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A dynamic pricing approach for returned products in integrated forward/reverse logistics network design

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ABSTRACT

During the last decade, the stringent pressures from environmental and social requirements have spurred an interest in designing a reverse logistics network. In this paper, we address the problem of designing and planning a multi-echelon, multi-period, multi-commodity and capacitated integrated forward/reverse logistics network. Returned products are categorized with respect to their quality levels, and a different acquisition price is offered for each return type. Furthermore, the reservation incentive of customers, the expected price of customers for one unit of used product described by uniform distribution, is applied to model the customers' return willingness. Due to the fact that the remaining worthwhile value in the used products is the corporation's key motivation for buying them from customers, a dynamic pricing approach is developed to determine the acquisition price for these products and based on it determine the percentage of returned products collected from customer zones. The used products' acquisition prices at each time period are determined based on the customers' return willingness by each collection center.

A novel mixed-integer linear programming is developed to consider dynamic pricing approach for used products, forward/reverse logistics network configuration and inventory decisions, concurrently. The presented model is solved by commercial solver CPLEX for some test problems. Computational results indicate that the effect of a dynamic pricing approach for used products versus a static pricing one, and the linearization of pricing concept for this model have the acceptable solution. In addition, sensitivity analysis is conducted to show the performance of the proposed model.

1. Introduction

Logistics network design problem that takes into account the facility locations and the shipment of product flows has gained considerable attention in both practice and academia. Since opening and closing facilities is both a time-consuming and expensive process, changing the network design is impossible in the short run. Moreover, due to the fact that after conducting the strategic decisions, the tactical and operational decisions are made, the design of logistics network will become a restriction for tactical and operational decisions. Considering these facts, the logistics network configuration is a very complex location problem and it is also required to be efficiently and effectively optimized for a long time [1].

During the last decade, growing attention has been paid to reverse logistics, which refers to activities, such as collection, recovery, repair, recycling, remanufacturing and disposal of the used products. An increasing number of companies such as

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Dell, General Motors, Kodak and Xerox have focused on these activities and achieved significant success [2]. The main causes of this increasingly attention are named environmental and business factors. The former relates to the used products' environmental impacts, environmental legislation, waste management, customers' increasingly careful attention to environmental issues, and pollution reduction. The latter includes economical advantages of using returned products, improving customer satisfaction, increasing market share, reducing costs, and adding value to logistics network [3]. Efficient and appropriate design of the logistics network leads to meeting these objectives. Therefore, the configuration of logistics network is considered as a significant subject within logistics and supply chain management that has an indispensable influence on the total performance of the supply chain.

The literature dedicated to the logistics network design problem can be divided into three parts, namely forward logistics network design (FLND), reverse logistics network design (RLND), and integrated forward/reverse logistics network design (IFRLND). The first division only addresses the traditional supply chain network design. The reverse logistics network focuses on the backward network, known as recovery network. Given the fact that designing the forward and reverse logistic network separately leads to sub-optimal designs, the configuration of forward and reverse logistics network should be integrated as the third part of the related literature [4,5]. Most of the logistics network design models have been constructed based on the facility location theory. According to the body of literature, the primary works start with simple facility location models (e.g. [6,7]). Then, more complex models are developed by taking the real life features of logistics network into account (e.g. [8–10]). In the next section, a comprehensive literature review of logistics network is provided.

In the RLND problem, making acquisition price decisions for the returned product is one of the most interesting and challenging issues [11,12]. The reason that makes the used products attractive for many corporations is twofold. The first one is the environmental aspect of collecting used products. Nowadays, because of tightened environmental laws, manufacturers need to devise products and production processes that make the recovery of used products possible for capturing the remaining advantages value. The second one is economical. Recovery and remanufacturing can reduce the unit cost of production by 40–60% by reutilizing the product components [13]. In this issue, Guide et al. [14] proposed a method to calculate the optimal acquisition price and the optimal selling price for remanufactured products. Based on anticipated demand, Liang et al. [11] presented an option model for acquisition pricing for the returned products. Choi et al. [15] and Yalabik et al. [16] also developed some strategies to calculate the optimal acquisition price. However, as suggested by Pokharel and Mutha [12] for future researches, the researchers do not explicitly consider network design and pricing for the acquisition of used products based on their quality. Therefore, in the context of the IFRLND problem, there is not any research containing determining the acquisition price for used products and location-allocation decisions at the same time, which is considered in this paper as the main contribution.

With regard to the matters enumerated, this paper develops a novel model for a multi-stage, multi-period, multi-product and capacitated integrated forward/reverse logistics network design including two echelons in forward direction (i.e., production/recovery centers, and distribution centers) and two echelons in backward direction (i.e., collection centers, and disposal centers). The goal of IFRLND model is to minimize its logistics cost. Furthermore, a complete sensitivity analysis is presented to investigate this model from different perspectives. To differentiate our efforts from those already published on this issue, the main innovations of this paper could be summarized, as follows:

- Designing and modeling a novel integrated forward/reverse logistics network as a mixed-integer linear programming (MILP) model to integrate both strategic and tactical decisions.
- A dynamic pricing approach is used to make the acquisition price decision for the used products with different quality levels returning from customer zones.
- The concept of transshipment among stages of IFRLN is considered to reduce the cost of logistics network.
- The IFRLN is designed based on a push–pull strategy in such a way that the periodic review inventory policy is used for the forward logistics of IFRLN.
- Based on product life cycle, the IFRLN is defined in which three return-recovery pairs: recoverable, scrapped and commercial returned products are considered.

The rest of this paper is organized, as follows. In the next section, we review the related literature and provide a comprehensive table. The concerned problem and its characteristics are defined in Section 3 in detail. The proposed MILP model for IFRLND and also the dynamic pricing approach are presented in Section 4. Sections 5 and 6 provide the computational results and sensitivity analysis for some test problems, respectively. Finally, Section 7 concludes this paper and offers guidelines for further research.

2. Literature review

The vast majority of existing literature in respect to designing the logistics network is comprised of diverse facility location models most of which is based upon the MILP. These studies encompass a wide scope of models range greatly from simple uncapacitated facility location models to complex capacitated multi-stages, multi-product, multi-period or multi-objectives ones. Melo et al. [17] and Klibi et al. [18] present comprehensive reviews on the logistics network design problem to support a wide variety of future research streams. In the following, we will review the literature of represented models concerning the logistics network design problem dividing into forward logistics network (FLN), reverse logistics network

(RLN), and finally integrated forward/reverse logistics network (IFRLN). Moreover, since the pricing of returned products is a very important aspect in this paper, we review a limited number of existing papers.

To begin with, a forward logistics network, as a conventional logistics, is made up of facilities performing the function of procurement of raw materials, transformation of these materials into finished products, and in the eventual step, the distribution of these products to end customers to satisfy their demands [19]. In the realm of forward logistics network known as a traditional supply chain, quite a lot of models have been developed; nevertheless, we brush up merely a number of related papers. Amiri [20] developed an MILP model for a multi-stage FLN with facilities having possible multiple capacity levels. His model not only was able to find the number and location of facilities, but it also determined the optimal capacity level for each facility. Yeh [21] presented an MILP model for a production–distribution network design. To solve this intractable model, an efficient hybrid heuristic algorithm is proposed. Miranda and Garrido [9] proposed a mixed-integer non-linear programming (MINLP) model for a FLN incorporating inventory control decisions, such as safety stock level. A heuristic solution approach based on lagrangian relaxation is developed to solve it. To design a responsive FLN, Altiparmak et al. [8] developed a multi-objective MINLP model, and a multi-objective genetic algorithm based on a priority-based encoding method to solve the model.

A reverse logistics network puts accentuation on the backward flow of materials and products from customers to suppliers, manufacturers, or disposal centers with the intention of minimizing total logistics cost or maximizing revenue from the returned items [19]. The high number of published case studies shows how this subject is of extreme importance: recycling of construction sand [22], carpet recycling [23,24], paper recycling [25], battery recycling [19], and iron and steel industry [26] among others. As one of the seminal works in the RLND problem, Barros et al. [22] proposed an MILP model for a sand recycling network, and also a heuristic algorithm was used to solve this problem. Jayaraman et al. [27] developed an MILP model for RLN under a pull system based on customer demands for recovered products. The objective of the proposed model was to minimize total costs. Additionally, Krikke et al. [28] proposed an MILP model for a two-stage RLN for a copier manufacturer. In this model, both the processing costs of returned products and inventory costs were included in the objective function for minimizing total costs. As mentioned, the research on RLN was triggered by some pioneering studies (e.g. [4,22,27]), but has experienced a strong development over the last decade (e.g. [29–31]).

In most of the past researches, the design of forward and reverse logistics was regarded separately. However, the configuration of the FLN is thoroughly impressed by the RLN and vice versa since they share a number of resources, such as transport and warehouse capacity. Moreover, returns information should be integrated with forward logistics information to achieve optimum planning and reduction of costs. Therefore, to avoid the sub-optimalities caused by a sequential design, the design of the forward and reverse logistics network should be integrated [5]. In general, an IFRLN consists mainly of supplying raw materials from suppliers, converting these materials to end products, shipping them to proper distribution centers and delivering to customer zones, then collection of used products from customer zones and finally recovering or remanufacturing and disposal in suitable way. The first time, this kind of logistics network was proposed by Fleischmann et al. [4]. They represented an extension of the traditional warehouse location problem in which forward and reverse logistics networks were integrated. In order to show the benefits of integrating networks, two cases of photocopier remanufacturing and paper recycling were used to examine the model. They found that an integrated approach, optimizing the forward and reverse network simultaneously, could provide a significant cost benefit against a segregated approach. During this decade, there have been a few papers in this category (e.g. [32–36]), all of which develop discrete facility location-allocation models formulated as an MILP model.

