OPTIMIZATION DESIGN OF MULTI-ECHELON RECYCLING NETWORKS FOR THIRD-PARTY REVERSE LOGISTICS PROVIDER IN THE CONTEXT OF BINARY PATH SELECTION

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***ABSTRACT**: This paper aims to design a multi-echelon recycling network with binary path selection for the third-party reverse logistics provider (3PRLP). To this end, the network location and allocation of the 3PRLP were discussed under the selection of binary parallel route of returned products, and a specific transport-routing problem model was put forward for the 3PRLP based on route selection constraint. The model is a nonlinear integer program for routing selection and services allocation in multi-echelon recycling networks for 3PRLP with multiple path structures and cross-level reverse logistics. Then, the model was verified through a case study on a 3PRLP responsible for collecting waste paper from generation sites to the 3 remanufacturing outlets according to some proportion. Finally, the author carried out a sensitivity analysis to reveal the influence of parameters. The research findings provide useful insights for reverse logistics system design for 3PRLP.*

***KEYWORDS**: reverse logistics, third-party reverse logistics providers (3PRLP), reverse logistics network (RLN), route structure, binary path selection*

1 INTRODUCTION

Reverse logistics, a key to green supply chains, retrieves a product in the end of its useful life from the client and returns it to the manufacturer through a series of points, such as collection and inspection centres. For many reasons, the reverse logistics operations have aroused increasing interests in many sectors. Firstly, the amount of returned products is constantly growing, along with the environmental awareness of clients. Secondly, the discarded products provide a hotbed for secondary markets. Finally, enterprises are required by rules and regulations to properly handle returned products.

The reverse logistics is commonplace in the manufacturing sector. Manufacturers have been relying on the reverse logistics to extend the life of materials and return products to the logistics cycle. In this way, the industrial operations exert less environmental impacts, and the scarcity of raw materials is partially solved. Over the years, more and more enterprises started to manufacture new products with the raw materials recovered from the returned products (Mutha & Pokharel, 2009; Sun et al., 2017; Yuan et al., 2014).

The reverse logistics is often integrated with the popular business strategy of ousourcing (De Almeida, 2007). The business strategy can bring about various benefits, namely efficient production, good product/service quality, rapid response, high reliability, and diverse products and processes (McCarthy et al., 2013). Many enterprises, especially manufacturing ones, give priority to logistics outsourcing. Manufacturers and remanufacturers are working with the third-party reverse logistics provider (3PRLP) to establish an efficient social recovery system. Featuring profound assets, funds and expertise, the 3PRLP can enhance its own core business and reach maximum social utility, in addition to enhance the efficiency of the reverse logistics (Anttonen et al., 2013; Bai & Sarkis, 2013; Colicchia et al., 2013; Puglia et al., 2017; Calabrò and Panzera, 2017; Cogliandro et al., 2017).

Over the years, many scholars have explored the outsourcing decision, evaluation and selection of the 3PRLP (Govindan et al., 2015; Guarnieri et al., 2015; Prakash & Barua, 2016; Farzipoor Saen, 2009; Senthil et al., 2014). Liu and Lyons identified the most important aspects of operation performance and services of 3PRLPs (Liu & Lyons, 2011). Govindan et al. analysed and validated the relationship among the attributes of 3PRLP (Govindan et al., 2012). Bai and Sarkis applied rough set to flexibility evaluation for 3PRLP management (Bai & Sarkis, 2013). Ko and Evans proposed a genetic algorithm for the design of a dynamic capacitated closed-loop supply chain network, which enables a third-party logistics (3PL) to simultaneously handle the forward and backward flows of multiple re-manufacturable products (Ko & Evans, 2007). Lee et al. designed an integrated forward and reverse distribution network for 3PLs (Lee et al., 2007). Focusing on the reverse logistics problem involving the location and allocation of repair facilities for 3PLs, Du and Evans investigated the outsourcing of post-sale services of a manufacturer to a 3PL, and presented a bi-objective mixed integer program model and a genetic algorithm (Du & Evans, 2008). Suyabatmaz et al. discussed the reverse logistics network (RLN) design of a 3PL under supply uncertainty in terms of quantity of returns (Suyabatmaz et al., 2014). Krumwiede and Sheu developed a reverse logistics decision-making model to guide the implementing of reverse logistics in transport enterprises and other third-party providers (Krumwiede & Sheu, 2002). Ko et al. proposed a hybrid simulation-analytical approach for the distribution network design of a 3PL that considers the performance of each operating warehouse (Ko et al., 2006). However, there is only limited studies on the design of RLN from the perspective of the 3PRLP (Mutha & Pokharel, 2009; Zhou & Zhou, 2015; Min & Ko, 2008). Nearly all of them are constrained in the context of cascade route. Admittedly, multi-path and cross-level logistics indeed saves time, enhances client engagement, and reduces unnecessary deliveries in reverse supply chains. However, this method cannot solve all the problems of reverse logistics. Therefore, this paper aims to design a multi-echelon recycling network with binary path selection for the 3PRLP. To this end, the network location and allocation of the 3PRLP were discussed under the selection of binary parallel route of returned products or renewable raw materials, and a specific transport-routing problem model was put forward for the 3PRLP based on route selection constraint.

