best of our knowledge, this is the first study that addresses this specific problem targeting the CRD industry in this geographical area from a reverse logistics perspective. This research could be beneficial for the local authorities providing some useful insights about the expected impact of the environmental policy targeting the recycled wood material from the CRD industry, thus possibly preventing illegal dumping and border landfilling under the regulation.

To reach this goal, we propose a MILP formulation that allows making decisions at a strategic facility level such as 1) Should an existing sorting facility be closed or not? 2) Should we expand the treatment capacity of an existing facility? and 3) Should we relocate some of the existing facilities to decrease transportation distances in the RL network? Also, our model considers the RL tactical flow decisions between logistics units. The contribution of this work lies in two particularities. First, the model is able to capture both dynamic change in supply sources locations and also the variations in the quality levels of the collected wood materials. A scenario-based approach is proposed in this study to assess the potential impacts of these sources of uncertainty by selecting relevant discrete values of the uncertain parameters. The applicability of the model is illustrated with a case study in the province of Quebec, Canada.

The remainder of this paper is structured as follows. Section 2 presents the relevant literature review in the RL field. Section 3 presents in detail the mathematical formulation of the proposed model. Section 4 introduces the case study for the recycled wood from the CRD industry in the province of Quebec. Section 5 discusses some managerial insights based on the main findings. Finally, conclusions and future research perspectives are derived in Section 6.

2. Literature review

We have recently noted an increased number of research papers addressing RL problems and several literature reviews were also published in this field: Pokharel and Mutha (2009), Agrawal et al. (2015), Govindan et al. (2015). The first studies addressing network design problems in RL appeared less than 20 years ago (Barros et al., 1998). From this point, we denote an increased variation in the RLN design models with collection centres and refurbishing facilities' location with multiple products consideration. Kara and Onut (2010) proposed a stochastic programming model to select a long-term strategy under uncertainties regarding the facility locations and the optimal flow in an RL network design problem with an application in the paper industry. Lieckens and Vandaele (2012) developed a mixed-integer nonlinear program (MINLP) considering uncertainties on the collected quantities and quality of the products parts in order to make decisions about collection facility location. Lieckens et al. (2013) also proposed a MINLP that helps make decisions on reverse facility locations, capacity allocation and flow between the network nodes. The study of Toso and Ahem (2014) investigates both deterministic and stochastic capacitated facility location model considering discrete time intervals. Another stochastic programming model is presented in Dai and Wang (2014) that investigates the impact of uncertain collected quantity and secondary market demand for the returned products. A genetic algorithm is used to decide on collection point locations and flow decisions in the RL network. Later, Jeihoonian et al. (2016a, 2016b) also considered the unknown amount of returned products in a multi-stage stochastic model in order to locate the collection facilities in the reverse network. A scenario clustering decomposition is proposed to solve the multi-period model and its utility is illustrated in the sector of large household appliances. Fattahi and Govindan (2017) used a two-stage stochastic formulation to address the uncertainty related to new products demand and potential returns of used products. The proposed model is solved using a novel simulated annealing algorithm for large-sized problems. Finally, Nakatani et al. (2017) propose a robust multi-period formulation to address the optimal flow decisions in the context of uncertain demand and material prices. Table 1 shows that facility location and flow are the most common decision variables. Moreover, capacity expansion decisions are not very common in RL and CLSC models. The main sources of uncertainties are the demand and the collected quantity of the returned products in the RL network.

Very few papers address quality issues of collected products. However, to the best of our knowledge, studies that consider variation in the supply sources locations while making reverse network design decisions are unavailable. Indeed, this characteristic is very specific to the CRD industry. It is difficult to predict where the building materials collection points will be located in the future. Such feature has a real impact on the RLN design decision. Indeed, transportation distances play a major role on the recovery rate of building materials as the building contractors will not accept to travel too far to the nearest sorting facility. Finally, we denote a significant number of decision models that are applied to industrial case studies, sometimes for a specific sector or from a more general perspective, without targeting a particular product category. In Table 2 we reviewed 103 papers in the RL and CLSC fields by industrial sector.

We can clearly see the lack of case application in the CRD industry. Only the research of Sinha et al. (2009) proposes a stochastic formulation to design an RL recovery network in the construction sector. Although the proposed model considers demand and return uncertainties, supply sources locations change and quality issues are not addressed. However, information about material waste quality is a key element in the construction industry in order to manage RL activities properly (Sobotka and Czaja, 2015). There is a need to address this gap in order to build an appropriate model for this particular sector, showing some specificities compared to the traditional reverse logistics practices applied to the manufacturing industry (Hosseini et al., 2014).

In order to minimise the RL costs of the wood building-material recovery process and to ensure compliance with the legislation, it is critical to develop innovative models that consider the particularities of the CRD industry: unpredictable quality of the recycled wood material collected, the variable location of the supply sources and the collected quantity of materials.

3. Model development

3.1. Assumptions

In order to build a model adapted to the reality of the wood building-material recycling supply chain, we consider a RL network

Table 1
Recent RL and CLSC decision models considering uncertainties (2007–2017).

	Model formulation	Uncertain parameters			Decision variables of the model			Planning horizon		Type of data set		Proposed case study
		SSL	CV	MQ	FL	CE	FD	SP	MP	FD	CS	Industry
Salema et al. (2007)	MILP		×		×		×	×		×		–
Chouinard et al. (2008)	2 stage ST		×		×		×	×			×	Medical
Pishvaee et al. (2009)	ST program		×	×	×		×	×		×		–
Lee et al. (2010)	2 stage ST		×		×		×	×			×	Electronics
Kara and Onut (2010)	2 stage ST		×		×		×	×			×	Paper
Gomes et al. (2011)	MILP		×		×		×		×		×	Electronics
Gomes et al. (2011)	2 stage ST		×	×	×		×		×	×		–
Pishvaee and Rabbani (2011)	Robust		×		×		×	×		×		–
Lieckens and Vandaele (2012)	MINLP		×	×	×	×	×		×		×	
Cardoso et al. (2013)	MILP		Else		×		×		×		×	–
Lieckens et al. (2013)	MINLP		Else		×		×		×		×	Manufacturing
Toso and Ahem (2014)	ST program		×		×		×		×		×	Residential
Dai and Wang (2014)	ST program		×		×		×	×		×		–
Zeballos et al. (2014)	Multi-stage ST		Else		×		×		×	×		–
Subulan et al. (2015)	Fuzzy		Else		×		×		×		×	Automotive
Jeihoonian et al. (2016a, 2016b)	Multi-stage ST		×	×	×		×		×		×	Electronics
Sun and Shen (2017)	Robust		×	×	×		×	×			×	Electronics
Nakatani et al. (2017)	Robust		Else		×		×		×	×		Plastics
Amin and Baki (2017)	Fuzzy		Else		×		×	×			×	Electronics
Amin et al. (2017)	MILP		×		×		×	×			×	Automotive
Proposed model	MILP	×	×	×	×	×	×	×			×	CRD

SSL: Supply Sources Location; CV: Collected Volume; MQ: Material Quality; FL: Facility Location; CE: Capacity Expansion; FD: Flow Decisions; SP: Single Period; MP: Multi-Period; FD: Fictive Data; CS: Case Study; ST: Stochastic.

that includes the main actors of this industry. First, we assume that a set of CRD sites, also referred to as collection sites or supply sources are available. Collection activities are performed at these nodes. Mixed building-material waste is collected into containers and loaded onto trucks. Then, there is a choice to make between two possibilities: the landfilling or the recycling option. The materials moved to the landfills have reached the end of their useful life and are ultimately disposed. On the other hand, each container shipped to a sorting facility increases the opportunity to extract wood to be sold and used by final customers: the wood material recyclers. In this work, we assume that capacities and locations of existing sorting facilities are known in advance, as well as the location for the new potential sorting facilities and the recyclers demand for each grade (g_i) of recycled wood. The main assumptions regarding the building-material containers are synthesized in Fig. 1.

3.2. Mathematical formulation

We formulated the RL network design problem of recycled wood from the CRD industry as a mixed-integer linear program (MILP). The proposed formulation helps in making decisions regarding the sorting centres operation, facilities relocation, capacity expansion and material flow decisions between the network nodes under the environmental policy. The structure of the RL network is illustrated in Fig. 2.

The sets, parameters, decisions variables, objective function and the

Table 2
RL and CLSC papers by sectors (2007–2017).