The pricing problem plays a paramount role in the logistics network design through which a firm can execute its competitive strategies. In the area of RLND, pricing is the process by which a company decides how much to pay for returned products from customer zones as an acquisition price. As pointed out by Aras et al. [13], the firm's crucial motivation for the collection of end-of-use products is the remaining worthwhile value in these products that can be captured by a number of recovery activities. Hence, pricing for returned products is an imperative issue in the logistics network design problem. The literature in the area of the acquisition pricing of the used products is quite scarce. Aras and Aksen [37] and Aras et al. [13] formulated a MINLP model to determine both the optimal locations of the collection centers and the optimal acquisition price for returned products with the objective of maximizing the total profit. They considered two factors to affect the willingness of customers to drop off their used products. The first is the amount of incentive offered at the time of drop-off, and the other is the proximity of the nearest collection center to customer zones. However, they presented a very simple and primary RLN including only collection centers and customer zones with a few simple assumptions, which is different from our work.

To structure the literature review of logistics network design problem and to show difference of this paper from others, we have classified the basic and most cited papers in this area according to five general characteristics: problem definition, modeling, objectives, outputs, and solution method. It must be asserted that the characteristics of the concerned problem have been presented in the last row of Table 1.

As the overview of the literature in Table 1, a small part of the literature is associated with the IFRLND. It must be noted that a majority of existing models have, so far, focused on the single type of used products and also neglected the time sensitivity of various parameters in multiple planning horizons. Thus, the proposed model aims to design a multi-period logistics network involving multiple products due to defects and transit damages. Moreover, selecting an appropriate capacity level from predetermined capacity levels for each facility as the decision variables is an important issue in real-life applications, which is regarded in this paper. Because of the fact that single sourcing related to customers makes management of

Table 1
The basic and most cited articles in the logistics network design problem.

Articles	Problem definition																		Modeling		Objectives			Outputs					Solution method		
	Type of Network		Network stages									Period		Product		Parameters		Facility Capacity													
	Forward	Reverse	Forward stages			Reverse stages						Multi-period	Single-period	Multi-product	Single-product	Deterministic	Stochastic	Uncapacitated	Capacitated	MILP	MINLP	Cost	Profit	Others	Location/ Allocation	Transportation Amount	Inventory	Facility Capacity	Price	Heuristic	Metaheuristic	Exact
Jayaraman et al. [27]		✓				✓	✓		✓				✓	✓		✓			✓	✓		✓			✓	✓						Commercial solver
Krikke et al. [28]		✓				✓	✓		✓				✓		✓	✓		✓		✓		✓			✓	✓	✓					Commercial solver
Jayaraman et al. [38]		✓				✓			✓				✓		✓	✓			✓	✓		✓			✓	✓				✓		
Listes and Dekker [39]		✓				✓				✓			✓	✓			✓		✓	✓		✓			✓	✓						Commercial solver
Min et al. [40]		✓				✓			✓			✓			✓	✓		✓		✓		✓			✓	✓					GA	
Uster et al. [2]		✓		✓	✓	✓		✓	✓				✓	✓		✓		✓		✓		✓			✓	✓						Benders
Lieckens and Vandaele [41]		✓							✓		✓		✓		✓	✓			✓		✓		✓		✓	✓					GA	
Demirel and Gökçen [42]		✓		✓	✓			✓	✓				✓	✓		✓			✓			✓			✓	✓						Commercial solver
Du and Evans [43]		✓		✓	✓			✓	✓				✓	✓		✓			✓	✓		✓		✓	✓	✓		✓		✓	SS	
Aras et al. [13]		✓				✓							✓	✓		✓		✓			✓	✓			✓	✓			✓	✓	TS	
Pishvaee et al. [44]		✓				✓			✓		✓		✓		✓	✓			✓	✓		✓			✓	✓					SA	
Fleischmann et al.[4]	✓	✓		✓	✓	✓		✓	✓		✓		✓		✓	✓		✓		✓		✓			✓	✓						Commercial solver
Salema et al. [45]	✓	✓		✓	✓	✓		✓	✓				✓		✓	✓			✓	✓		✓			✓	✓						Commercial solver
Ko and Evans [46]	✓	✓		✓	✓			✓	✓			✓		✓		✓			✓		✓	✓			✓	✓					GA	
Salema et al. [47]	✓	✓		✓	✓	✓		✓	✓				✓	✓			✓		✓	✓		✓			✓	✓						Commercial solver
Lu and Bostel [32]	✓	✓		✓	✓	✓			✓		✓		✓		✓	✓		✓		✓		✓			✓	✓				✓		
Min and Ko [48]	✓	✓		✓	✓	✓	✓	✓	✓			✓		✓		✓			✓		✓	✓			✓	✓					GA	
Lee and Dong [33]	✓	✓		✓	✓	✓	✓	✓				✓		✓			✓		✓		✓	✓			✓	✓				✓	SA	
El-Sayed et al. [34]	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓			✓	✓			✓	✓			✓		✓	✓						Commercial solver
Pishvaee et al. [29]	✓	✓		✓	✓	✓		✓			✓		✓		✓	✓			✓			✓		✓	✓	✓		✓			Memetic	
Wang and Hsu [49]	✓	✓	✓	✓	✓	✓		✓		✓			✓		✓	✓			✓		✓	✓			✓	✓					GA	
Our paper	✓	✓		✓	✓	✓			✓		✓	✓		✓		✓			✓	✓		✓			✓	✓	✓	✓	✓			Commercial solver

logistics network considerably simpler, in this paper this matter is considered. Finally, to the best of our knowledge, this paper is a leading attempt to optimize the IFRLN considering an inventory and pricing decisions with location-allocation decisions.

3. Problem definition

The IFRLN discussed in this paper is a multi-period, multi-product and multi-stage logistics network including production/recovery, distribution, collection, disposal centers and customer zones considering single sourcing of customers.

The general structure of the proposed IFRLN is illustrated in Fig. 1. In the forward flow, heterogeneous forward products are delivered to a number of geographically dispersed customer zones from production/recovery centers via distribution centers to meet the given demand of each customer in the multi-period of the planning horizon. In the backward flow, returned products are collected in collection centers and, after quality inspection; they are divided into three return–recovery groups: recoverable, scrapped and commercial returned products [50]. The recoverable products are shipped to production/recovery centers, and scrapped ones are sent to disposal centers. Commercial returned products are repaired in collection centers and then carried to distribution centers as new ones. Considering this strategy, returned products' excessive transportation especially scrapped ones is inhibited and the returned products can be directly transferred to the proper facilities. It should be noted that after the recovery process, the recovered products are entered to forward flow as new ones. Also, the location of customer zones and disposal centers are assumed to be fixed and predetermined.

In this paper, the defined IFRLN is designed based on push–pull strategy. To this end, the periodic review inventory policy is used by the distribution centers in which the inventory levels are reviewed at each time period and then the appropriate orders are placed after each review. That is, based on the base-stock level, the production/recovery centers produce new products and recover used products in such a way that the inventory level at distribution center should reach base-stock level at each time period. This concept is known as the push-based strategy in the associated literature. On the other hand, the customer zones order their needed products from distribution centers. These orders should be satisfied through the inventories of distribution centers. This system is known as a pull-based system. The interface between the push- and pull-based stages in the FLN denoted as the push–pull boundary. However, it must be mentioned that the RLN operates based on a pull-based strategy ending in production/recovery and disposal centers [51].

In this paper, instead of only regarding forward processing facilities (i.e., distribution centers) and backward processing facilities (i.e., collection centers) separately, this integrated network takes the hybrid processing facilities into account wherein both distribution and collection centers are established at the same locations. In comparison to separate distribution or collection centers, hybrid processing facilities suggest more advantages consisting of cost savings and pollution reduction as consequences of sharing material handling equipment and infrastructures [33]. Hence, in this integrated network, hybrid distribution-collection facilities are considered so as to accomplish more saving costs. Whether the hybrid processing facility is used or not depends on the trade-off of fixed opening costs and variable costs. That is, in such a logistics network, using hybrid processing facilities is a decision variable.

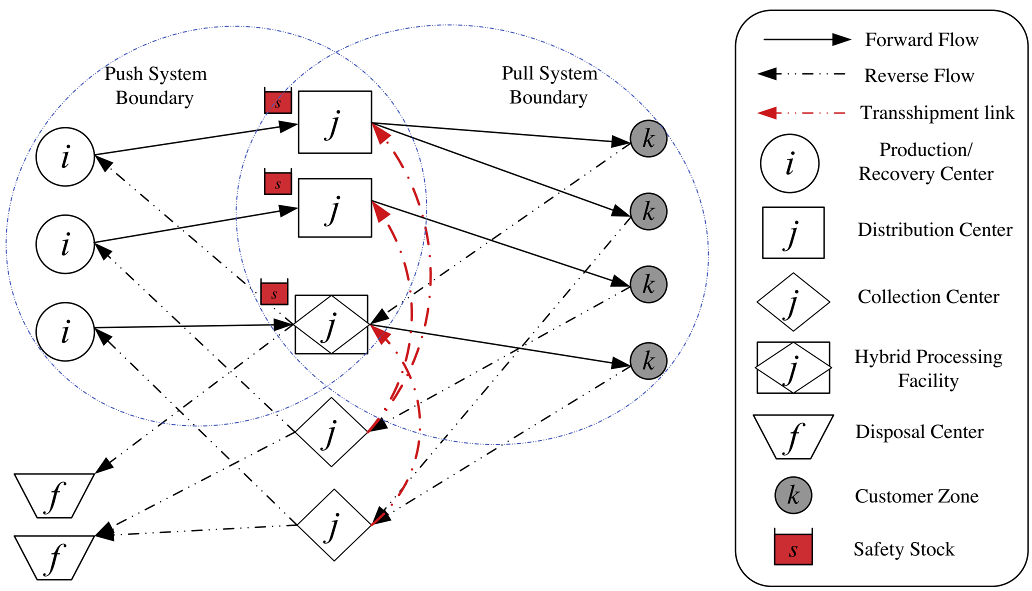

Fig. 1. The proposed integrated forward/reverse logistics network.