The remainder of this paper is organized as follows: Section 2 introduces the problem and its formula, and propose a nonlinear integer programming model for deriving the optimal network structure of the 3PRLP; Section 3 applies the proposed model to a case study, and analyses the sensitivity of some parameters; Section 4 wraps up this paper with some meaningful conclusions.

2 NETWORK DESIGN AND OPTIMIZATION FOR REVERSE LOGISTICS OF 3PRLP IN THE CONTEXT OF BINARY PATH SELECTION

2.1 Problem statement

This section describes the research problem and makes several assumptions. It is assumed that a qualified 3PRLP RLN consists of initial collection points and final recycling centres, and that it relies on the existing RLN to provide clients with a single collection service.

The process of the collection services can be summarized as follows. The 3PRLP delivers the returned products from generation points to collection points or recycling centres. After being classified and gathered at the recycling centres, the returned products are sent to different remanufacturing clients according to the specific delivery proportions. Each generation site chooses cascade or direct delivery route based on the path selection rule.

Here, the recycling path for each origin-destination (OD) pair is determined by the 3PRLP binary path selection rule. The type of the binary paths depends on whether the recycling path between each OD pair passes an initial collection point. If yes, it is a cascade transport route; otherwise, it is a direct recycling route that goes directly from the generation point to the final recycling centre, and then to remanufacturing clients. The two types of recycling paths are assumed to have different cost coefficients.

According to the 3PRLP RLN in Figure 1, the 3PRLP collects the returned products form the generation sites, and then transports them to the downstream clients like remanufactures. The returned products from each generation site must be collected and transported to a recycling centre, before being sent to clients. For each generation site, two types of transport routes are ready for selection: the cascade transport and the direct transport. The former skips no collection point, while the latter skips all collection points.

For this 3PRLP, the goal is to pursue the minimum total cost by selecting proper collection points and recycling centres, and assigning clients to open nodes and recycling routes. Of course, the 3PRLP has to comply with the following constraints:

Each generation site is used by one route at the most;

Each generation site is served by exactly one collection point, and each collection point is served by exactly one recycling centre;

Each path begins at the generation site and ends at the client;

Vehicle-routing problem is not within the responsibility of the 3PRLP.