Sector	Proportion	Published papers
General	30.1%	Zikopoulos and Tagaras (2007), Lieckens and Vandaele (2007) Salema et al. (2007), Zhu et al. (2008), Francas and Minner (2009) Xiaofeng and Tijun (2009), Pishvaee et al. (2009), Salema et al. (2010), Pishvaee and Torabi (2010), Wongthatsanekorn et al. (2010), Chen and He (2010), Gomes et al. (2011), Pishvaee and Rabbani (2011), Cardoso et al. (2013), Dai and Wang (2014), Zeballos et al. (2014), Amin and Zhang (2012), Diabat et al. (2013), Huang and Su (2013), Ramezani et al. (2013), Vahdani et al. (2013), Lieckens et al. (2013), Gu and Tagaras (2014), Niknejad and Petrovic (2014), Eskandarpour et al. (2014), Demirel et al. (2014), Wei et al. (2015), Tan and Chanchaichujit (2016), Zhalechian et al. (2016), Esmaeili et al. (2017), Battini et al. (2017)
Electronics	19.4%	Hammond and Beullens (2007), Lee and Dong (2008), Kumar and Putnam (2008), Lau and Wang (2009), Xiaofeng and Tijun (2009), Tsai and Hung (2009), Janse et al. (2010), Gomes et al. (2011), Lieckens and Vandaele (2012), Rahman and Subramanian (2012), Daim et al. (2012), Chiou et al. (2012), Kissling et al. (2012), Krapp et al. (2013), Kilic et al. (2015), Ayvaz et al. (2015), Jeihoonian et al. (2016a, 2016b), Guarnieri et al. (2016), Sun and Shen (2017), Amin and Baki (2017)
Manufacturing	13.6%	Xanthopoulos and Iakovou (2009), Atasu and Boyaci (2010), Kapetanopoulou and Tagaras (2011), Sharma et al. (2011), Millet (2011), Drake et al. (2012), Rahman and Subramanian (2012), Lieckens et al. (2013), Jaber et al. (2013), Mittal and Sangwan (2013), Abdulrahman et al. (2014), Galvez et al. (2015), Otay and Çebi (2016) Bazan et al. (2017),
Materials	9.7%	Kara and Onut (2010), Zeballos et al. (2012), Kannan et al. (2012), Giannetti et al. (2013), Lundkvist et al. (2013), Schweiger and Sahamie (2013), Bing et al. (2014), Bing et al. (2015), Kumar et al. (2016), Alshamsi and Diabat (2017), Nakatani et al. (2017)
Automotive	6.8%	Gerrard and Kandlikar (2007), Zhu et al. (2007), González-Torre et al. (2010), Gołębiewski et al. (2013), Mahmoudzadeh et al. (2013), Demirel et al. (2014), Subulan et al. (2015), Amin et al. (2017),
E-waste	3.9%	Gomes et al. (2008), Kannan et al. (2009), Dat et al. (2012), Liu et al. (2014), Agrawal et al. (2014)
Agri-food	3.9%	Hasani et al. (2012), Kim et al. (2014), Accorsi et al. (2016), Banasik et al. (2017)
Cell phones	2.9%	Hanafi et al. (2007), Mitra (2007), Geyer and Blass (2010)
Packagings	1.9%	Silva et al. (2013), Edgar et al. (2014)
Hazardous	1.9%	Ardjmand et al. (2015), Shojaeipour (2015)
Containers	1.9%	Di Francesco et al. (2009), Meng and Wang (2011)
Paper	~1%	Zhou and Zhou (2015)
Construction	~1%	Sinha et al. (2009)

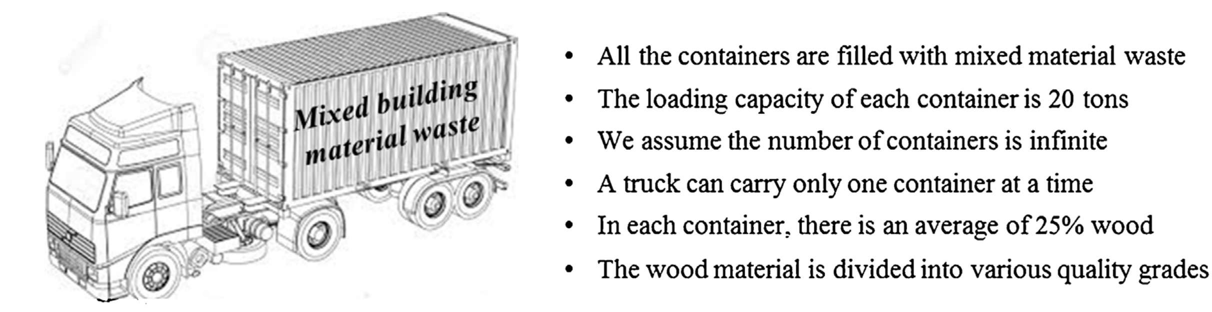

Fig. 1. Main assumptions regarding the containers collected at CRD sites.

constraints of the model are listed below. The nodes of the network $\{i, j\}$ represent any CRD site, sorting facility, landfilling area and the demand markets of wood recyclers.

Sets$i, j \in N$Nodes of the network$s \in S \subset N$Set of supply sources$f \in F \subset N$Set of existing sorting facilities$f' \in F \subset N$Set of potential sorting facilities$k \in K$Set of possible existing facility sizes$k' \in K$Set of available sizes for expanded sorting facilities$l \in L \subset N$Set of landfilling areas$c \in C \subset N$Set of customers (i.e. building material recyclers)$m \in M$Set of collected materials$g \in G$Set of various quality grades for the materials$z \in Z$Set of geographic zones$u \in U$Set of scenarios

Parameterst_{ij}Transportation cost for shipping one metric ton of materials between node $i\in N$ and node $j\in N$$\xi_{ij}$Transportation distances between node $i\in N$ and node $j\in N$$\omega$Loading capacity of the trucksd_{mgc}Demand for material $m\in M$ of grade $g\in G$ at customer $c\in C$$h_{fk}$Annual treatment capacity at sorting facility $f\in F$ of size $k\in K$$h'_{fk}$Added capacity in case sorting facility $f\in F$ of initial size $k\in K$ is expandingr_mRecycling rate at sorting facilities for material type $m\in M$$c^L_m$Unit landfilling cost for one ton of material $m\in M$ at a landfilling areac^R_mUnit recycling cost for one ton of material at the sorting facilitiesΩ_{fk}Fixed annual operating cost for an existing sorting facility $f\in F$ of size $k\in K$$\Omega_{f'k'}$Fixed annual operating cost for an existing sorting facility $f'\in F$ of size $k'\in K$$\delta_{fkk'}$Expansion cost of sorting facility from size $k\in K$ to size $k'\in K$$\pi_{fkz}$Opening cost for sorting facility $f\in F$ of size $k\in K$ in geographical zone $z\in Z$$\Psi_m$Target proportion of material type $m\in M$ that must be sent to sorting facilities$LS_u(x_u, y_u)$Coordinates of the supply sources of the network in scenario $u\in U$$V_{mgsu}$Quantity of material $m\in M$ of quality grade $g\in G$ collected at supply source $s\in S$ in scenario $u\in U$$Q_{mgu}$Proportion of quality grade $g\in G$ in one ton of collected material $m\in M$ at supply sources in scenario $u\in U$

Decision variablesX_{mgsfu}Flow of material of type $m\in M$ of quality grade $g\in G$ transported from supply source $s\in S$ to sorting facility $f\in F$ in scenario $u\in U$$X_{mgslu}$Flow of material of type $m\in M$ of quality grade $g\in G$ transported from supply source $s\in S$ to landfilling area $l\in L$ in scenario