One of the contributions of this paper is using the concept of transshipment in this integrated logistics network. Transshipment is the shipment of items between different facilities at the same level in the logistics network that can be used to reduce costs and meet some immediate need [51]. In addition, Banerjee et al. [52] asserted that transshipment can be used to balance the inventory level of different locations at the same echelons in the supply chain before shortages occur. Contrary to the previous researches in which the flow is only permitted between two consecutive stages, there exist transshipments between distribution and collection centers in this network. By using this transshipment, commercial returned products after being repaired in collection centers could be transported to distribution centers or hybrid facilities in order to be redistributed as new ones to customer zones.

As pointed out by Aras et al. [13], environmental protection and remaining advantages value in the used products that can be captured by recovery processes is the corporation's principal motivation for the collection operation. In this IFRLND model, each customer decides whether or not to return their used product on the base of the financial incentive offered by the company. Regarding to their quality level, returned products are classified into different type and thereupon, a various acquisition price is offered for each returned type. Therefore, our main innovation is to incorporate the customers' willingness to return used products in modeling the IFRLN. And by adopting a dynamic pricing strategy, not only does the model have to determine the acquisition price according to the quality level of the used products, but based on this price it has to decide on the percentage of potential returned products as well.

In addition to the aforementioned assumptions, the following characteristics and limitations are made in the development of the IFRLND model:

1. The IFRLND model is multi-product.
2. To accommodate the changing parameters of the business environment during the life-time of the logistics network, the IFRLND model is considered multi-period.
3. The potential locations of production/recovery, distribution, and collection centers are known.
4. In forward network, all of the customers' demands should be satisfied, but only a percentage of returned products are collected based on the acquisition price determined by the model.
5. Distribution centers incur in inventory holding costs at the end of each period.
6. There is no limitation on the capacity of the material flows through the network.
7. Apart from disposal centers, all the facilities supposed to be located are capacitated.
8. The quality of returned products from customer zones is different.
9. The cost values (i.e. fixed, production, distribution, collection/inspection, repair, recovery, disposal, and holding costs) are known.

With the abovementioned assumptions in mind, the crucial issues to be addressed by this paper are to simultaneously determine the locations of network facilities, allocation of customers to facilities, capacity of facilities, the quantity of production at production/recovery centers, base-stock and inventory of products at distribution centers, the quantity of flows between each pair of network facilities, acquisition price and percentage of collected potential returned products from customers. Moreover, it is noticeable that for the sake of its generic nature, this logistics network is not a case-based one; however, it can include a wide variety of industries such as electronic and digital equipment and vehicle industries (e.g. [2,5]), in particular computer companies. In other words, this IFLRN can be applicable to businesses in which the customers are not obliged to totally return their used products; rather, they can return them according the proposed acquisition price. What is more, the returned products having different quality level can be recovered. The design of this integrated logistics network may involve a trade-off relationship between the total fixed costs and total variable costs.

4. Model formulation

To support the presentation of the proposed mathematical IFRLND model, first we provide a verbal description of the model, as follows:

Minimize Costs

=Fixed opening costs − Saving costs from integrating facilities + Production costs + Recovery costs + Holding costs + Distribution costs + Collection and inspection costs + Disposal costs + Transportation costs + Capacity costs + Purchasing costs.

Subject to:

- Allocation constraints: Satisfying all forward demands of customer zones. (It must be noted that only a fraction of potential returned products could be collected based on their acquisition price.)
- Balance constraints: Balancing the flows of products among nodes of network.
- Inventory constraints: Calculating the base-stock and inventory level of each distribution center.
- Location constraints: Logical constraints relating to opening facilities.
- Capacity constraints: Logical constraints associated with selecting an appropriate capacity level for each facility.

- Pricing constraints: Logical constraints pertinent to choosing one level of price for returned products and calculating the acquisition price and the percentage of collected potential returned products from customer zones based on the calculated acquisition price.

The following notations are used for the MILP model in the formulation of the IFRLN:

Sets:	
I	Set of potential locations of production/recovery centers, $(i = 1, 2, \ldots, \lvert I\rvert)$
J	Set of potential locations available for distribution centers, collection centers, and hybrid processing facilities, $(j, j' = 1, 2, \ldots, \lvert J\rvert)$
K	Set of fixed locations of customers, $(k, k' = 1, 2, \ldots, \lvert K\rvert)$
F	Set of fixed locations of disposal centers, $(r = 1, 2, \ldots, \lvert R\rvert)$
N	Set of capacity levels available for facilities, $(n = 1, 2, \ldots, \lvert N\rvert)$
Q	Set of quality levels for used products, $(q = 1, 2, \ldots, \lvert Q\rvert)$
L	Set of price levels for buying used products, $(l = 1, 2, \ldots, \lvert L\rvert)$
P	Set of products, $(p = 1, 2, \ldots, \lvert P\rvert)$
T	Set of time periods in planning horizon, $(t, t' = 1, 2, \ldots, \lvert T\rvert)$
Parameters:	
Demand and potential return:	
D^t_{kp}	Demand of customer k for product p in time period t
R^t_{kpq}	Potential return of used product p with quality level q from customer k in time period t
Fixed costs:	
FW_i	Fixed cost for opening production/recovery center i
FY_j	Fixed cost for opening distribution center j
FZ_j	Fixed cost for opening collection center j
SC_j	Fixed saving cost associated with opening hybrid processing facility j
Variable costs:	
PC_{ip}	Unit production cost of product p at production/recovery center i
RC_{ip}	Unit recovery cost of product p at production/recovery center i
H_{jp}	Inventory carrying cost per unit of product p per period at distribution center or hybrid processing facility j
OC_{jp}	Unit processing cost of product p at distribution center or hybrid processing facility j
CC_{jp}	Unit collection/inspection cost of product p at collection center or hybrid processing facility j
CPR_{jp}	Unit repairing cost of product p at collection center or hybrid processing facility j
DC_{fp}	Unit disposal cost of product p at disposal center f
Transportation costs:	
CX^t_{ij}	Unit transportation cost for product p shipped from production/recovery center i to distribution center or hybrid processing facility j in time period t
CQ^t_{jk}	Unit transportation cost for product p shipped from distribution center or hybrid processing facility j to customer k in time period t
CU^t_{kj}	Unit transportation cost for returned product p shipped from customer k to collection center or hybrid processing facility j in time period t
$CG^t_{jj'}$	Unit transportation cost for repaired product p shipped from collection center or hybrid processing facility j to distribution center or hybrid processing facility j' in time period t
CT^t_{ji}	Unit transportation cost for recoverable product p shipped from collection center or hybrid processing facility j to production/recovery center i in time period t
CP^t_{jf}	Unit transportation cost for scrapped product p shipped from collection center or hybrid processing facility j to disposal center f in time period t
Capacity costs:	
CWM_{ipn}	Cost for production capacity level n of production/recovery center i for product p
CWR_{ipn}	Cost for recovery capacity level n of production/recovery center i for product p
$CYDC_{jpn}$	Cost for capacity level n of distribution center j for product p
$CZCL_{jpn}$	Cost for capacity level n of collection center j for product p
Capacity of facilities:	
$CAPWM_{ipn}$	Production capacity of production/recovery center i with capacity level n for product p
$CAPWR_{ipn}$	Recovery capacity of production/recovery center i with capacity level n for product p

$CAPMAXW_i$	Maximum available capacity of production/recovery center i
$CAPYDC_{jpn}$	Capacity of distribution center j with capacity level n for product p
$CAPZCL_{jpn}$	Capacity of collection center j with capacity level n for product p
$CAPMAX_j$	Maximum available capacity of distribution center, or collection center or hybrid processing facility j
Coefficients and ratios:	
SL_{pq}	Average redistribution fraction of returned product p with quality level q
SI_{pq}	Average recovery fraction of returned product p with quality level q
λM_p	Coefficient of using production capacity of a production/recovery center for production per unit of product p
λR_p	Coefficient of using recovery capacity of a production/recovery center for recovery per unit of product p
λD_p	Coefficient of using capacity of a distribution center for distribution per unit of product p
λC_p	Coefficient of using capacity of a collection center for collection per unit of product p
Pricing parameters:	
a^t_{kpq}	Minimum expected price of customer k for one unit of the returned product p with quality level q in time period t
b^t_{kpq}	Maximum expected price of customer k for one unit of the returned product p with quality level q in time period t
PRC^t_{kpq}	Expected price of customer k for one unit of the returned product p with quality level q in time period t (This parameter has a uniform distribution)
Decision variables:	
Binary variables (relating to opening facilities):	
W_i	Binary variable equals to 1 if a production/recovery center is opened at location i, 0 otherwise
Y_j	Binary variable equals to 1 if a distribution center is opened at location j, 0 otherwise
Z_j	Binary variable equals to 1 if a collection center is opened at location j, 0 otherwise
X_j	Binary variable equals to 1 if a hybrid processing facility is opened at location j, 0 otherwise
Binary variables (relating to selecting one level of capacity for each facility):	
WM_{ipn}	Binary variable equals to 1 if a production/recovery center with capacity level n at location i produces product p, 0 otherwise
WR_{ipn}	Binary variable equals to 1 if a production/recovery center with capacity level n at location i recovers product p, 0 otherwise
YDC_{jpn}	Binary variable equals to 1 if a distribution center with capacity level n at location j processes product p, 0 otherwise
ZCL_{jpn}	Binary variable equals to 1 if a collection center with capacity level n at location j collects and inspects product p, 0 otherwise
Binary variables (relating to the single sourcing of serving customers):	
AJK_{jk}	Binary variable equals to 1 if in the forward network, shipment link is created between distribution center or hybrid processing facility j and customer k, 0 otherwise
BJK_{jk}	Binary variable equals to 1 if in the reverse network, shipment link is created between customer k and collection center or hybrid processing facility j, 0 otherwise
Binary variable (relating to selecting one level of price for used products):	
δ^t_{kpql}	Binary variable equals to 1 if the level price l is allocated to the used product p with quality level q returned by customer k in time period t, 0 otherwise
Continuous variables (relating to the flows of network):	
XIJ^t_{ijp}	Quantity of products p shipped from production/recovery center i to distribution center or hybrid processing facility j in time period t
QJK^t_{jkp}	Quantity of products p shipped from distribution center or hybrid processing facility j to customer k in time period t
UKJ^t_{kjpq}	Quantity of returned products p with quality level q shipped from customer k to collection center or hybrid processing facility j in time period t
$GJJ^t_{jj'p}$	Quantity of repaired products p shipped from collection center or hybrid processing facility j to distribution center or hybrid processing facility j' in time period t
TJI^t_{jip}	Quantity of recoverable products p shipped from collection center or hybrid processing facility j to production/recovery center i in time period t
PJF^t_{jfp}	Quantity of scrapped products p shipped from collection center or hybrid processing facility j to disposal center f in time period t

