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A developed nonlinear model for cross-docking supply chain network design with possibility of linking between cross-docks

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Abstract
This paper studies location-allocation and transportation problem in cross-docking distribution networks that consists of suppliers, cross-docks and plants. A developed mixed-integer nonlinear model is proposed for a post-distribution cross-docking strategy with multi cross-docks and products that cross-docks can be connected. The objective function is to minimize the total cost comprising the cost of established cross-docks and transportation cost. For obtaining this model, at first two models are introduced and compared with each other by solving five short simulated problems (basic nonlinear model 1 and nonlinear model 2 with the possibility of connections between cross-docks). Results indicate that the total cost is decreased when the connection between cross-docks exists. So, model 2 is more efficient and suitable than the basic model. Then, in the following, consolidation of plant orders is added to model 2 and the developed model is formulated. Finally, some problems with different sizes are generated randomly and solved by GAMS software. Computational results show that the developed model is suitable to solve the location-allocation and transportation problem in cross-docking distribution networks.
Keywords: Cross-docking, location-allocation, transportation problem, consolidation**.**

1-Introduction

Cross-docking is a distribution strategy in which the less-than-truckload shipments can be consolidated into full truckloads after arriving at cross-docks and without long-term storage (Buijs et al. 2014). Cross-docking reduces the transportation cost and the inventory holding cost by minimizing or even eliminating order picking and storage activity (Van Belle et al. 2012).

Subject to decision levels in a making decision environment, cross-docking models are classified into the operational, tactical, and strategic levels (Agustina et al. 2010).

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Scheduling, dock door assignment, transshipment problem, and vehicle routing are discussed and modeled at the operational level generally. For tactical and strategic level, researches are mainly related to layout and network design of cross-docking respectively.

Cross-docking network design includes some problems such as the determination of the number and location of cross-docks, the number of vehicles, product flow, and allocation of cross-docks to original nodes (suppliers) and destination nodes (customers).

In this research, a cross-docking distribution network is developed by linking between cross-docks and using variable covering radius for them. So, for obtaining this goal, a nonlinear location-allocation model is formulated for distributing consolidated multi-products from suppliers to customers via cross-docks.

The remainder of this paper is organized as follows: Section 2 reviews the literature on the cross-docking problem and various algorithms to solve it. Section 3 provides a brief definition of the problem and its assumptions. Section 4 represents two models (basic model 1 and model 2) and in section 5 for comparing the models, some simulated problems are generated and solved. Section 6 expresses a developed model and then section 7 shows the computational results of the model. Finally, section 8 concludes the paper and indicates future research directions.

2-Literature review

There are many kinds of research about the cross-docking problem and also several literature reviews about this subject. Concerning three decision-making levels of operational, tactical, and strategic, the following articles play an important role to review a lot of papers about cross-docking models. Agustina et al. (2010), Belle et al. (2012), Buijs et al. (2014), and Sheikholeslam and Emamian (2016) provided a literature review of cross-docking models in all of the decision-making levels. Boysen and Fliedner (2010) and Ladier and Alpan (2016) studied researches of cross-docking models only at the operational level.

According to the location-allocation and transportation problem in the cross-docking supply chain, the following articles are more similar to this paper. A first paper about the location of cross-docks was written by Sung and Song (2003). The authors presented an integer programming model to determine the location of cross-docks and the number of vehicles. The problem is NP-hard and a tabu search-based algorithm is proposed to solve the model. Jayaraman and Ross (2003) proposed an integer programming model in which goods are transported from a central plant to one or more distribution centers and then moved to the customers via cross-docks. Gumus and Bookbinder (2004) considered direct shipments and multiple products and provided a mixed-integer programming model. Sung and Yang (2008) extended the model of Sung and Song (2003) and improved the tabu search algorithm. Bachlaus et al. (2008) studied a multi-echelon supply chain network to optimize the number and location of suppliers, plants, distribution centers, cross-docks, and also the material flow throughout the supply chain. For achieving this goal, they proposed a multi-objective optimization model that minimizes the total cost and maximizes the plant and volume flexibility. Finally, for solving the model, a variant of particle swarm optimization was presented. Ross and Jayaraman (2008) addressed the cross-docking location-distribution problem and examined the results of two new heuristic solutions (including TABU-SA and RESCALE-SA). They concluded that integrating simulated annealing with tabu search improves the results and needs less CPU time.