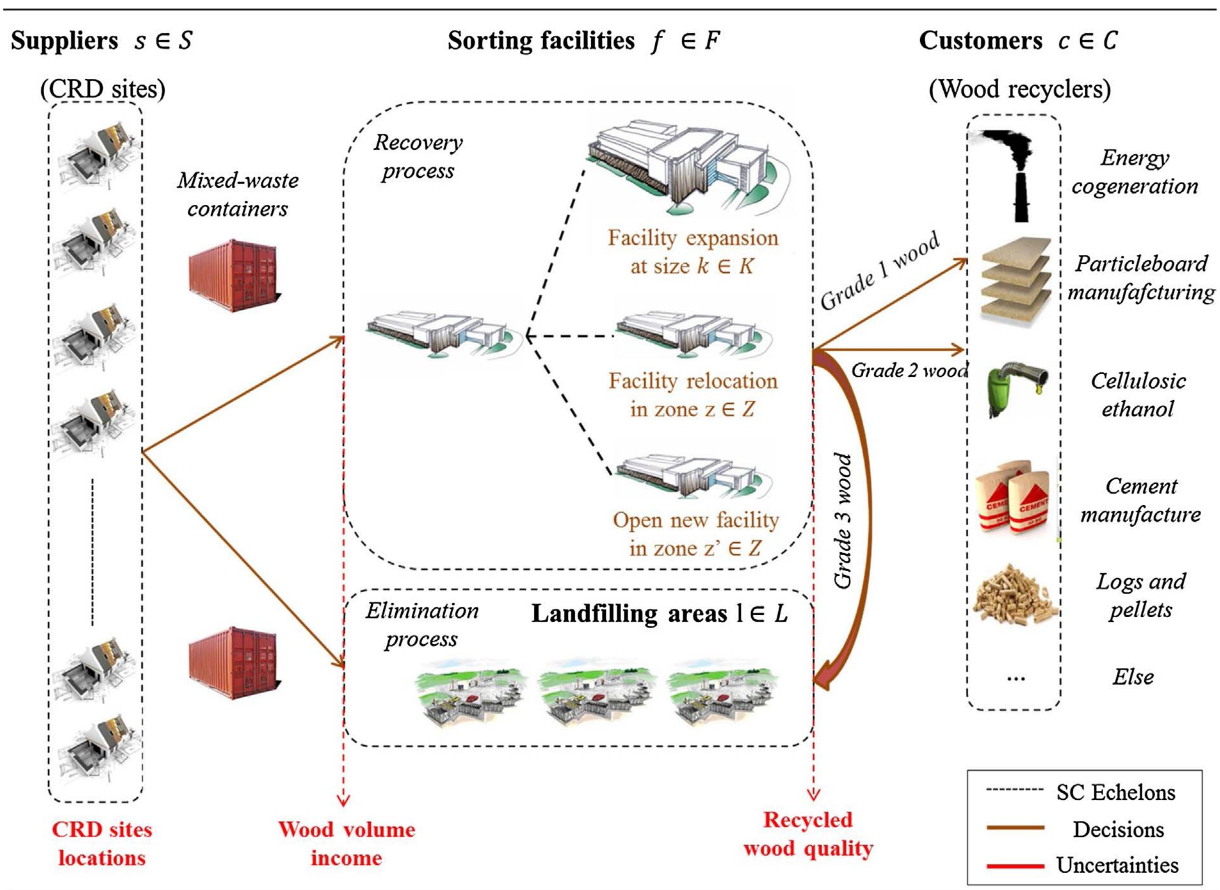

Fig. 2. RL network for the recycled wood material from the CRD industry.

$u \in X_{mgfcu}$Flow of material of type $m \in M$ of quality grade $g \in G$ transported from sorting facility $f \in F$ to customer $c \in C$ in scenario $u \in UX_{mgflu}$ Flow of material of type $m \in M$ of quality grade $g \in G$ transported from sorting facility $f \in F$ to landfilling area $l \in L$ in scenario $u \in UN_{su}$ Number of trucks required to perform collection activities on supply site $s \in S$ in scenario $u \in U\beta_{fku}$

$$\begin{cases} 1 & \text{if sorting facility } f \in F \text{ of size} k \in K \text{ is operating in scenario } u \in U \\ 0 & \text{ifnot} \end{cases}$$

$$\alpha_{fkk'u} \begin{cases} 1 & \text{if sorting facility } f \in F \text{ should expand its treatment capacityfrom size k} \in \text{K to size } k' \in \text{K in scenario } u \in U \\ 0 & \text{ifnot} \end{cases} \quad \theta_{f'kzu}$$

$$\begin{cases} 1 & \text{ifa new sorting facility } f' \in F \text{ of size } k \in K \text{ should open in geographical zone } z \in Z \text{ in scenario } u \in U \\ 0 & \text{ifnot} \end{cases}$$

3.3. Objective function

The objective function minimises the total reverse supply chain operation cost as follows:

Min = Transportation costs + Recycling costs + landfilling costs + operating costs + expansion costs + opening costs

$$\text{Min} \sum_{m\in M}\sum_{g\in G}\sum_{i\in I}\sum_{j\in J} t_{ij}\xi_{ij}X_{mgiju} + \sum_{m\in M}\sum_{g\in G}\sum_{s\in S} c_m^R\left[\sum_{f\in F} X_{mgsfu} + \sum_{f'\in F} X_{mgsf'u}\right]$$
$$+ \sum_{m\in M}\sum_{g\in G}\sum_{l\in L} c_m^L\left[\sum_{s\in S} X_{mgslu} + \sum_{f\in F} X_{mgflu} + \sum_{f'\in F} X_{mgsf'u}\right]$$
$$+ \sum_{f\in F}\sum_{k\in K}\sum_{k'\in K}\left[\Omega_{fk} + \sum_{z\in Z}(\pi_{fkz} + \Omega_{f'k'})\theta_{fkzu} + \delta_{fkk'u}\alpha_{fkk'u}\right] \quad \forall u \in U$$

3.4. Subject to the following constraints

3.4.1. Demand satisfaction

$$\sum_{f\in F} X_{mgfcu} \le d_{mgc} \qquad \forall u \in U, \forall m \in M, \forall g \in G, \forall c \in C \tag{1}$$

3.4.2. Flow conservation at the supply sources

$$V_{mgsu} = \sum_{f\in F} X_{mgsfu} + \sum_{l\in L} X_{mgslu} \qquad \forall u \in U, \forall m \in M, \forall g \in G, \forall s \in S \tag{2}$$

3.4.3. Environmental policy target

$$\sum_{f\in F} X_{mgsfu} \ge \Psi_m V_{mgsu} \qquad \forall u \in U, \forall m \in M, \forall g \in G, \forall s \in S \tag{3}$$

3.4.4. Flow conservation at sorting facilities

$$\sum_{s\in S} X_{mgsfu} = \sum_{c\in C} X_{mgfcu} + \sum_{l\in L} X_{mgflu} \qquad \forall u \in U, \forall m \in M, \forall g \in G, \forall f \in F \tag{4}$$

3.4.5. Flow conservation at potential sorting facilities

$$\sum_{s\in S} X_{mgsf'u} = \sum_{c\in C} X_{mgf'cu} + \sum_{l\in L} X_{mgf'lu} \qquad \forall u \in U, \forall m \in M, \forall g \in G, \forall f' \in F \tag{5}$$

3.4.6. Achievable recycling rates at sorting facilities

$$\sum_{s\in S} X_{mgsfu}.\ r_m \ge \sum_{c\in C} X_{mgfcu} \qquad \forall u \in U, \forall m \in M, \forall g \in G, \forall f \in F \tag{6}$$

3.4.7. Achievable recycling rates at potential sorting facilities

$$\sum_{s\in S} X_{mgsf'u}.\ r_m \ge \sum_{c\in C} X_{mgf'cu} \qquad \forall u \in U, \forall m \in M, \forall g \in G, \forall f' \in F \tag{7}$$

3.4.8. Treatment capacity at sorting facilities

$$\sum_{m\in M}\sum_{g\in G}\sum_{s\in S} X_{mgsfu} \le h_{fk}\beta_{fku} + h'_{fk}\alpha_{fkk'u} \qquad \forall u \in U, \forall k, k' \in K, \forall f \in F \tag{8}$$

3.4.9. Treatment capacity at potential sorting facilities

$$\sum_{m\in M}\sum_{g\in G}\sum_{s\in S} X_{mgsf'u} \le h_{f'k}\theta_{f'kzu} \qquad \forall u \in U, \forall z \in Z, \forall f' \in F, \forall k \in K \tag{9}$$

3.4.10. Trucks loading capacity

$$\sum_{m\in M}\sum_{g\in G} V_{mgsu} \le \omega N_{su} \qquad \forall u \in U, \forall s \in S \tag{10}$$

3.4.11. Integrity and binary constraints

$$X_{mgiju} \in \mathbb{R}^+ \text{ Where } \mathbb{R}^+ = \{x \varepsilon \mathbb{R}, x \ge 0\}, \quad \forall m \in M, \forall g \in G\ \forall i \varepsilon N, \forall j \varepsilon N, \forall u \in U \tag{11}$$

$$N_{su} \in \mathbb{N} \quad \text{Where } \mathbb{N} = \{x \varepsilon \mathbb{R}, \textit{integer}\}, \quad \forall s \in S, \forall u \in U \tag{12}$$

$$\beta_{fku}, \alpha_{fkk'u}, \theta_{f'kzu} \varepsilon \{0,1\} \qquad \forall u \in U, \forall f \varepsilon F, \forall k, k' \varepsilon K, \forall z \in Z \tag{13}$$