(*continued on next page*)

Other continuous variables:

PQ_{ip}^{t}	Quantity of products p produced by production/recovery center i in time period t
INV_{jp}^{t}	Inventory level of product p at distribution center or hybrid processing facility j at the end of time period t
BS_{jp}	Base-stock level of product p of distribution center or hybrid processing facility j at the beginning of each period
RE_{kpq}^{t}	Percentage of used product p with quality level q collected from customer k in time period t
PR_{kpq}^{t}	Acquisition price of used product p with quality level q collected from customer k in time period t

According to the above-mentioned notations, the IFRLND problem can be formulated, as follows:

4.1. Objective function

The objective of the presented model is to minimize the total cost of the IFRLN, as follows:

$$\begin{aligned}\text{Min Cost} = &\sum_i FW_i \times W_i + \sum_j FY_j \times Y_j + \sum_j FZ_j \times Z_j - \sum_j SC_j \times X_j \\ &+ \sum_i\sum_p\sum_t PC_{ip} \times PQ_{ip}^t + \sum_j\sum_i\sum_p\sum_t RC_{ip} \times TJI_{jip}^t + \sum_j\sum_p\sum_t H_{jp} \times INV_{jp}^t \\ &+ \sum_j\sum_k\sum_p\sum_t OC_{jp} \times QJK_{jkp}^t + \sum_j\sum_k\sum_p\sum_q\sum_t CC_{jp} \times UKJ_{jkpq}^t + \sum_j\sum_f\sum_p\sum_t DC_{fp} \times PJF_{jfp}^t \\ &+ \sum_j\sum_{j'}\sum_p\sum_t CPR_{jp} \times GJJ_{jj'p}^t + \sum_i\sum_j\sum_p\sum_t CX_{ij}^t \times XIJ_{ijp}^t + \sum_j\sum_k\sum_p\sum_t CQ_{jk}^t \times QJK_{jkp}^t \\ &+ \sum_k\sum_j\sum_p\sum_q\sum_t CU_{kj}^t \times UKJ_{jkpq}^t + \sum_j\sum_i\sum_p\sum_t CT_{ji}^t \times TJI_{jip}^t + \sum_j\sum_f\sum_p\sum_t CP_{jf}^t \times PJF_{jfp}^t \\ &+ \sum_j\sum_{j'}\sum_p\sum_t CG_{jj'}^t \times GJJ_{jj'p}^t + \sum_i\sum_p\sum_n WM_{ipn} \times CWM_{ipn} + \sum_i\sum_p\sum_n WR_{ipn} \times CWR_{ipn} \\ &+ \sum_j\sum_p\sum_n YDC_{jpn} \times CYDC_{jpn} + \sum_j\sum_p\sum_n ZCL_{jpn} \times CZCL_{jpn} \\ &+ \sum_l\sum_k\sum_p\sum_q\sum_t a_{kpq}^t \times \left(\frac{l-1}{L-1}\right) \times R_{kpq}^t \times \delta_{kpql}^t + \sum_l\sum_k\sum_p\sum_q\sum_t (b_{kpq}^t - a_{kpq}^t) \times \left(\frac{l-1}{L-1}\right)^2 \times R_{kpq}^t \times \delta_{kpql}^t \end{aligned} \tag{1}$$

The objective function minimizes the total cost, which includes fixed costs for establishing facilities, the cost saving pertinent to integrating distribution and collection centers at the same locations, production cost for manufacturing the products and recovery cost for recoverable products in production/recovery centers, inventory carrying cost of handling the inventory and operating cost in distribution centers, collection/inspection cost for the returned products in collection centers, disposal cost for the scrapped products in disposal centers, transportation costs, capacity costs of facilities, and purchasing cost of the used products collecting from customer zones. The two last terms of the objective function are described in detail in Section 4.2.6.2.

4.2. Constraints

The constraints of the proposed mathematical IFRLND model are explained in details in the following subsections.

4.2.1. Allocation constraints

$$QJK_{jkp}^t = D_{kp}^t \times AJK_{jk}, \quad \forall t,k,j,p, \tag{2}$$

$$\sum_j AJK_{jk} = 1, \quad \forall k, \tag{3}$$

$$\sum_j UKJ_{kjpq}^t = RE_{kpq}^t \times R_{kpq}^t, \quad \forall t,k,p,q, \tag{4}$$

$$UKJ_{kjpq}^t \leqslant M \times BJK_{jk}, \quad \forall t,k,j,p,q, \tag{5}$$

$$\sum_j BJK_{jk} = 1, \quad \forall k, \tag{6}$$

Constraint (2) states that at each time period for any kind of product, the existing flow from distribution centers or hybrid processing facilities should satisfy the given demand of allocated customers. According to constraint (3), each customer zone is only assigned to one distribution center or hybrid processing facility; in other words, it shows the single sourcing of serving customer zones in forward direction. Constraint (4) ensures that only a percentage of the potential returned product at each time period is collected from each customer zone. Constraint (5) imposes that if in the reverse network, there does not exist any flow from a customer to a collection center or hybrid processing facility, this customer zone is not assigned to this collection center or hybrid processing facility. Upon the constraint (6), any customer zone can be assigned to only one collection center or hybrid processing facility.

4.2.2. Balance constraints

$$\sum_{j'} GJJ^t_{jj'p} = \sum_k \sum_q (SL_{pq}) \times UKJ^t_{kjpq}, \quad \forall j, p, t, \tag{7}$$

$$\sum_f PJF^t_{jfp} = \sum_k \sum_q (1 - SL_{pq} - SI_{pq}) \times UKJ^t_{kjpq}, \quad \forall j, p, t, \tag{8}$$

$$\sum_i TJI^t_{jip} = \sum_k \sum_q (SI_{pq}) \times UKJ^t_{kjpq}, \quad \forall j, p, t, \tag{9}$$

$$PQ^t_{ip} + \sum_j TJI^t_{jip} = \sum_j XIJ^t_{ijp}, \quad \forall i, p, t. \tag{10}$$

Constraints (7)–(10) assure the flow balance at collection centers or hybrid processing facilities, and also production/recovery centers.

4.2.3. Inventory constraints

$$\sum_{t' \leqslant t} \sum_i XIJ^{t'}_{ijp} + \sum_{t' \leqslant t} \sum_{j'} GJJ^{t'}_{j'jp} - \sum_{t' < t} \sum_k QJK^{t'}_{jkp} = BS_{jp}, \quad \forall j, p, t, \tag{11}$$

$$\sum_{t' \leqslant t} \sum_i XIJ^{t'}_{ijp} + \sum_{t' \leqslant t} \sum_{j'} GJJ^{t'}_{j'jp} - \sum_{t' \leqslant t} \sum_k QJK^{t'}_{jkp} = INV^t_{jp}, \quad \forall j, p, t. \tag{12}$$

Constraint (11) which refers to the push-based strategy ensures that subtracting the amounts of product p supplied to all customer zones until time period $t-1$ from the total input flows to a distribution center until time period t should be equal to the respective base-stock level. That is, for each type of product at each time period, the production/recovery centers produce new products and recover used products in such a way that the inventory level of distribution centers reaches base-stock level. Fig. 2 shows more clearly the inventory level changes for time period t, product p and distribution center j.

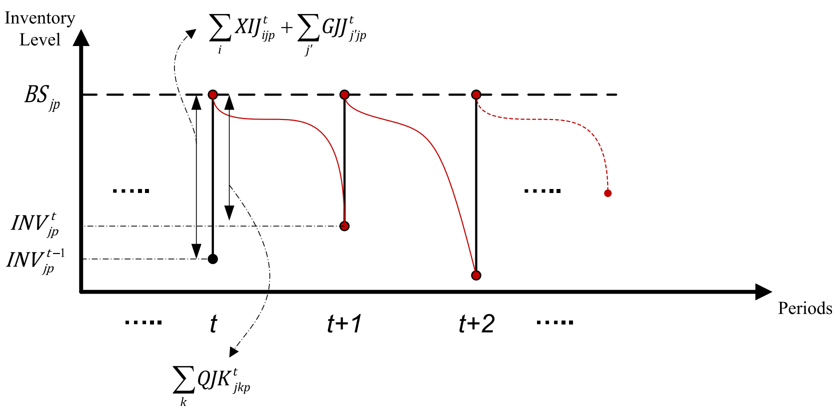

Fig. 2. The inventory level changes for time period t, product p and distribution center j.