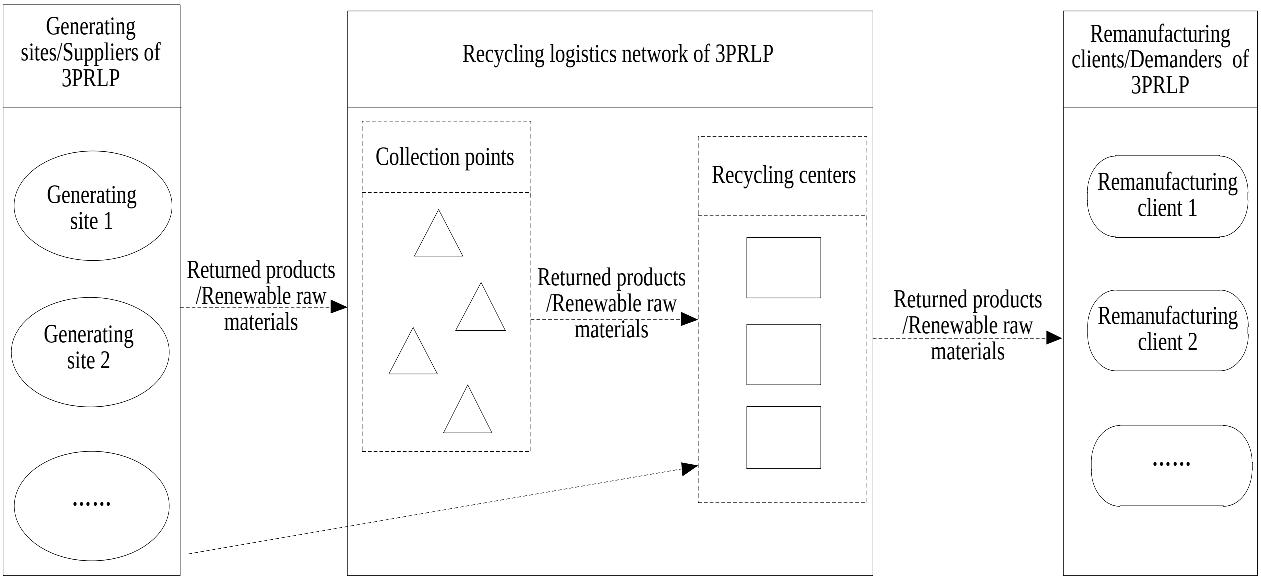

Figure 1. 3PRLP RLN in the context of binary path selection

2.2 Model design

2.2.1 Model assumptions

The following assumptions were made for our model:

The products from each generation point must be collected, and should not be split to different recycling points, that is, the products from a generation points should not be split to different initial collection points or different final recycling centres.

Both the location and the amount of the returned products are known. So it is with the location and the number of the potential initial collection points and the final recycling centres. To save time and enhance client engagement, the returned products from generation points can be delivered to the nearest initial collection points or the final recycling centres. Similarly, the returned products from initial collection points can be sent to the nearest final recycling centres. This assumption is a prerequisite for the binary path selection.

Only one of the two paths should be selected for each generation point. In addition, no matter which path is selected, only one node can be selected at the initial collection points and the final recycling centres. Both the cost coefficients of two paths are known.

There are capacity limitations at the initial collection points and the final recycling centres.

At the final recycling centres, the returned products should be sent to different destinations

with specific proportions. This paper only considers the transport cost and ignores the classification cost.

The total cost of the 3PRLP network includes transport cost and the operation cost. The transport cost is assumed to be proportional to the number of returned products and the distance between two points.

To achieve the minimal total cost of 3PRLP RLN, it is necessary to determine the path for each generation site and the service allocation between network nodes. Based on the above assumptions, the mathematical model for our nonlinear integer programming model of 3PRLP RLN is detailed below.

2.2.2 Parameters and variables

For simplicity, the notations for model parameters and the descriptions of decision variables are respectively listed in Tables 1 and 2.

Table 1. Model parameters

Notation/Symbol	Description
I	Total number of generating sites.
J	Total number of initial collection points.
K	Total number of ultimate recycling centers.
N	Total number of clients.
G_i	The location where returned products or renewable raw materials are being generated, $i \in I$.
CP_j	The collection point, $j \in J$.
RC_k	The recycling center, $k \in K$.
M_n	The client of 3PRLP, $n \in N$.
f_j	The fixed cost of CP_j.
F_k	The fixed cost of RC_k .
v_j	The variable cost of CP_j.
V_k	The variable cost of RC_k .

a_i	The amount of returned products or renewable raw materials generated at G_i.
d_{ij}	The distance between G_i and CP_j.
d_{ik}	The distance between G_i and RC_k.
d_{jk}	The distance between CP_j and RC_k.
d_{kn}	The distance between RC_k and M_n.
r_n	The proportion of recycled products transported to M_n.
tp1	The transportation and labor costs per unit distance of the cascade delivery.
tp2	The transportation and labor costs per unit distance of the direct delivery.
tp3	The transportation and labor costs per unit distance between recycling centers and clients.
C	Constant, the cost coefficient of direct delivery path.
C_j	The maximum capacity of CP_j.
H_k	The maximum throughput of RC_k.