The objective function minimises the total cost. The latter includes the transportation costs, the recycling and landfilling costs, and facility-related costs for operation, expansion and new openings. Finally, the additional cost incurred in case of poor quality materials is also included. Constraint (1) ensures that customer demand is not exceeded for each material type and quality grade. Constraint (2) guarantees that all the materials are collected from the supply sources to be either landfilled or shipped to a sorting facility, while constraint (3) imposes the compliance with the government policy target in terms of material flow shipped to certify sorting infrastructure. Constraints (4) and (5) ensure that all the materials leaving a sorting facility (existing or new) are either landfilled or shipped to a customer while respecting the recycling rates mentioned in constraints (6) and (7). Constraints (8) and (9) guarantee the treatment capacities of the sorting and the potential new sorting facilities are not exceeded. Constraint (10) limits the amount of collected materials that can be loaded on a truck. Finally, constraints (11)–(13) ensure flow decision variables positivity or integrity and that the operating, expanding and opening decisions are binary variables.

4. Case study description and data collection

The province of Quebec is the largest Canadian province with a territory of 1,667,441 km^2. Moreover, there is a relatively small number of inhabitants, barely exceeding 8 million people, thus implying a very low average density population of around 5 inhabitants per km^2. Although the average population density seems very low, it is however unequally distributed and almost 52% of the inhabitants are concentrated in 3 regions out of 17 (see Fig. 3). For example, the north

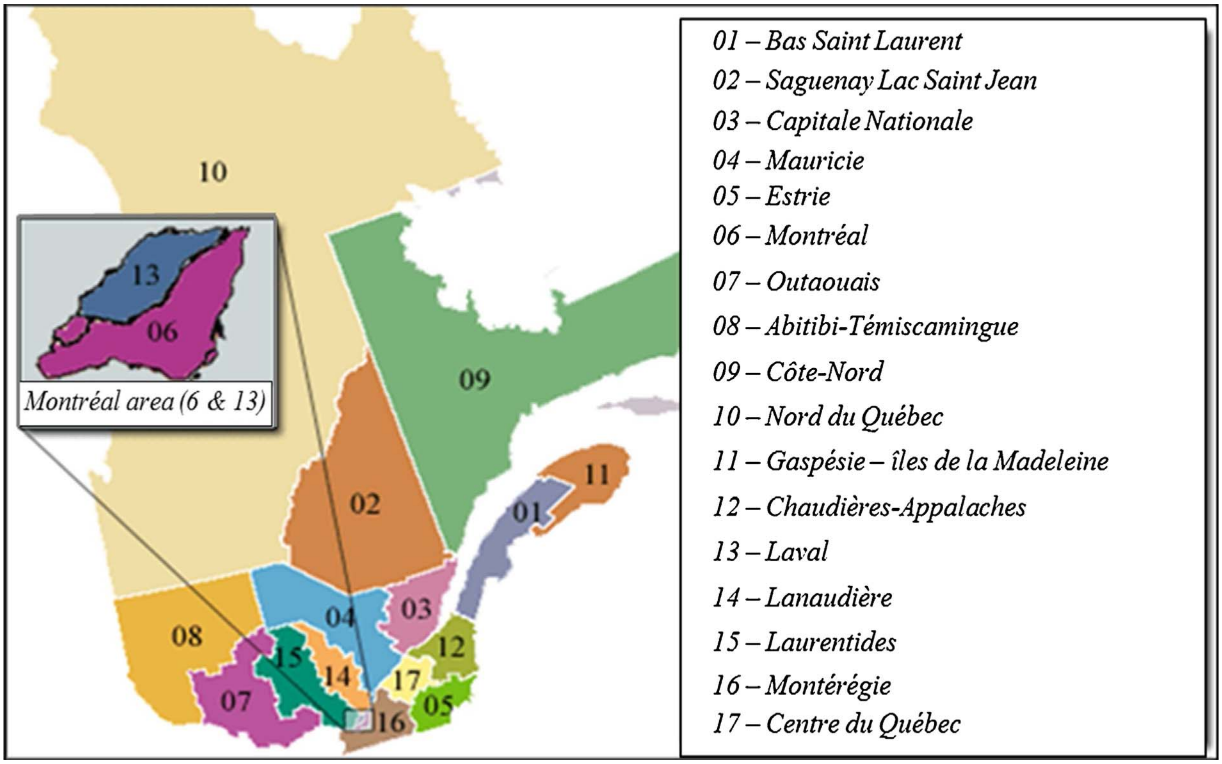

Fig. 3. Repartition of Quebec provinces into regions.

of Quebec is characterised by a density of 0.1 inhabitant per km^2 while a city like Montreal has 5500 inhabitants per km^2 (Statistical Institute of Quebec, 2014). These characteristics make the redesign of the RL network for the recycled wood that can efficiently serve the entire territory a real challenge.

For the purpose of this study, we used several sources of data for the recycled wood industry in Quebec: Statistical Institute of Quebec, RECYQ-QUEBEC and historical data provided by wood recyclers. These data were used to estimate the annual quantity of CRD waste generated in the province and the proportions of each grade of recycled wood. With an average of 0.65 tons of waste generated per inhabitant per year, the average of building-material waste to be collected on the CRD sites in the province of Quebec is estimated to reach 5.3 million annually. As the historical data about the exact number and locations of CRD sites are not available, we divided the total amount of waste generated into 203 collection sites taking into account the population density of each region. Table 3 gives more details about the characteristics and the geographical configuration of the different regions.

We identify 38 sorting centres dealing with CRD building-material waste today in Quebec (as listed in Appendix A). The treatment capacity varies from 10,000 to 400,000 tons per year. Moreover, in order to redesign the RL network, we assume that each sorting facility is able to increase its annual treatment capacity (i.e. capacity expansion) by a factor of 2. Also, 51 potential locations are selected for opening new sorting facilities based on the population density of each region. Each new sorting facility has three possible treatment capacities, either of 20,000 tons, 50,000 tons or 100,000 tons per year. We also considered 36 registered certified landfill sites. We assume that sorting facilities receive mixed-waste containers from the building contractors. After that, wood has to be extracted from these containers before being redirected to the recyclers. We consider that every landfill site has an infinite capacity for a one-year planning horizon. Thus, the proposed RL network is composed of 343 nodes including collection sites, sorting facilities, landfilling areas and finally the recyclers of building materials (customers). For the transportation of waste collected at CRD, we assume that containers have a capacity of 20 tons each, and the cost structure is defined in a way that the shipping cost is correlated with the travelling distance and vehicle load (i.e. container filling rate). Three quality levels (grades) of collected wood are considered in this study. "Grade 1" is free of contaminants with a very high demand. "Grade 2" is slightly contaminated, sometimes simply by contact with other building materials (painting, chemical treatment against moisture, insects) or simply by time degradation. Grade 2 accounts for 65% to 70% of the total wood quantity. Finally, "Grade 3" is highly contaminated, sometimes with dangerous substances which are potentially harmful to the environment and/or for human health. This type wood is likely to be landfilled all the time. In this case study, the annual demand for grade 1 and grade 2 is shared between 15 recyclers (customers) according to the

Table 3
Annual estimated CRD waste generation by administrative region in Quebec.

Administrative region	1	2	3	4	5	6	7	8	9
Population (K-inhabitants)	200	277	732	267	320	1 988	383	148	95
CRD waste generated (K-tons)	130	180	476	174	208	1 292	249	96	62
Number of CRD sites per region	4	5	15	5	6	61	7	3	2
Administrative region	10	11	12	13	14	15	16	17	Total
Population (K-inhabitants)	44	92	420	421	492	586	1 508	240	8 213
CRD waste generated (K-tons)	29	60	273	274	320	381	980	156	5 338
Number of CRD sites per region	1	3	8	8	10	12	46	7	203

Table 4
Annual market demand for recycled wood material in Quebec.