Constraint (12) calculates the inventory level of any kind of product at the end of each time period for each distribution center. The inventory carrying cost is calculated based on the inventory level at the end of each time period. It is worth mentioning that the base-stock levels of distribution centers are calculated in such a way that we do not have any shortage.

4.2.4. Location constraints

$$\sum_{n} WM_{ipn} \leqslant W_i, \quad \forall i,p, \tag{13}$$

$$\sum_{n} WR_{ipn} \leqslant W_i, \quad \forall i,p, \tag{14}$$

$$\sum_{n} YDC_{jpn} \leqslant Y_j, \quad \forall j,p, \tag{15}$$

$$\sum_{n} ZCL_{jpn} \leqslant Z_j, \quad \forall j,p, \tag{16}$$

$$Y_j + Z_j \leqslant X_j + 1, \quad \forall j, \tag{17}$$

$$Y_j + Z_j \geqslant 2X_j, \quad \forall j. \tag{18}$$

Constraints (13) and (14) assert that if at one location, a production/recovery center is not opened, no level of production and recovery capacity are assigned, respectively. Constraint (15) states if at one location, a distribution center is not opened, no level of distribution capacity is allocated to this kind of facility. Likewise, constraint (16) is for collection centers. Constraints (17) and (18) make sure that if a hybrid processing facility is opened at a location j, both a distribution and collection center should be opened in this location concurrently.

4.2.5. Capacity constraints

$$\sum_{n}\sum_{p} WM_{ipn} \times CAPWM_{ipn}(\lambda M_p) + \sum_{n}\sum_{p} WR_{ipn} \times CAPWR_{ipn}(\lambda R_p) \leqslant CAPMAXW_i \times W_i, \quad \forall i, \tag{19}$$

$$\sum_{n}\sum_{p} YDC_{jpn} \times CAPYDC_{jpn}(\lambda D_p) \leqslant CAPMAX_j \times Y_j, \quad \forall j, \tag{20}$$

$$\sum_{n}\sum_{p} ZCL_{jpn} \times CAPZCL_{jpn}(\lambda C_p) \leqslant CAPMAX_j \times Z_j, \quad \forall j, \tag{21}$$

$$\sum_{n}\sum_{p} YDC_{jpn} \times CAPYDC_{jpn}(\lambda D_p) + \sum_{n}\sum_{p} ZCL_{jpn} \times CAPZCL_{jpn}(\lambda C_p) \leqslant CAPMAX_j \times X_j + (1 - X_j) \times M, \quad \forall j, \tag{22}$$

$$PQ_{ip}^{t} \leqslant \sum_{n} CAPWM_{ipn} \times WM_{ipn}, \quad \forall i,p,t, \tag{23}$$

$$\sum_{j} TJI_{jip}^{t} \leqslant \sum_{n} CAPWR_{ipn} \times WR_{ipn}, \quad \forall i,p,t, \tag{24}$$

$$\sum_{k} QJK_{jkp}^{t} + INV_{jp}^{t} \leqslant \sum_{n} CAPYDC_{jpn} \times YDC_{jpn}, \quad \forall j,p,t, \tag{25}$$

$$\sum_{q}\sum_{k} UKJ_{kjpq}^{t} \leqslant \sum_{n} CAPZCL_{jpn} \times ZCL_{jpn}, \quad \forall j,p,t. \tag{26}$$

By considering the coefficients of using capacity for each kind of product, constraint (19) ensures that the capacity of an opened production/recovery center, which consists of the summation of production and recovery capacities, does not exceed the maximum available capacity of relevant location. Same as constraint (19), constraints (20) and (21) are associated to distribution and collection centers, respectively. Constraint (22) asserts that if a hybrid processing facility is opened, the summation of its distribution and collection capacities should not exceed the maximum available capacity of its location. Moreover, it should be noted that for each unit of product, a coefficient of using distribution and collection capacity is defined, respectively. Constraint (23) ensures that the production amount of any kind of product at each time period does not exceed the production capacity of the relevant production/recovery center for each type of product. Constraint (24) states that the sum of the flows entering to each production/recovery center from all collection centers or hybrid processing facilities does not exceed the recovery capacity of this center at each time period for each type of product. Constraint (25) shows that the flow exiting from each distribution center or hybrid processing facility to all customer zones plus the inventory level of this facility do not exceed the distribution capacity of this center at each time period for each type of product. Constraint (26) states that the sum of the flows entering to each collection center or hybrid processing facility from all customer zones at each time period for each type of product does not exceed the collection capacity of this center.

4.2.6. Pricing constraints and others

The major innovation of this paper is associated with a dynamic pricing strategy to calculate the acquisition price for the used products. To explain this, the approach is illustrated at first, and then the mathematical constraints (31–35) to model this pricing approach are remarked in Section 4.2.6.2.

4.2.6.1. Preliminaries of the dynamic pricing approach. In the pricing framework, it is assumed that customer zones are aggregated at a number of fixed locations. Clearly, the used products are not of the same quality level. That is, upon the usage rate and duration at each use, the deterioration of used products will vary, which brings about different quality levels of the returns. Therefore, in our study, we assume that the used products can be divided into Q discrete quality levels. Furthermore, without loss of generality, we assume that type 1 and type Q returns have the highest and lowest quality, respectively.

To model customers' return willingness, we use the notion of consumer surplus. Therefore, we assume that each customer having the used product of type q has a reservation incentive PRC^t_{kpq} named the expected price of customer zone k for one unit of used product p with quality level q in time period t.

In light of this, each customer would be willing to return if the firm offered an acquisition price at least as large as the reservation incentive PRC^t_{kpq}. Given the fact that the customers are different in terms of their willingness, the diversity of customers is described by assuming a uniform distribution for the reservation incentive in the form of uniform $[a^t_{kpq}, b^t_{kpq}]$. Here a^t_{kpq} and b^t_{kpq} represent the minimum and maximum expected price of customer zone k for one unit of used product p with quality level q in time period t, respectively. Regarding uniform distribution, the probability density and cumulative distribution functions of PRC^t_{kpq} are given by $f(PRC^t_{kpq}) = 1/(b^t_{kpq} - a^t_{kpq})$ and $F(PRC^t_{kpq}) = (PRC^t_{kpq} - a^t_{kpq})/(b^t_{kpq} - a^t_{kpq})$, respectively. It must be alleged that the uniform distribution assumption is a frequently one in the area of logistics literature since it not only provides analytical tractability, but also helps to encompass a large degree of variability among customer zones [37,53].

When a collection center offers an acquisition price PR^t_{kpq} for the used product p with quality level q collected from customer zone k in time period t, the consumer surplus is $PR^t_{kpq} - PRC^t_{kpq}$. Therefore, the proportion RE^t_{kpq} of used product p with quality level q collected from customer zone k in time period t can be written, as follows:

$$RE^t_{kpq} = P(PR^t_{kpq} - PRC^t_{kpq} \geqslant 0) = \min\left\{1, \frac{\max\{0, PR^t_{kpq} - a^t_{kpq}\}}{b^t_{kpq} - a^t_{kpq}}\right\}. \tag{27}$$

By considering the uniform distribution for the reservation incentive of customer, a closer look at the expression of RE^t_{kpq} illustrated in Fig. 3 reveals that:

$$RE^t_{kpq} = P(PR^t_{kpq} - PRC^t_{kpq} \geqslant 0) = \begin{cases} 0 & PR^t_{kpq} \leqslant a^t_{kpq}, \\ \frac{PR^t_{kpq} - a^t_{kpq}}{b^t_{kpq} - a^t_{kpq}} & a^t_{kpq} < PR^t_{kpq} \leqslant b^t_{kpq}, \\ 1 & PR^t_{kpq} > b^t_{kpq}. \end{cases} \tag{28}$$

As can be seen in Fig. 3, it draws for customer zone k that returns the used product p with quality level q at time period t. This means that the acquisition price of each type of used product could be different in each time period according to level of its quality. Note that if we want to use this continuous formulation of RE^t_{kpq} in the mathematical model, it will be a MINLP

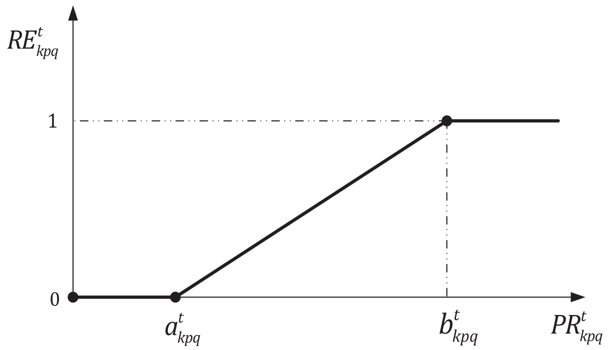

Fig. 3. Percentage of the returned products as a continuous function of incentive $CG^t_{jj'}$.