Table 2. Model decision variables

Notation/ Symbol	Description
x_{ij}	x_{ij} equals 1 if transport the returned products from G_i through CP_j and 0 otherwise.
x_{ik}	x_{ik} equals 1 if transport the returned products from G_i through RC_k and 0 otherwise.
G_{i_IJK}	G_{i_IJK} equals 1 if generating site i (G_i) selects the cascade transport routing and 0 otherwise.
G_{i_IK}	G_{i_IK} equals 1 if generating site i (G_i) selects the direct delivery path and 0 otherwise.
S_j	s_j equals 1 if the CP_j is selected and 0 otherwise.
S_k	s_k equals 1 if the RC_k is selected and 0 otherwise.

2.2.3 Model formulation

The nonlinear integer programming model for 3PRLP consists of the objective function (1) and the constraints (2)-(14):

$$
\begin{aligned}
&Min\sum_{j=1}^{|J|}\left[f_j\cdot s_j+v_j\cdot\sum_{i=1}^{|I|}\left(a_iG_{i\_IJK}x_{ij}s_j\right)\right]+\\
&\sum_{k=1}^{|K|}\left[F_k\cdot s_k+V_k\sum_{i=1}^{|I|}a_i\cdot\left(G_{i\_IJK}\sum_{j=1}^{|J|}x_{ij}\cdot x_{ik}\cdot s_j+G_{i\_IK}\cdot x_{ik}\right)\cdot s_k\right]+\\
&\sum_{i=1}^{|I|}\left\{\begin{array}{l}G_{i\_IJK}\cdot tp_1\cdot\sum_{k=1}^{|K|}\sum_{j=1}^{|J|}\left[a_ix_{ij}x_{ik}\left(d_{ij}+d_{jk}\right)\right]+\\ C\cdot G_{i\_IK}\cdot tp_2\left(\sum_{k=1}^{|K|}a_ix_{ik}d_{ik}\right)\end{array}\right\}+\\
&\sum_{n=1}^{|N|}\sum_{k=1}^{|K|}\left[r_n\sum_{i=1}^{|I|}\left(a_ix_{ik}s_k\right)\right]\cdot d_{kn}\cdot tp_3
\end{aligned}
\tag{1}
$$

The constraints:

$$G_{i\_IJK}+G_{i\_IK}=1,\forall i\in I \tag{2}$$

$$\sum_{k=1}^{|K|}x_{ik}=1,\forall i\in I,k\in K \tag{3}$$

$$G_{i\_IK}=1,\quad if\sum_{j=1}^{|J|}x_{ij}=0,\forall i\in I,j\in J \tag{4}$$

$$\left\{\begin{array}{l}G_{i\_IJK}(\sum_{j=1}^{|J|}x_{ij}-1)=0\\ G_{i\_IJK}(\sum_{k=1}^{|K|}x_{ik}-1)=0\end{array}\right.,\quad if\ G_{i\_IJK}=1,\forall i\in I,j\in J,k\in K \tag{5}$$

$$\left\{\begin{array}{l}G_{i\_IK}\sum_{j=1}^{|J|}x_{ij}=0\\ G_{i\_IK}(\sum_{k=1}^{|K|}x_{ik}-1)=0\end{array}\right.,\quad if\ G_{i\_IK}=1,\forall i\in I,j\in J,k\in K \tag{6}$$

$$x_{ij}\le s_j,\forall j\in J,i\in I \tag{7}$$

$$x_{ik}\le s_k,\forall k\in K,i\in I \tag{8}$$

$$G_{i\_IK}\le 1-x_{ij},\forall i\in I,j\in J \tag{9}$$

$$G_{i\_IJK}\ge x_{ij},\forall i\in I,j\in J \tag{10}$$

$$G_{i\_IJK}\le\sum_{j=1}^{|J|}x_{ij},\quad\forall i\in I,\ j\in J \tag{11}$$

$$\sum_{i=1}^{|I|}\left(a_iG_{i\_IJK}x_{ij}\right)\le C_j\cdot S_j,\forall j\in J,i\in I \tag{12}$$

$$
\begin{aligned}
&\sum_{i=1}^{|I|}\left\{a_i\cdot x_{ik}\left[G_{i\_IJK}\sum_{j=1}^{|J|}\left(x_{ij}\cdot s_j\right)+G_{i\_IK}\right]\right\}\le H_k\cdot S_k,\\
&\forall k\in K,i\in I,j\in J
\end{aligned}
\tag{13}
$$

$$
\begin{aligned}
&x_{ij},x_{ik},s_j,s_k,G_{i\_IJK},G_{i\_IK}\in\{0,1\},\\
&\forall i\in I,\forall j\in J,\forall k\in K,\\
&and\ all\ other\ \mathrm{var}\,iables\ are\ge 0.
\end{aligned}
\tag{14}
$$