Industrial activity	Energy cogeneration	Particleboard manufacturing	Cellulosic ethanol	Cement manufacture	Logs and pellets	Else
Recycled wood use (tons)	595,000	287,000	120,000	62,000	57,000	less than 11, 500
Market proportion	52%	25%	11%	6%	5%	less than 1%

proportions shown in Table 4 (3R-MCDQ, 2013). Among the recycled wood products, only the particleboard manufacturing requires grade 1. Grade 2 wood is good enough for the remaining customers.

5. Experimental evaluation and managerial insights

In order to deal with the reality of the wood recycling process, the experimental evaluation considers the reverse logistics redesign under wood waste-management constraint and the importance of uncertain parameters by adopting a scenario-based approach (Soleimani et al., 2016). Indeed, the strategic decisions to be made regarding the RLN design are very dependent on numerous parameters, and some of them are highly unpredictable: the location of the collection sites, the availability of recycled materials (i.e. the supplied quantity) and finally the quality level of collected wood for recycling. In order to evaluate the impact of these uncertainties, we built multiple scenarios considering three (3) discrete values for each of these parameters based on historical data analysis.

Let's consider $LS_1(x_1, y_1)$, $LS_2(x_2, y_2)$and$LS_3(x_3, y_3)$ three different locations for the set of supply sources $s \in S$. Let's define also V^{low}, V^{avg}, and V^{high} the possible values for the total quantity of CRD building-material waste collected annually. As mentioned previously, an average of 5.3 million tons (V^{avg}) of building-material waste is generated in Quebec annually. We suppose that this value can vary more or less 20% and we use these values for the realisations of V^{low} and V^{high}. Finally, we define Q^{low}, Q^{avg}, and Q^{high} as the potential quality levels for the collected wood. The difference between the various quality levels is related to the rates of Grades 1, 2 and 3 of recycled wood inside the container. Considering the different combinations, we obtain 27 scenarios as depicted in Appendix B. Scenario 1 (SC1) uses the combination of the mean values for the quality and volume parameters (Q^{avg}, V^{avg}) and the first set of supply sources LS_1 for the location of CRD sites. To evaluate the impact of environmental legislations, we conduct the experiments with the adoption of the following methodological steps:

Step 1 – Baseline scenario. As a first step, we run the optimisation model to obtain the optimal reverse logistics network without waste management policy constraint (Constraint 3 is not active).

Step 2 – Scenario 1. For this scenario, we run the optimisation but constraint 3 is active (70% of recycled wood shipped to sorting centres). We use the first set of supply sources LS_1 and the mean values of uncertain parameters V and Q are used to obtain the new reverse logistics network design (fixed network).

Step 3. SC2 to SC27. Solving all the scenarios without any change in the reverse logistics configuration obtained in SC1.

Step 4. SC2* to SC27*. Solving to optimality all the remaining scenarios allowing the adjustment of RLN design decisions obtained in SC1.

Step 5. Experiments and insights. At this level, the objective is to evaluate the impact of the uncertain parameters on RLN design optimal decisions and analyse the managerial insights.

5.1. Redesign of the current reverse logistics network

As a baseline scenario, the behaviour of the Quebec network before applying the waste management policy is evaluated. The results show that the overall utilisation rate of sorting facilities barely exceeds half of their global treatment capacities (58%). The landfilling activities represent a huge proportion of collected wood because the recycling process is not competitive compared to the "low" landfilling cost. These results are very representative of the current situation of the recycled wood industry in the province of Quebec where some sorting facilities are closed for some periods within a year. Indeed, a significant quantity of mixed waste containers from CRD sites is not shipped to the sorting centres. Moreover, 175,000 tons of collected wood are recycled. Thus the service level for the wood recyclers is very low, with 16.8% for grade 2 and 12.2% for grade 1. In this scenario, the model suggests that only 28 sorting centres among the 38 available are operating and neither expansion nor new sorting facility openings are required. As the annual demand for recycled wood material is estimated to be around 1.15 million tons in Quebec (3R-MCDQ, 2013), almost 15% of this quantity is provided from the Quebec CRD sites. Thus, the majority of the recycled wood used by the recyclers is imported from the US. The remaining demand is satisfied by using virgin wood fibre and implies a significant increase in procurement costs (about three times the price paid for the recycled wood material at the exit of the sorting centres).

In the second phase, and in order to comply with the waste management regulation, we run the decision model and we observe many adjustments compared to the network obtained for the baseline. The optimal network for scenario 1 (SC1), named "fixed network" for the rest of the study, is now composed of 38 sorting centres. Many sorting facilities (26 sites) have expanded their capacities and five (5) new facilities are added in strategic locations in order to minimise transportation distances. These adjustments require an investment of 35 M$. The main features of baseline scenario and SC1 are illustrated by Table 5.

The first observation from Table 5 is that the adjustment of the reverse logistics network leads to the reduction of wood recycling cost from $101.6/ton in the baseline scenario to $85.2/ton. This value considers facility processing costs and average distance travelled by the containers in the RL network. The reduction achieved is mainly due to the improved efficiency of sorting facilities (usage of 96.5%) and the economy of scale achieved in scenario 1. As the quantity treated by sorting centres increases, the fixed costs are spread out between the larger quantities of wood recycled. Also, the new RLN allows the relocation of sorting centres in order to reduce the average distance to travel in order to treat CRD waste at the recyclers. Finally, many landfilling sites are not used with scenario 1 and the average distance to travel for CRD waste increases. Thus, under the environmental policy, the sorting facilities are located near the CRD collection points and not close to landfilling site as for the baseline scenario.

Table 5
Baseline scenario versus scenario 1 (fixed network).

Activity	Criteria	Baseline scenario	Scenario 1 (fixed network)
Sorting facilities	Expansion (new opening)	–	26 (5)
	Number of sorting centres	28 from 38	38
	Facility investments (M$)	21.2	56.2
	Sorting facility use	58%	96.5%
	Avg. distance to recycle (km)	116	75.4
	Wood recycling cost ($)	17,780,000 ($101.6/ton)	74,493,086 ($85.2/ton)
Customers	Recycled wood (tons)	175,166	874,332
	Service level – Grade 1	12.2%	54%
	Service level – Grade 2	16.8%	84.7%
Landfills	Landfilling (tons)	1,426,234	727 068
	Number of sites used	33 from 36	26 from 36
	Average distance to landfills (km)	27.9	38.9
RL network	Total Cost ($)	268,699,279	359,830,582

5.2. Reverse logistics configuration under collection sites locations change

In SC1, we used the first set of supply sources location$LS_1(x_1, y_1)$and we obtained the RL network named "fixed network". Since these locations might change from one period to another, we evaluate the possible changes in the RL network under uncertainty. On average, the total travelling distance for recycled wood increases when the CRD sites locations change. Initially, the trucks travelled an average of 75.4 km to recycle one ton of wood building material against 91.6 km for LS_2 and 88.1 km forLS_3(see Appendix D). Although the second location presents the worst results in terms of average recycling distances, it is however the best one regarding the landfilling options with an average of 34.4 km travelled. These distances increase up to 35.7 km and 42.3 km for the first and the third locations respectively. The increase in the average transportation distances could be explained mainly due to two reasons. First, sorting facilities are not well located regarding the CRD collection points, and forced to move containers over long distances to reach the nearest sorting facility. Usually, such configuration is suitable when landfilling of CRD waste is the privileged option. However, the environmental policy prevents such behaviour and obliges the contractors to move CRD waste containers to sorting centres. The second reason is that sorting centres receive different quantities of grade 1 and grade 2. As grade 1 wood demand is difficult to fulfil, it may be supplied from more distant facilities than in the first scenario.

Also, it is important to mention that for the baseline scenario, it was an advantage to locate sorting centres very close to the landfilling sites considering the significant amount of building materials to eliminate (see Table 5). However, under the environmental policy, it is less costly when the sorting centres are located near the CRD. Indeed, as 70% of the building material waste collected must be shipped to a certified sorting facility, in this case, there is a need to adjust the network design in order to minimise the related travelling distances in scenario 1. The overall transportation cost using the data set of $LS_1(x_1, y_1)$ is $41,926,882. This cost increases by 18.2% using $LS_2(x_2, y_2)$ locations named SC10 and by 21.2% with $LS_3(x_3, y_3)$ locations named SC19. The total reverse logistics cost increases by 4.9% in SC10 and by 6% in SC19 when compared with scenario 1. Table 6 illustrates the impact of changing the CRD site locations in terms of travelling distances between the supply sources and the sorting centres.