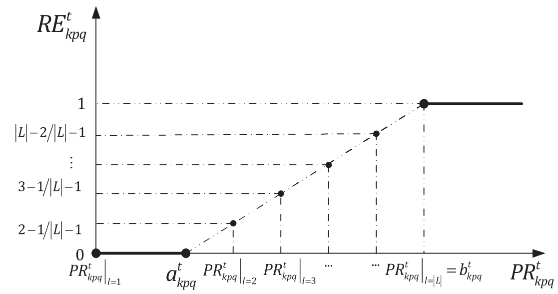

Fig. 4. Percentage of returned products as a discrete function of incentive FW_i.

model. To avoid the complexity of such MINLP model, we divide the acquisition prices of used products into $|L|$ disjoint levels. Thus, the percentage of returned products as a function of incentive can be drawn as Fig. 4.

To put this issue more simply by sample, suppose now that for one type of the used product with definite quality level, there appears to be five levels of price ($l = 1-5$). In each time period, only one level of price is selected for the customer zone returning this kind of used product. It must mention that if the level of price for a specific used product and a specific customer zone at a certain time period equals one, it means that its acquisition price equals zero and we do not collect any used products from this customer zone at this time period. Thus, we have $\sum_{l=1}^{5} \delta^t_{kpql} = 1$. Afterwards, according to horizontal axis of Fig. 4, the acquisition price for this used product is calculated for each time period, as follows:

$$PR^t_{kpq} = a^t_{kpq} + (b^t_{kpq} - a^t_{kpq}) \times \left[\left(\frac{1-1}{5-1}\right)\delta^t_{kpq1} + \left(\frac{2-1}{5-1}\right)\delta^t_{kpq2} + \left(\frac{3-1}{5-1}\right)\delta^t_{kpq3} + \left(\frac{4-1}{5-1}\right)\delta^t_{kpq4} + \left(\frac{5-1}{5-1}\right)\delta^t_{kpq5}\right] - a^t_{kpq} \times \delta^t_{kpq1}. \tag{29}$$

In addition, according to vertical axis of Fig. 4, the percentage of this used product collecting from a definite customer zone is calculated for each time period, as follows:

$$RE^t_{kpq} = \left(\frac{1-1}{5-1}\right)\delta^t_{kpq1} + \left(\frac{2-1}{5-1}\right)\delta^t_{kpq2} + \left(\frac{3-1}{5-1}\right)\delta^t_{kpq3} + \left(\frac{4-1}{5-1}\right)\delta^t_{kpq4} + \left(\frac{5-1}{5-1}\right)\delta^t_{kpq5}. \tag{30}$$

Another point that must be mentioned here is that although the acquisition prices of used products are divided into $|L|$ disjoint level, with the increase in the number of price levels, this discrete function will tend to the continuous function. That is, we can have a reasonable approximation of the acquisition price function when the number of price levels is increased to an adequate large quantity. This fact is illustrated by Fig. 5. By doing so, the intractable MINLP model could change into the MILP model. In the Section 6.3, we demonstrate that this linearization does not have any considerable impact on the IFRLND model.

4.2.6.2. Mathematical pricing constraints. In order to mathematically show the pricing approach described above, we present the following constraints:

$$\sum_{l} \delta^t_{kpql} = 1, \quad \forall t, k, p, q. \tag{31}$$

In each time period, one level of price should be selected for each customer zone returning used products with specific quality level. To this end, constraint (31) assures that in each time period, for each type of used product with definite quality level, one level of price is selected for each customer zone.

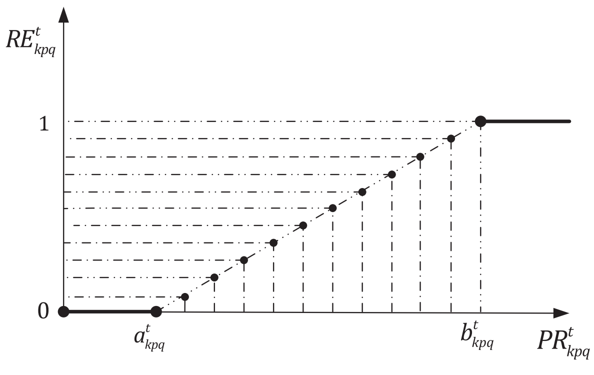

Fig. 5. The linear approximation of percentage of returned products as a function of incentive FY_j.

$$a^t_{kpq} + \sum_l \delta^t_{kpql} \times \left(\frac{l-1}{L-1}\right) \times (b^t_{kpq} - a^t_{kpq}) - a^t_{kpq} \times \delta^t_{kpq1} = PR^t_{kpq}, \quad \forall k,p,q,t. \tag{32}$$

As shown in Fig. 4, constraint (32) calculates the acquisition price of each type of used product with specific quality level for each customer zone that can be varied in each time period. In this constraint, the term $a^t_{kpq} \times \delta^t_{kpql}$ states that when only the first level of price ($l = 1$) is selected, the acquisition price should equal to zero ($PR^t_{kpq} = 0$).

$$PR^t_{kpq} - (1 - BJK_{jk}) \times M \leqslant PR^t_{k'pq} + (1 - BJK_{jk'}) \times M, \quad \forall k,k',j,p,q,t, \tag{33}$$

$$PR^t_{k'pq} - (1 - BJK_{jk'}) \times M \leqslant PR^t_{kpq} + (1 - BJK_{jk}) \times M, \quad \forall k,k',j,p,q,t. \tag{34}$$

Constraints (33) and (34) guarantee that if two different customer zones are assigned to one collection center or hybrid processing facility to drop off their used products, the returned products from these customers should be purchased with the same acquisition prices.

$$\sum_l \left(\frac{l-1}{L-1}\right) \times \delta^t_{kpql} = RE^t_{kpq}, \quad \forall k,p,q,t. \tag{35}$$

As can be seen from Fig. 4, the percentage of used products collected from customer zones can vary depending on the level of acquisition price selected. Constraint (35) calculates the percentage of each type of used product with specific quality level in each time period for each customer zone. Obviously, the total buying cost of returned products is calculated, as the two last terms of objective function by multiplying the buying cost for each unit of used product to the amount of returned products. Finally, constraints (36) and (37) enforce the binary and non-negativity restrictions on corresponding decision variables, respectively.

$$W_i, Y_j, Z_j, X_j, WM_{ipn}, WR_{ipn}, YDC_{jpn}, ZCL_{jpn}, AJK_{jk}, BJK_{jk}, \delta^t_{kpql} \in \{0,1\} \quad \forall i,j,k,l,n,p,q,t, \tag{36}$$

$$XIJ^t_{ijp}, QJK^t_{jkp}, UKJ^t_{kjpq}, GJJ^t_{jj'p}, TJI^t_{jip}, PJF^t_{jfp}, PQ^t_{ip}, INV^t_{jp}, BS_{jp}, RE^t_{kpq}, PR^t_{kpq} \geqslant 0, \quad \forall k,j,j',p,q,t. \tag{37}$$

5. Computational results

To assess the performance of the IFRLND model, several numerical experiments are implemented and the related results are reported in this section. To this aim, the characteristics of six test problems are demonstrated in Table 2, in such a way that the sizes are selected in the range of test problems in the recent literature (e.g. [29,35,54]). Other parameters of test problems are generated randomly using uniform distributions specified in Table 3. In the next section, the verification of mathematical model and sensitivity analysis and are presented. In this paper, the presented model is solved by commercial software GAMS 22.2 using CPLEX solver.

It is assumed that the number of price levels for buying used products ($|L|$), quality levels for used products ($|Q|$), and capacity levels for facilities ($|N|$) are equal to 4, 3 and 4, respectively for all problem instances. Additionally, average recovery and redistribution fractions are set in such a way that the more the quality level, the more these fractions. It is worth mentioning here that due to economy of scale, cost of capacity level has not a linear relation with capacity level. That is, the more capacity level is, the less the cost of capacity for a unit of product. This fact is illustrated by Fig. 6 for example.

The optimal solutions of test problems are reported in Table 4. In this table, the second column shows the optimal values of objective functions of tests. Moreover, percentages of the used products collecting from customer zones for each type of quality in each time period are reported in the horizontal rows. It should be maintained that these values are average percentage of the used products for all customer zones and all kind of products. As explained in Section 4.2.6.1, there are $|Q|$ return types differentiated with respect to their quality in such way that type 1 and type Q returns have the highest and lowest quality, respectively. Thus, you see from results that $q = 1$and $q = 3$ have the maximum and minimum percentage of returns from customer zones, respectively.

Table 2
Test problems' sizes.

Test problems No.	No. of potential production/ recovery centers	No. of potential distribution/ collection centers	No. of customer zones	No. of disposal centers	No. of types of product	No. of time periods
1	2	3	4	1	3	4
2	3	6	6	1	3	4
3	5	10	10	2	3	6
4	5	15	15	2	3	8
5	10	20	20	3	4	8
6	10	30	30	3	4	10

Table 3
The values of the parameters used in the test problems.