The objective function (1) minimizes the total system cost, including the fixed and variable costs of the collection points (CP_j) (the first item of (1)) and those of the recycling centres (RC_k) (the second item of (1)), the transport costs of returned products from generation sites to recycling centres in the context of binary path (the third item of (1)), and the transport costs of returned products from recycling centres to clients of 3PRLP (the last item of (1)).

Equation (2) ensures that all the returned products from generation sites are collected, and only one of the two paths is selected for each generation point. Equation (3) guarantees that products from each generation point is collected and transported to recycling centres without splitting. Equation (4) assures that the direct route is selected for any generation site that decides to skip all collection points. Equation (5) specifies that only one node is selected respectively from collection points and recycling centres when a generation site selects the cascade route. Equation (6) states that only one node is selected from recycling centres, while no node is selected from collection points, when a generation site selects the direct route.

Inequality (7) indicates that only the selected collection points can receive returned products. Inequality (8) reveals that only the selected recycling centres can accept returned products. In equality (9) shows that the direct route should not be selected for the generation site, if the returned products from a certain generation site passes through a certain collection point. Inequality (10) means the cascade route must be selected for the generation site, if the returned products from a certain generation site passes through a certain collection point. Inequality (11) ensures that the cascade route is not selected if a generate site decides to skip all collection points. Inequality (12) limits the capacity of collection points. Inequality (13) constrains the throughput capacity of recycling centres. Inequality (14) determines that the variables are either zero or one, and are nonnegative integers.

3 CASE STUDY

Table 3. Locations of generation sites and amount of waste paper

No.	Coordinates		Amount of generated (t/annual)
	x	y	
G_1	15.69	3.8	116
G_2	18.67	24.28	75
G_3	1.6	59.13	1.5
G_4	9.43	2.27	1.9
G_5	49.08	54.43	57
G_6	33.14	10.85	3.2
G_7	24.86	59.39	43
G_8	33.23	21.9	38.5
G_9	45.32	27.23	4
G_{10}	28.07	33.38	1.8
G_{11}	2.77	0.5	55
G_{12}	51.71	46	90
G_{13}	41.98	22	7.5
G_{14}	2.81	37	4.4
G_{15}	36.72	62.35	10.5
G_{16}	22.15	33.3	2.3
G_{17}	25.63	20.51	110
G_{18}	9.1	26.42	47
G_{19}	24.79	11.26	2.6
G_{20}	45.4	45.4	8.2

Table 4. Locations and transport proportions of the 3 remanufacturing outlets

No.	Site coordinates		r_n
	x	y	
M_1	65	35	0.4
M_2	75	75	0.1
M_3	39.54	87.5	0.5

Table 5. Locations of the network nodes of the 3PRLP

collection points	Site coordinates		Recycling centers	Site coordinates	
	x	y		x	y
CP_1	43.97	49.89	RC_1	8.58	30.25
CP_2	1.57	12.65	RC_2	32.36	28.59
CP_3	41.23	30.25	RC_3	49	60.53
CP_4	5.04	58.97			
CP_5	24.79	19			
CP_6	16.18	20.66			

This chapter attempts to verify the effect of our model through a case study. In this case, the 3PRLP, relying on its own recycling network, is responsible for collecting waste paper from generation sites to the 3 remanufacturing outlets according to some proportion. Table 3 gives the locations of the generation sites locations and the amount of waste paper. Table 4 shows the locations and transport proportions of the 3 remanufacturing outlets. Table 5 presents the locations of the network nodes of the 3PRLP. In total, the 3PRLP RLN has 20 generation nodes, 6 candidate collection points, 3 candidate optional recycling centres and 3 clients.