In a second phase, SC10 and SC19 were solved to optimality offering the possibility to make adjustments within the RL network: capacity expansion and opening new sorting facilities. These two scenarios are named SC10* and SC19*. The optimised network using LS_2 data set leads to a configuration of twenty-five (25) expansions and new opening for five (5) sorting centres. Finally, using data set of LS_3, the model suggests twenty-nine (29) expansions and three (3) new openings. It is interesting to denote that in SC10*, the optimised network configuration allows achieving a better result than the one obtained in SC1. Indeed, the slight decrease in the average distances travelled for recycling and landfilling reduces the total transportation cost from 8.9% compared to scenario 1. However, SC19* shows a slight increase in both recycling and landfilling distances compared to SC1, thus leading to a total transportation cost increase of 6.7%. This is mainly due to the fact that only 3 sorting centres are opening instead of 5 under the fixed network.

Overall, this analysis underlines the advantages of allowing RL redesign under CRD sites location changes when compared with SC10 and SC19. The potential total cost reduction for the RL network is 6.8% with SC10*and 4.6% for SC19*. Indeed, the policy makers could use such model to relocate or expand strategically some sorting facilities closer to supply sources in order to minimise the transportation distances and make the building materials landfilling option less attractive.

Table 6
Potential impact of a change in collection site locations (LS_1 versus LS_2 and LS_3).

CRD Location set	LS1	LS2		LS3	
Criteria	SC1	SC10	SC10*	SC19	SC19*
Distance travelled for recycling (km)	**75.4**	91.6	70.2	88.1	76.7
Distance travelled for landfilling (km)	**34.4**	35.7	31.8	42.3	36.5
Transportation cost ($) (Δ %)	**41,926,882** –	49,557,574 (+18.2%)	37,520,366 (−10.5%)	50,815,380 (+21.2%)	44,755,851 (+6.7%)
Number of expanded sorting centres	**26**	–	25	–	29
New openings	**5**	–	5	–	3
Total cost ($)	**359,830,582**	377,709,715	353,511,880	381,722,441	364,772,979

Table 7
Impact of recycled wood quality variations on the RL network performance.

Activity	Criteria	Average Quality	High Quality		Low Quality	
		SC1 (fixed network)	SC2	SC2*	SC3	SC3*
Sorting facilities	Expansion (opening)	**26 (5)**	–	25 (8)	–	23 (4)
	Number of sorting centres	**38**	–	38	–	38
	Sorting facility use	**96.5%**	98.2%	94.7%	94.9%	89.9%
	Recycled wood (tons)	**874,332**	905,199	959,980	732,589	795,685
	Wood recycling cost ($)/ Avg. cost per ton	**74,493,086 ($85.2/ ton)**	77,122,954 ($85.2/ ton)	75,454,428 ($78.6/ ton)	62,416,582 ($85.2/ ton)	72,805,177 ($91.5/ ton)
	Avg. distance to recycle one metric ton (km)	**75.4**	75.4	59	75.4	91.3
Customers	Service level Grade 1	**54%**	65.2%	81.1%	19.1%	28,4%
	Service level Grade 2	**84.7%**	89.9%	89.9%	55%	69.8%
Landfills	Landfilling (tons)	**727 068**	696,201	641,420	868,811	805,715
	Number of sites used	**26/36**	–	21/36	–	30/36
	Average distance to landfills (km)	**38.9**	38.9	43.6	38.9	34.4
RL Network	Total Cost ($)	**359,830,582**	389,666,110	370,577,443	357,004,919	349,662,571
	Facility investments (M$)	**56.2**	56.2	61.5	56.2	49.9

5.3. Reverse logistics configuration under recycled wood quality grades uncertainties

The quality of the recycled wood collected on the CRD sites plays an important role in fulfilling the needs of the recyclers. On the one hand, it is difficult to estimate the quality level of the wood to be recycled in the collection centres in advance. On the other hand, poor quality lots imply lower recycling rates at the sorting facilities and ultimately also a lower service level for the wood recyclers. Thus, the main goal of this section is to evaluate the impact of the recycled wood quality uncertainty on the overall RL network behaviour and performance. To do so, we used the first set of supply sources location (LS_1) and an average collected quantity at CRD sites, and we compared the average, high and low-quality scenarios (i.e. SC1, SC2 and SC3 respectively). Then, in a second time, we analyse the results of scenarios SC2* and SC3* in order to highlight the loss of performance caused by using a fixed network for the various quality realisations. The results of these experiments are illustrated in Table 7. The performance of the network is expressed in terms of network configuration, overall facility use, recycling and landfilling proportion and average distances, recyclers' service level, and all the related costs.

First, we note that in case of high-quality scenario, the number of opening sorting centres increases from 5 in the fixed network to 8facilities in SC2*. Indeed, as there is a significant increase of good quality wood suitable for recycling, it is well-advised to open a few sorting centres in strategic areas in order to minimise the transportation distances to reach the closest facility from the CRD sites. If grade 2 wood service level is not impacted a lot when comparing SC1 and SC2, the fixed network can however only fulfil 55% of the demand in SC3. This value can be increased to 69.8% with the optimised network as proposed in SC3*. In a second time, we can see that grade 1 recycled wood service level is highly influenced by the predefined network design. Indeed, allowing the change in the RL network leads to the fulfilment of 81.1% of the grade 1 demand instead of 65.2% in SC2* and SC2 respectively. However, in the case of low-quality scenario, the service level achieves 28.4% for grade 1 with scenario SC3* instead of 19.1% with SC3. It is also important to mention that for scenario 1, twenty-six (26) landfills are active, while only twenty-one (21) are active in SC2*. The number of active landfills achieves thirty (30) sites with SC3* due to the significant amount of poor quality wood waste, and which is not usable.

The total RL network cost increases by 8.3% from SC1 to SC2 which is mainly due to the fact that recycling is more expensive than landfilling. Finally, an optimised RL network allows improving the total cost from 5.2% in the case of high-quality scenario from SC2 to SC2*, but this improvement is reduced to 2% in the case of poor quality scenario from SC3 to SC3*.

Thus, an effort toward improving the quality level and better estimation will lead to an improvement in the RLN design process and to a better control in the investment and opening decisions. Plus, in terms of network facilities investments and average recycling cost per ton of wood building-material, redesigning the RLN allows some economies of scale that would be revealed significant on a longer planning horizon.

5.4. RLN design under joint waste collected quantities and collection sites locations change

The quantity of the building material collected at the CRD sites is one of the most influential parameters on the RL configuration (expansion, new openings). Plus, the variability in the collected quantity impacts greatly the recycled wood service level offered to the recyclers. Only the scenarios with high quantity realisations allow satisfying entirely the demand of the recyclers. While low volume scenarios provide around 1.2 million tons of recycled wood from the collection sites, high volume scenarios exceed 2.1 million tons supply which means that the recycling rate increases but also the landfilling quantity increases in the meantime. Table 8 presents the sorting facility expansion decisions, new openings and the associated initial investments required to adjust the RLN design. Plus, it provides the total network capacity and the variation compared to the fixed network from scenario 1. The scenarios depicted in this table are respectively SC4*, SC13* and SC22* (different locations with low volume collected); SC1* (fixed network), SC10* and SC19* (different locations with average volume collected); SC7* SC16* and SC25* (different locations with high volume collected). All the scenarios proposed in this table consider an average quality realisation.

The optimisation model suggests 11–13 expansions plus 1 or 2 new

Table 8
Optimal RLN design according to the CRD sites locations and waste quantity.