Parameters	Range	Parameters	Range
D^t_{kp}	~Uniform(2100, 4200)	DC_{fp}	~Uniform (3, 5)
R^t_{kpq}	~Uniform(600, 1500)	$CX^t_{ij}CQ^t_{jk}CU^t_{kj}CT^t_{ji}CG^t_{jj'}CP^t_{jf}$	~Uniform (2, 4)
FW_i	~Uniform (450000, 550000)	CWM_{ipn}	~Uniform (24000, 35000)
FY_j	~Uniform (170000, 210000)	CWR_{ipn}	~Uniform (20000, 26000)
FZ_j	~Uniform (170000, 210000)	$CYDC_{jpn}$	~Uniform (18000, 26000)
SC_j	~Uniform (170000, 210000)	$CZCL_{jpn}$	~Uniform (12000, 20900)
PC_{ip}	~Uniform (90, 100)	$CAPWM_{ipn}$	~Uniform (10400, 19500)
RC_{ip}	~Uniform (8, 14)	$CAPWR_{ipn}$	~Uniform (10400, 17550)
H_{jp}	~Uniform (5, 8)	$CAPMAXW_i$	~Uniform (100000, 140000)
OC_{jp}	~Uniform (4, 8)	$CAPYDC_{jpn}$	~Uniform (7800, 13000)
CC_{jp}	~Uniform (7, 12)	$CAPZCL_{jpn}$	~Uniform (5200, 10400)
CPR_{jp}	~Uniform (5, 8)	$CAPMAX_j$	~Uniform (60000, 100000)

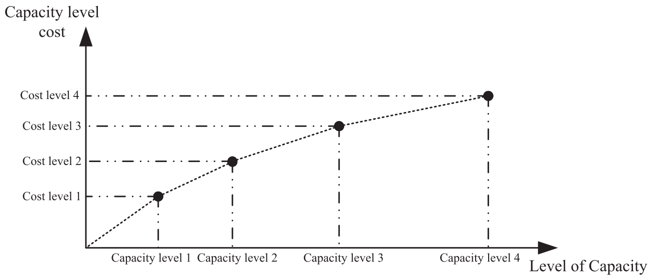

Fig. 6. Relation between levels of capacity and capacity cost.

Table 4
The optimal values of objective functions and percentage of the returned products.

Percentage of Returned products																
Period:		$t = 1$			$t = 2$			$t = 3$			$t = 4$			$t = 5$		
Test	Objective Function	$q = 1$	$q = 2$	$q = 3$	$q = 1$	$q = 2$	$q = 3$	$q = 1$	$q = 2$	$q = 3$	$q = 1$	$q = 2$	$q = 3$	$q = 1$	$q = 2$	$q = 3$
Test1	15821690	100%	66.7%	0%	100%	66.7%	0%	100%	66.7%	0%	100%	66.7%	0%	–	–	–
Test2	23874230	100%	77.7%	0%	100%	76.9%	0%	90.1%	77.4%	0%	100%	78.9%	0%	–	–	–
Test3	42747560	100%	100%	0%	100%	100%	0%	100%	100%	0%	100%	100%	0%	100%	100%	0%
Test4	80821360	78.8%	75.3%	75%	92.6%	76.6%	68.1%	87.5%	74.5%	70.7%	76.2%	75.7%	70.8%	86.9%	81.8%	80.8%
Test5	98298980	82.9%	81.3%	80%	84.8%	83.4%	82%	78.5%	78.4%	72.2%	83.7%	83.6%	83.5%	85.8%	82.5%	85.8%
Test6	143646000	85.7%	79.4%	78.6%	85.7%	83.9%	75.9%	82.5%	80.3%	79%	82.7%	79.7%	79.6%	86.8%	85.3%	85%
Period:		$t = 6$			$t = 7$			$t = 8$			$t = 9$			$t = 10$		
Test		$q = 1$	$q = 2$	$q = 3$	$q = 1$	$q = 2$	$q = 3$	$q = 1$	$q = 2$	$q = 3$	$q = 1$	$q = 2$	$q = 3$	$q = 1$	$q = 2$	$q = 3$
Test1		––	–	–	–	–	–	––	–	–	–	–	–	–	–	–
Test2		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Test3		100%	100%	0%	–	–	–	–	–	–	–	–	–	–	–	–
Test4		81.4%	79.2%	74.2%	89.8%	84.3%	64.9%	80.8%	82.0%	64.2%	–	–	–	–	–	–
Test5		82.2%	82.7%	82.0%	84.2%	80.9%	73.6%	85.7%	82.9%	76.6%	–	–	–	–	–	–
Test6		85%	82.9%	75.3%	85.5%	84.2%	80.3%	87.4%	84.6%	87.4%	83.8%	82.3%	79.6%	88.6%	84.6%	80.8%

6. Sensitivity analysis

To illustrate the applicability of the proposed IFRLND model, sensitivity analysis is performed in three subsections: cost analysis, dynamic pricing analysis, and model linearization analysis. In the first subsection, a cost analysis on three important logistics costs of the IFRLN is conducted to validate the model. In the next subsection, the impact of dynamic pricing on the IFRLND model is studied. And the final subsection investigates the effect of linearization of the model on objective functions that is explained in detail in Section 4.2.6.1.

6.1. Cost analysis

In order to validate the mathematical IFRLND model, the sensitivity analysis is conducted on three substantial logistics costs, namely recovery, repair, and transportation costs in this section. Duo to the fact pricing of the used products is influenced by these costs, changing these costs has effect on the amounts of returned products from customer zones. These changes are exerted by multiplying some constant coefficients to these costs. By doing so, the sensitivity of amounts of returned products from customer zones to these costs is examined. The Fig. 7 gives percentages of the returned products for different change coefficients of recovery cost for test problem 1, 3 and 5. It must be mentioned that these percentages are the average percentages of all types of returned products for all customer zones and period times for each quality level.

As illustrated in Fig. 7, with increase in recovery cost, percentages of the returned products will decrease to the extent that these returns are zero. For instance, assuming change coefficient of recovery cost equals to 10 for test problem 1 and 5, there are not any used products returning from customer zones. In other words, it is not quite economical to acquire returned products from customers in the RLN. This means that we have only a FLN, as a traditional supply chain. This analysis is done for repair and transportation costs as Figs. 8 and 9 illustrate for test problems 1, 3 and 5.

Same as analysis for recovery cost, increasing repair and transportation costs lead to having no returns from customer zones because collecting used products cannot be economically reasonable, as illustrated in Figs. 8 and 9. It is noteworthy to mention that according to Section 4.2.6.1 quality level 1 has the highest quality among other levels of quality; therefore, percentage of returned products having this quality level should be highest. This result is reflected in Figs. 7–9. As explained in the model formulation, the amount of retuned products is dependent upon the acquisition price determined by the IFRLND model. Furthermore, when costs are increased, the acquisition price for returned products will be decreased to the extent that we do not collect any used products from customer zones. The main cause is that the IFRLND model is a cost-based model.

6.2. Dynamic pricing analysis

In this subsection, the impact of dynamic pricing on the IFRLND model is investigated. Fig. 10 is drawn for the test problem 3 and shows changes of acquisition price for customer zone 1 returning the used product 1 with different quality levels at different time periods.

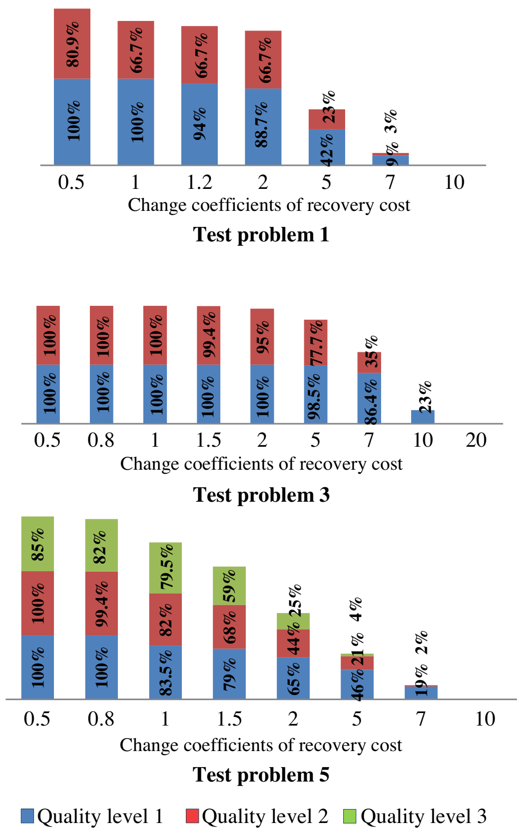

Fig. 7. Percentages of the returned products for different change coefficients of recovery cost.

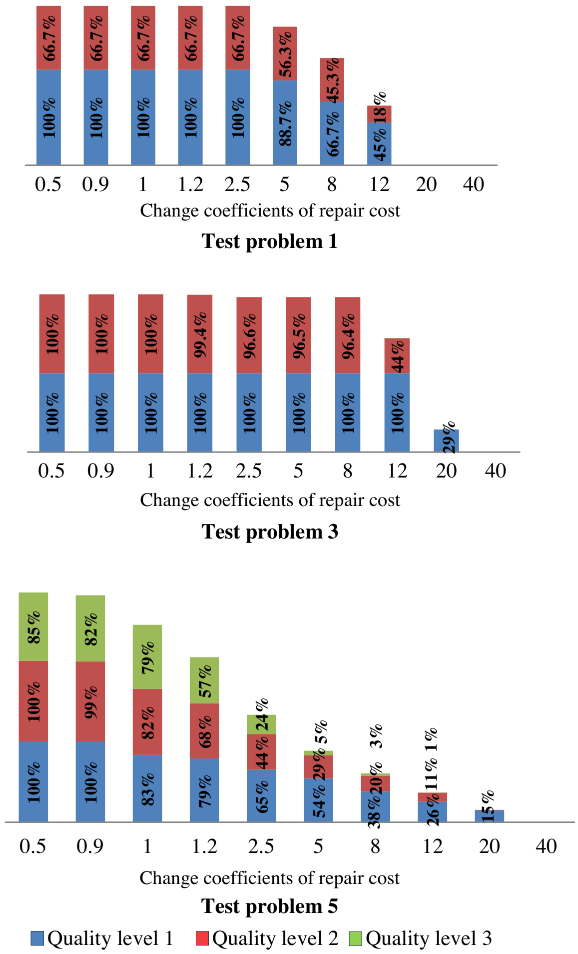

Fig. 8. Percentages of the returned products for different change coefficients of repair cost.