The initial collection points of the 3PRLP are assumed to have the same fixed and variable costs. The same assumption is made for all the recycling centres. For the initial collection points, it is further assumed that the annual maximum capacity is 300 tonnes, the average annual fixed cost is $6,511.69, and the average annual variable cost is $162.79 per tonne; for the recycling centres, it is also assumed that the annual maximum capacity is 6,000 tonnes, the average annual fixed cost is $162,792.212, and the average annual variable cost is $130.23 per tonne. In addition, suppose that all paths share the same unit transport cost of $8.14 per tonne-km. It is also assumed that the cost coefficient of direct route is 2 (C=2), twice as much as that of cascade route.

3.1 Optimization results

The location optimization of facility with limited capacity has been approved to be an NP-complete problem (Current et al., 2002). This means the RLN optimization problem in this research is at least an NP-complete one. The Lingo software, a popular choice for solving largescale optimization problems, was adopted to solve our problem. The optimal cost is $764,070.5 with the recycling centre RC_3 and collection points CP_1 and CP_5 being selected. The service allocations between networks are presented in Table 6.

Table 6. Relationships between collection points/recycling centres and generation sites

Recycling centers (RC_k)	Corresponding collection points (CP_j)	Corresponding generating sites (G_i)
3	1	2, 3, 4, 6, 8, 9, 10, 13, 14, 16, 17, 18, 19 (cascade transport path).
	5	1, 11 (cascade transport path).
		5, 7, 12, 15, 20 (direct transport path).
Total costs	$764,070.5	

3.2 Sensitivity analysis

The above results were obtained based on the initial assumptions. Considering the variation in some parameters under different real-world scenarios, the sensitivity analysis was performed to observe the final optimization results after changing the location and the number of recovery points at recycling centres and some other operation parameters. (The detailed results of sensitivity analysis can be obtained by contacting authors)

3.2.1 Changing the proportion of returned products from recycling centres to clients

The initial transport ratio to the three downstream clients is 4: 1: 5. By the one-factor-at-a-time method, the proportion of one client was kept unchanged and that of the other two was changed. Finally, the recycling centre RC_2 or RC_3 were selected. Because of the change in transport cost, the total cost varies with the transport proportion from the recycling centre to downstream clients. The optimal result changes with the transport ratio, due to the impact of distance on the transport cost.

According to the final results, the minimum cost ($679,588) was achieved in the case of 10:0:0 for CP_3, CP_5 and RC_2; the maximum cost ($766,018.9) was obtained in the case of 4:5:1 for CP_1, CP_5 and RC_3; the number of direct routes decreased from 11 to 5.

3.2.2 Changing the cost coefficient of direct route

According to transport rationalization principle and the triangular inequality ($c_{ij}+c_{jk} \geq c_{ik}$), the direct transport maintains an obvious edge over transit transport. Under binary path selection, if cascade route and direct route share the same cost coefficient, the direct route would be selected between each OD pair. In practice, however, the transit transport is often adopted for scale efficiency and better equipment utilization. In this research, the cost coefficient of direct route in the context of binary path selection is changed between each OD pair to investigate its impact on the RLN. Note that the variation in unit transport cost between different phases is not considered for the existence of different cost coefficients.

Based on the original data, the cost coefficients of the direct route was changed from -30% to 30% by the step length of 10% to disclose its impact on the optimal result and the total cost. The other inputs remained unchanged. Table 8 shows the results of three extreme cases.

It can be seen from the final results that the total cost is positively correlated with the cost coefficient of direct route, while the number of generation sites choosing the direct route is negatively correlated with the cost coefficient of direct route. For instance, as the cost coefficient of direct route decreased from 2 to 1.4, the total cost declined from $764,070.5 to $704,002.6, while the number of generation sites choosing the direct route grew from 5 to 20. When the cost coefficient of direct route climbed up to 2.6, the total cost increased from $764,070.5 to $777,318.9, and the number of generation sites choosing the direct route fell from 5 to 3. With the increase in the cost coefficient of direct route, the optimal recycling centre RC_3 was more and more likely to be selected. Collection points CP_1 and CP_5, and recycling centre RC_3 were chosen, when the cost coefficient varied from the original data to 30%. The recycling centre RC_3 was chosen and all generation sites selected the direct route, when the cost coefficient of direct route was the same with that of cascade route. All generation sites selected the cascade route when the cost coefficient of direct route is sufficiently large (e.g. 10).