SSL	SF.E	SF.O	CAP	CV/FN	T.INV	U.RC
Low collected quantity scenarios						
LS1	11	2	2 755 000 t	(−) 28,4	11,2 M$	92,3 $/t
LS2	13	1	2 703 500 t	(−) 29,7	11,1 M$	96,7 $/t
LS3	11	2	2 685 000 t	(−) 30,2	10,5 M$	93,5 $/t
Average collected quantity scenarios						
LS1	26	5	3 845 000 t	N/A	34,7 M$	85,2 $/t
LS2	25	5	3 995 000 t	(+) 3,9	36,1 M$	87,1 $/t
LS3	29	3	3 770 000 t	(−) 2,1	32,2 M$	89,4 $/t
High collected quantity scenarios						
LS1	30	13	5 105 000 t	(+) 32,7	67 M$	72,4 $/t
LS2	29	14	5 210 000 t	(+) 35,5	68,7 M$	69,5 $/t
LS3	31	10	4 920 000 t	(+) 27,9	65,8 M$	76,9 $/t

SSL: Supply Sources Location; **SF.E**: Sorting Facility Expansions; **SF.O**: Sorting Facility Openings; **CAP**: Network Capacity; **CV/FN**: Capacity Variation compared to the Fixed Network; **T.INV**: Total Investment; **U.RC**: Unit Recycling cost per 1 t of wood.

facility openings with a 20,000 ton-capacity in the case of low collected quantity scenarios. For an average quantity scenario, between 25–29 expansions and 3–5 openings are recommended. In this case, only the new sorting centres 13 and 47 have 100,000-ton treatment capacity and the remaining are 20,000-ton facilities. Finally, a complete reconfiguration is required in case we face the high quantity scenarios with 29–31 expansions and 10–14 openings with a majority of facilities with 100,000-ton treatment capacity. Depending on the scenario the investment cost required for network optimal configuration varies from 10.5 M$ up to 68.7 M$. However, the required investments are not proportional to the additional capacity of the network. Indeed, it is less expensive to expand some existing sorting facilities than to build new ones. Thus, as the increasing quantity of debris collected also implies additional sorting center openings, if the collected waste at the CRD sites increases, the average investment required per ton of material increases in the meantime. We also denote that the RL network increases its capacity on average from 28.4% from low quantity to average quantity scenarios, and from 24.7% from average quantity scenarios to high ones. In the case of low volume scenarios, the optimisation allows saving around 30% capacity compared to the fixed network. However, high volume scenarios require an increase in the overall treatment capacity from 27.9% to 35.5% from the fixed network in order to guarantee regulatory compliance. Depending on the collected quantity at the CRD sites, the optimal RL network suggests between 11 and 31 sorting facility expansions and between 2 and 14 new openings. Thus, we denote a very significant difference with the fixed network proposing 26 expansions and 5 openings.

In summary, in order to guarantee a more efficient RLN redesign in the CRD industry, there is a real need to get more accurate information about the supply sources locations and the expected wood quantity recovered from sorting facilities.

6. Conclusion

This paper addresses the reverse logistics network redesign for wood waste in the CRD industry under the environmental policy, based on a case study conducted on recycled wood building-materials in Quebec, Canada. The key decisions are the relocation and capacity investment of sorting facilities. A MILP model has been developed in order to analyse the direct impact of different key uncertain parameters on RL network design decisions under the waste management policy. The objective is to minimise the total cost under such restrictions. Although existing sorting facilities were not used at their full capacity in the baseline scenario, results from this study show clearly that the enforcement of environmental policy will lead to increase in the RL network efficiency and reduce the cost of recycling. Indeed, using the proposed model, the decision makers could ensure maintaining a wood recycling cost under the cost of virgin wood fibre procurement, estimated at around 120$ per ton. Moreover, under the uncertainty of parameters, the different RLN configurations are quite different. A precise estimation of the location and the available quantities of wood in future CRD collection sites will lead to efficient investment and relocation decisions that will reduce transportation costs and decrease landfilling activities. Efforts towards the improvement of the quality level of the collected wood (sorting at CRD sites, reducing material contamination in the construction process, etc.) will increase the service level for customers and avoid importing recycled wood or use of virgin wood. In the model assumptions, we assume demand for each grade of recycled wood is known in advance. The concept of wood quality grades was used to classify demand of the different recyclers. The uncertainty in demand is also a parameter that might be included in future research especially with the development of new opportunities to use recycled wood in new emerging industrial activities regardless of the quality level.

With the proposed case study in the province of Quebec, these results provide valuable insights on the importance of implementing efficient reverse logistics network as an incentive to reducing landfilling from the CRD industry. Practically, this paper provides a decision support for policy makers involved in CRD waste recycling management. It offers some useful logistics insights before setting new regulations that could be an issue for the recycled wood industry and non-sustainable in terms of environmental impacts. Although the paper focused on a case study for wood recycling from CRD in the province of Quebec, Canada, the application of this model is not limited to this country. Also, the model can be applied to a reverse supply chain for waste recycling in general.

In this work, we present various optimal RLN designs according to the uncertainty outcomes. However, in practice, the decision makers will have to choose a unique network configuration for the coming years that will efficiently handle various supply sources locations, waste collected quantities, and quality of the building materials. Although the scenario-based approach is efficient to handle uncertainty in the decision model, it is based essentially on the discrete realisation of uncertainty which considerably reduces the number of tractable scenarios. As a future research direction, we suggest the development of a stochastic programming version of this model to avoid this limitation and propose the best supply chain configuration for a longer planning horizon. For the coming years, trends related to the uncertain parameters may be estimated using historical CRD data (Kalcher et al., 2016). Finally, it would be of major interest to include an environmental evaluation after policy implementation in the decision model as a future work.

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Appendix A

See Table A1.

Table A1
Listing of the 38 sorting facilities used in the Quebec case study.
Source: RECYQ-QUEBEC, internal report 2014.

Facility	Street adress	Postal code	Coordinates (lon – lat)	
1	220 rue de Rotterdam	G3A 1T4	46,75883	−71,45950
2	11450 boulevard industriel	G9A 5E1	46,40551	−72,71264
3	1060 rue Fréchette	J0 K 2M0	45,54464	−73,48161
4	3525 Boulevard Laurier Est	J2R 2B2	45,63755	−72,90979
5	75 rue Savard	G4W 0H9	48,82813	−67,57264
6	435 Montée Cushing	J8G 1B9	45,61129	−74,42559
7	815 rue Vernon	J9J 3K4	45,45237	−75,80691
8	5 rang Moreau	J0A 1M0	45,92999	−71,99627
9	146, rang 9	J1A 2S1	45,42871	−72,69650
10	225 rue du progrès	J0 K 3K0	45,52472	−75,49257
11	118 rue des équipements	G5R 3Z3	47,83659	−69,50282
12	3200 Boulevard industriel	J3L 4 x 3	45,41083	−71,96439
13	61 rue Montcalm	J0 K 1A0	45,89935	−73,66577
14	1985 rue Jean Marie Langlois	J5R 5Z8	45,39876	−73,50248
15	315 rue Jackson	G1N 4C4	46,80277	−71,26341
16	18055 rue Gauthier	G9H 2A6	46,28879	−72,55064
17	16795 rue Oakwood	H9H 5C9	45,46329	−73,86731
18	1131 rue Principale	J0E 1A0	45,41943	−72,77021
19	2400 montée Saint Francois	H7E 4P2	45,70740	−71,46118
20	493, deuxième Avenue	G8L 1V3	46,62997	−72,70915
21	3389, quatrième rue	G9T 5K5	46,07887	−71,94941
22	365 Boulevard Bonaventure	G6P 6V7	48,22094	−79,01307
23	303 Boulevard Industriel	J6J 4Z2	45,88973	−72,54540
24	1005 rue Réha	J2 B 8A9	45,62751	−73,51838
25	10930 rue Sherbrooke Est	H1 B 1B4	45,46930	−73,43318
26	5431 rue Jonergin	J3Y 2S1	45,65137	−73,68278
27	3030 montée Saint Francois	H7E 4P2	45,42565	−75,73352
28	31 boulevard Saint Joseph	H8S 2K9	45,61913	−73,56715
29	9501 boulevard Ray Lawson	H1J 1L4	46,28537	−73,38358
30	1752 rue Saint Cléophas	J0 K 2N0	45,38869	−72,74561
31	530 rue Édouard	J2G 3Z6	46,15706	−70,61171
32	8191 route 204	G6 B 2S1	45,68790	−74,15601
33	6000 route Sir Wilfrid-Laurier	J7N 2Z8	45,68687	−74,15662
34	4 chemin du Tremblay	J4 B 6Z5	45,55504	−73,43128
35	3878 Boulevard Frontenac Est	G6H 4G2	46,12434	−71,24602
36	17245 rang Sainte-Marguerite	J7J 2E9	45,75559	−73,94137
37	9990 Boulevard Métropolitain Est	H1 B 1A2	45,62651	−73,54706
38	107 chemin Maine central	J0 B 1J0	45,48808	−71,57484

Appendix B

See Table A2.

Table A2
Scenario-based approach considering uncertainties.