One important point should mention that it is possible that some supply chain networks based on their business conditions want to prevent their prices from dramatic changes. Hence, in this condition, constraint (38) can be added to the IFRLND model. In this constraint, $\bar{P}$ is possible maximum change in acquisition prices between subsequent time periods.

$$|PR^{t}_{kpq} - PR^{t-1}_{kpq}| \leqslant \bar{P}, \quad \forall k, p, q, t. \tag{38}$$

A comparison between two cases is made. In the first case, values of optimal objective functions of test problems are calculated when acquisition prices for used products are dynamic and could be different in each time period. In the next case, these calculations are done when acquisition prices for used products should be the same for all of the time periods, which is named static pricing.

In order to have static pricing for all time periods, the following constraint should be added to the defined IFRLND problem. This constraint states that for each kind of used product with definite quality level from each customer zone, the acquisition price should be the same in different time periods. By defining this constraint, we do not need to model a non-dynamic IFRLND problem, separately.

$$PR^{t'}_{kpq} = PR^{t}_{kpq}, \quad \forall k, p, q, t, t'. \tag{39}$$

It is evident from Fig. 11 when the size of test problems is increased, and we have a real-case IFRLND problem, the effect of assuming dynamic pricing is quite highlighted. It is clearly demonstrated that difference between two pricing approaches will be increased as the size of the problems are increased. This difference is reflected in the dynamic pricing that the optimal values of objective functions are decreased in compared with the static pricing.

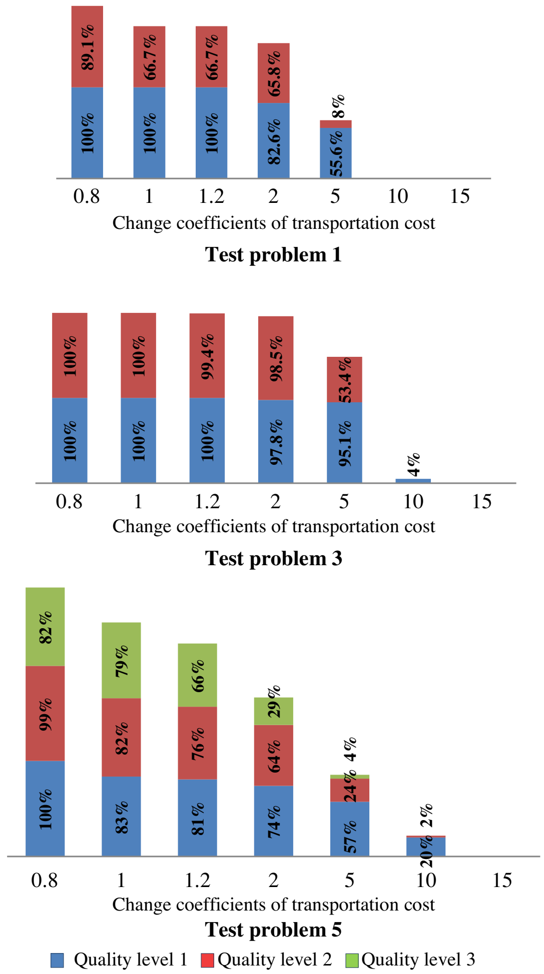

Fig. 9. Percentages of the returned products for different change coefficients of transportation cost.

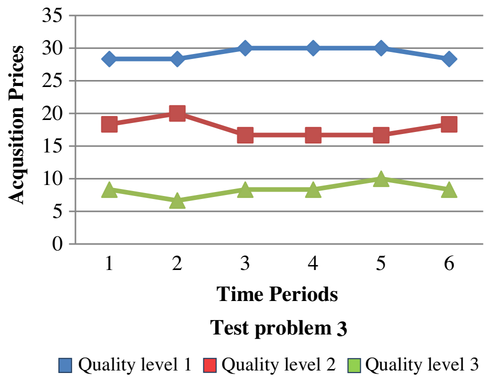

Fig. 10. Acquisition price changes in different time periods.

6.3. Model linearization analysis

In this subsection, the effect of linearization of the IFRLND model with defining discrete acquisition price levels for the returned products is studied. To study this issue, the amount of objective functions and the percentage of used products returning from customer zones are calculated when the levels of acquisition price are increased.

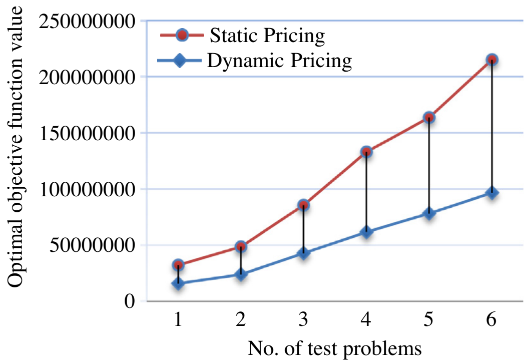

Fig. 11. Objective function values for different test problem sets in static and dynamic pricing.

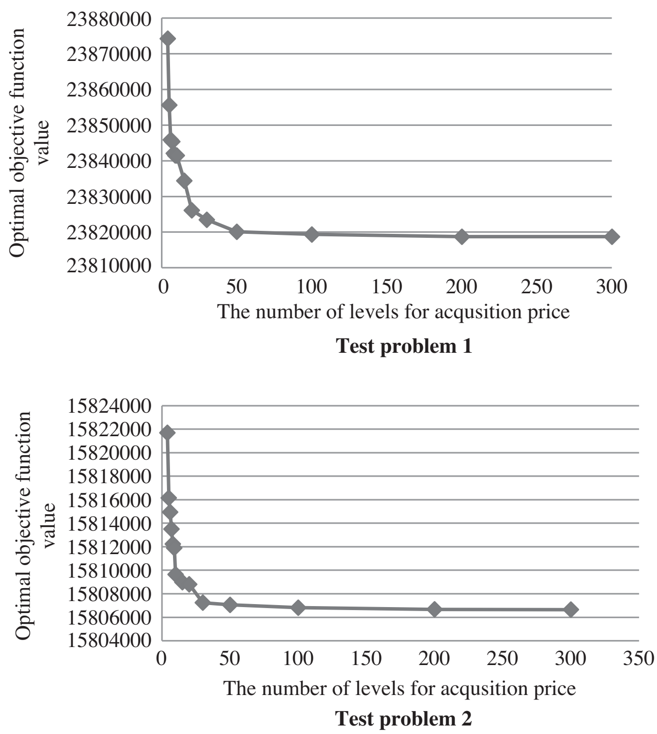

Fig. 12. Optimal objective function values for different number of levels for acquisition price.

As illustrated in Fig. 12, this kind of linearization does not have a considerable impact on the amount of objective functions after considering large enough levels for acquisition prices.

To linearize the IFRLND model, predetermined levels of acquisition price for used products are set based on the uniform distribution. In this section, it is shown that this kind of linearization has not a considerable error in optimal values of objective functions. To this end, the optimal values of objective functions of tests 1 and 2 are calculated when the number of levels for acquisition price is increased. As Fig. 12 illustrated, after a special level for the number of acquisition prices, the optimal value of objective functions does not change significantly and tends to a constant value. This optimal value of objective function is named the optimal objective function with minimum error ($OF_{\text{min-error}}$). The difference between the optimal value of objective function considering four acquisition price levels ($OF_{\text{4-price level}}$) and the optimal objective function with minimum error is called linearization error. The percentage of linearization error is calculated by the following equation:

$$\%\ \text{Linearization error} = \frac{(OF_{\text{min-error}} - OF_{\text{4-price levels}})}{OF_{\text{min-error}}} \times 100\%. \tag{40}$$

For example, the percentage of linearization error for test 1 and 2 are equal to 0.23% and 0.095%, respectively. These percentages of error are quite negligible.

7. Conclusions

In this paper, a novel mathematical programming framework is proposed for multi-period, multi-product, multi-stage and capacitated IFRLND problem to minimize the logistics costs. Moreover, the defined network is designed based on push–pull strategy in such a way that the periodic review inventory policy is used by the distribution centers in which the inventory levels are reviewed at certain intervals and then the appropriate orders are placed after each review. In addition to having hybrid processing facilities combining distribution and collection centers at same locations, there exist transshipments between these facilities in this network. Due to the environmental protection and the remaining economical value in the used products, returning these products is the key part of the RLN. Therefore, the major contribution of this research lies in determining acquisition price for these valuable products according to their quality level and based on this determined price, it calculates the percentage of potential returned products as well. To reduce the complexity of the proposed model from turning to a MINLP model, the model is linearized by dividing the acquisition prices of returned products into discrete levels.

The proposed IFRLND model is solved by CPLEX. In addition, numerical examples are performed to analyze and validate the model. Computational results demonstrate the efficiency and effectiveness of the presented model. The results of our paper indicate that dynamic pricing approach leads to obtaining a lower optimal total costs than static pricing one. Furthermore, by assuming discrete levels for acquisition price, we turn the MINLP model into MILP one. This kind of linearization does not have a considerable impact on the amount of optimal objective function after considering large enough levels for acquisition price. Hence, taking into account this assumption could be reasonable and efficient.

As this paper is a pioneering one that introduces a location-allocation-pricing model in the IFRLN configuration, there are many opportunities for future research. First, time complexity is not addressed in this paper; however, since the computational time increases significantly when the size of problem increases. Therefore, developing efficient exact or heuristic solution methods is a need in this area. Additionally, uncertainty is one of the important problems in logistics and supply chain management. Thus, it is worthwhile to take into account uncertainty of parameters such as demand and return. Besides minimizing the costs, other objective functions such as responsiveness could be considered in designing the IFRLN. Also, to have a sustainable logistics network, it is essential to incorporate the social and environmental considerations into logistics network design problem. We hope this line of research will gain attention from the researchers in the near future.

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