Changing the amount of returned products at generation sites

The amount of returned products fluctuates with the changes in business type and ancillary services.

The network needs to be redesigned at violent fluctuations.

Four generation sites were analysed, including G_1 (the maximum), G_3 (the minimum), G_8 (the closest to average) and G_{12}. In light of the original data, the amount of returned products at each generation site was changed from -30% to 30% by the step length of 10% to reveal its impact on the optimal result and the total cost. The other inputs remained the same.

Because of the variation in transport cost, it is obvious that the total cost varied with the amount of returned products at generation sites. Besides, the total cost is positively correlated with the variation in the amount of returned products. For example, as the amount of returned products from G_1 decreased from 116 to 81.2, the total cost reduced from \$764,070.5 to \$726,932.8. When the amount from G_1 increased to 150.8, the total cost rose to \$800,805.1. The optimal result changed along with the amount of returned products, provided that the latter varied by a sufficiently large amplitude. For example, the optimal result was not affected until the amount of returned products at G_1 and G_3 reached 30%.

3.2.3 Changing the throughput capacity of collection points

The throughput capacity of collection points was changed in two ways based on the assumption that all collection points have the same throughput capacity. First, all collection points underwent the same amplitude of variation in throughput capacity; Second, three collection points were selected (CP_1, CP_3, and CP_5), and the throughput capacity was changed one point at a time. To purpose is to find out how the optimal result and total cost are affected by the variation in throughput capacity.

Based on the original data, the throughput capacity was changed from -30% of its original value to 30% with the step length 10%. Note that the fixed cost is assumed to be constant despite the throughput variation, although the fixed cost will change with the throughput capacity in real life. Under the two ways of changes, the optimal result was calculated, leaving the other inputs and conditions unchanged.

From the final results, it is clear that the total cost generally changed with the maximum throughput capacity of collection points. Compared with the original data, as the maximum throughput capacity of all collection points decreased from 300 to 210, the total cost increased from \$764,070.5 to \$768,736.6. When the maximum throughput capacity of all collection points further increased to 390, the total cost continued to decrease from \$764,070.5 to \$ 763,737.3. Therefore, the optimal result varied with the maximum throughput capacity of collection points.

The total cost and the optimal result might not change with the maximum throughput capacity of a collection point. For instance, the total cost of the collection points and generation sites remained the same as the throughput capacity of collection point CP_3 shifted from -30% to 30% of the original value. Moreover, the throughput capacity variation of CP_1 had a greater impact on the optimal result than CP_5. Whether the optimal results may be affected by the variation in throughput capacity of a collection point may depends on the distance between network nodes and network structure. Compared with the original data, the total cost decreased when the maximum throughput capacity of CP_1 increased to 360 and 390. Nonetheless, the total cost dropped when the latter further climbed up to 330, and continued to fall when the latter decreased. The same trend is observed at all collection points.

It is concluded that the optimal throughput capacity of collection points should not be too large or too small, but be rationally determined based on the location and structure of the whole network nodes.

4 CONCLUDING REMARKS

Focusing on the 3PRLP RLN structure, this paper presents a mathematical model for routing selection and services allocation in multi-echelon recycling networks for 3PRLP with multi-path, cross-level reverse logistics. Then, a mathematical model was developed to design multi-echelon recycling networks in consideration of the multi-path, cross-level reserve logistics. The proposed model was verified through a case study on a 3PRLP responsible for collecting waste paper from generation sites to the 3 remanufacturing outlets according to some proportion. Finally, the author carried out a sensitivity analysis to reveal the influence of generation amount, the transport ratio of the recycling centres to the demanded clients, the cost coefficient of the direct path, and the change of the throughput over the location and the number of the collection points and the recycling centres.

The proposed model assumes that the 3PRLP is only responsible for collection service, failing to consider the quantity loss between OD pair. In addition, the entire reverse logistics system was assumed to be an open-loop, and the vehicle routing problem was not taken into account. Therefore, the future research will deal with the demand for multiple services or commodities and more complex routing problems.

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