	Supplier location			Supplied volume			Quality level		
	LS1	LS2	LS3	low	avg	high	low	avg	high
SC1	×				×				
SC2	×				×			×	×
SC3	×				×		×		
SC4	×			×				×	
SC5	×			×					×
SC6	×			×			×		
SC7	×					×		×	
SC8	×					×			×
SC9	×					×	×	×	
SC10		×			×				×
SC11		×			×		×		
SC12		×			×			×	
SC13		×		×					×
SC14		×		×			×		
SC15		×		×				×	
SC16		×				×			×
SC17		×				×	×		
SC18		×				×		×	
SC19			×		×				
SC20			×		×				×
SC21			×		×		×		
SC22			×	×				×	
SC23			×	×					×
SC24			×	×			×		
SC25			×			×		×	
SC26			×			×			×
SC27			×			×	×		

Appendix C

See Fig. A1.

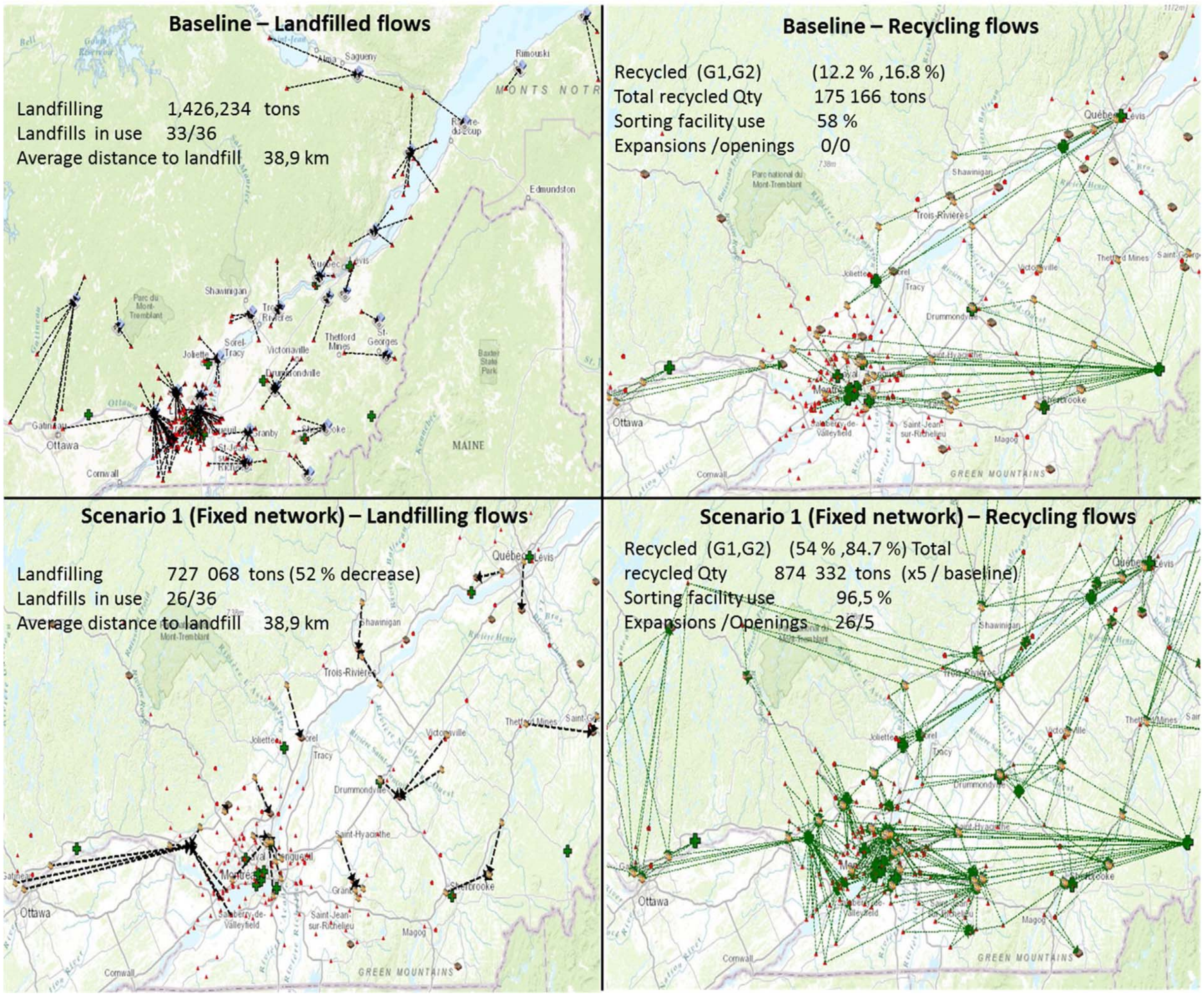

Fig. A1. Baseline scenarios versus scenario 1: Recycling and landfilling flows.

Appendix D

See Fig. A2.

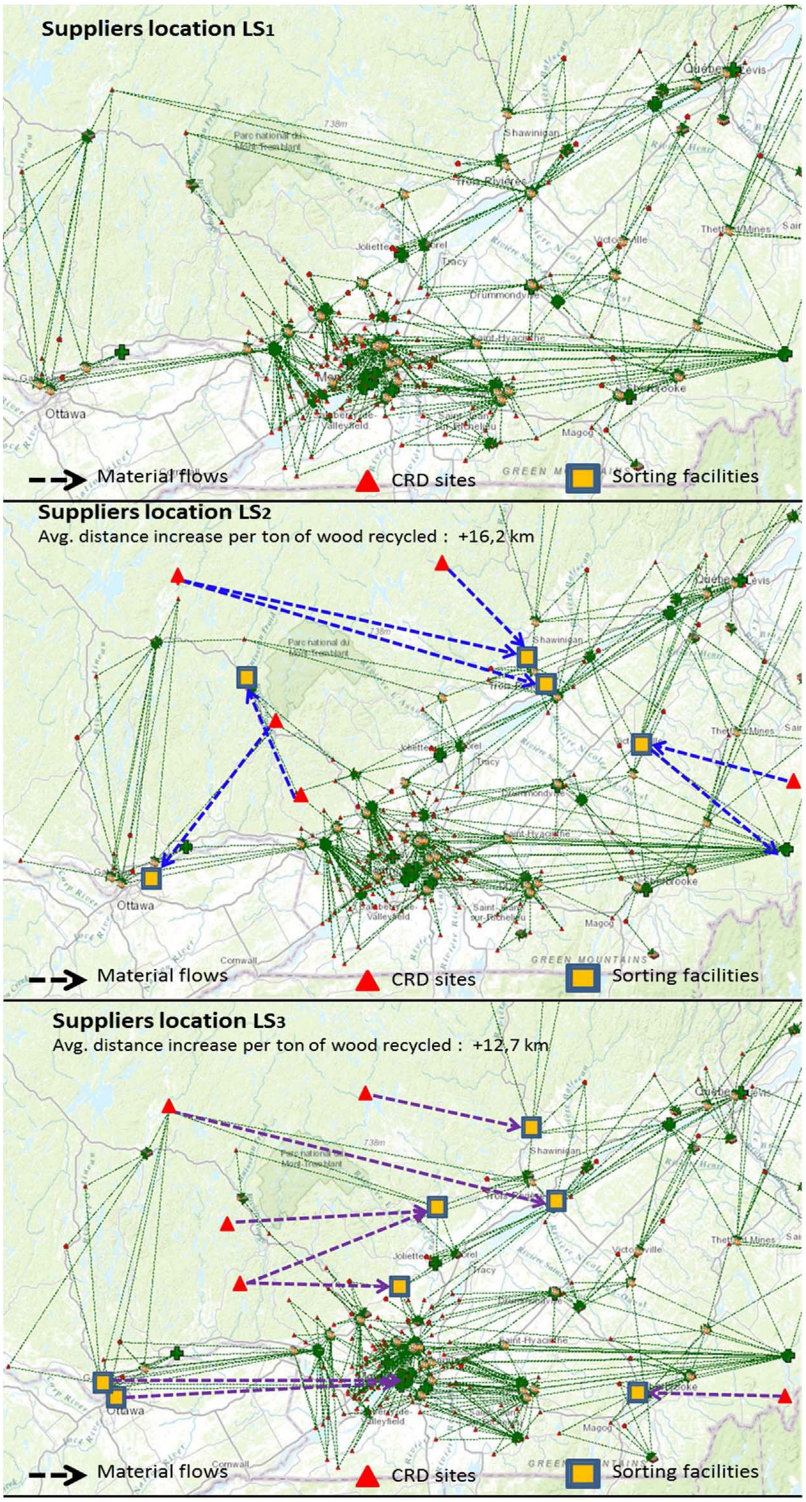

Fig. A2. Average distance increase for recycling with suppliers locations LS2 and LS3.

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