Yan and Tang (2009) represented analytical models for distribution strategies and compared the cost of pre-distribution and post-distribution cross-docking with the cost of a traditional distribution center system. In pre-distribution cross-docking, the preparation and sorting happen at the suppliers because they know the order quantities for each customer (destination nodes). But in post-distribution cross-docking, cross-docks are responsible for the preparation and sorting and the operation cost is increased at the cross-dock. The results of their study show that pre-distribution cross-docking is preferred when the supply lead time is short and customer demand is stable. However, post distribution cross-docking is preferred when the demand is uncertain, the supply lead time is long and the number of destination nodes increases.

Musa et al. (2010) presented a model that is very similar to the model of Sung and Song (2003) and proposed an ant colony optimization to solve the problem. Marjani et al (2011) addressed the cross-docking distribution planning problem with linking between cross docks and presented a bi-objective mixed-integer model for minimizing total costs and tardiness, simultaneously. They applied a hybrid metaheuristic procedure (Variable Neighbourhood Search (VNS), Tabu Search (TS), and Simulated Annealing (SA)) to solve the problem. Ma et al (2011) formulated an Integer linear model to distribute a single product from suppliers to customers directly or via cross docks. They considered a new shipment consolidation and time windows in the model and minimized the total cost including transportation cost and inventory cost. Finally, the genetic algorithm was designed for solving the model. Javanmard et al (2014) studied multi-product distribution planning in a cross-docking network. At first, they presented a mixed-integer linear model minimizing the holding and transportation cost. Then, an efficient heuristic procedure was offered to obtain an initial solution and finally, the imperialist competitive algorithm was applied to improve the solution.

Hosseini et al (2014) developed an integer linear model for a transportation problem with the direct shipment, cross-docking, and milk run strategies. In the end, a hybrid of harmony search (HS) and simulated annealing (SA) algorithm was suggested for solving the problem. The results demonstrated that the solving approach is better than GAMS/CPLEX because of reducing both the total transportation cost and computational time for large-size problems. Seyedhoseini et al. (2015) proposed a mixed-integer model to optimize the cross-docks network design. The goal of this paper is to minimize the total transportation and operating costs with a direct connection between cross-docks. The model combines queuing theory with a network of cross-docks and customers to explain the operations of indoor and outdoor trucks.

Yu et al. (2015) formulated an integer programming model to solve a multi-period cross-docking distribution problem. The author considered multiple products, consolidation of customer orders, and time windows. The objective function of the model is to minimize the transportation cost, inventory cost, and penalty cost, simultaneously. They showed that the problem is NP-complete and developed a particle swarm optimization algorithm with multiple social learning terms for solving it. Goodarzi and Zegordi (2017) studied a location and transportation problem in a cross-docking network with several suppliers, cross-docks, and assembly plants nominated as customers. Also, for eliminating unnecessary stops at cross-docks, direct shipment is allowable in addition to indirect shipment via cross-docks. Finally, a mixed-integer programming model was proposed to optimize the location of the cross-docks and allocation of suppliers and plants to them. Behnamian et al. (2018) proposed a two-phased programming model for solving a location-allocation and scheduling of inbound and outbound trucks problem. In the first stage, an integer programming model is formulated to obtain the best location of cross-docks and also the best allocation of cross-docks to suppliers and customers. In the second stage, a mixed-integer programming model is proposed to solve the scheduling of inbound and outbound trucks problem. For solving the above-mentioned problem, at first, the results of several meta-heuristic algorithms are compared and finally, simulated annealing is selected as the best algorithm.

In this paper cross-docks location-allocation problem with multi-product has been considered where the primary goal is to develop a model to answer the following key questions:

(1) Where cross-docks should be located?
(2) Which cross-docks can be connected?
(3) What is the optimum flow of products between nodes?
(4) What is the optimum number of trucks in each route?

3-Problem statement

This paper considers a multi-product, three-echelon cross-docking supply chain network including some suppliers, cross-docks, and plants (as customers). This cross-docking network uses the post-distribution strategy because the exact demand of plants is unknown at suppliers and should be determined at cross-docks. So, the cross-docks can be connected for compensating their shortages and satisfying the demands of their customers (plants) without any connections with suppliers again. Also, the following assumptions are considered:

(1) The products are transported from suppliers to plants via at least one cross-dock.
(2) Each supplier can be allocated to one or several cross-docks to transfer one or several types of various products.
(3) Each plant is allocated to only one cross-dock.
(4) The cross-docks have their covering radius to serve the plants.
(5) The cross-docks can connect (the connection between cross-docks).
(6) The cross-docks never keep any inventories which means that the total quantity of products transported from suppliers should be equal to the total amount that is received by plants.

With relation to the abovementioned assumptions, a sample of cross-docking networks with 3 suppliers, 3 cross-docks, 5 plants and connections between cross-docks has been shown in figure 1.

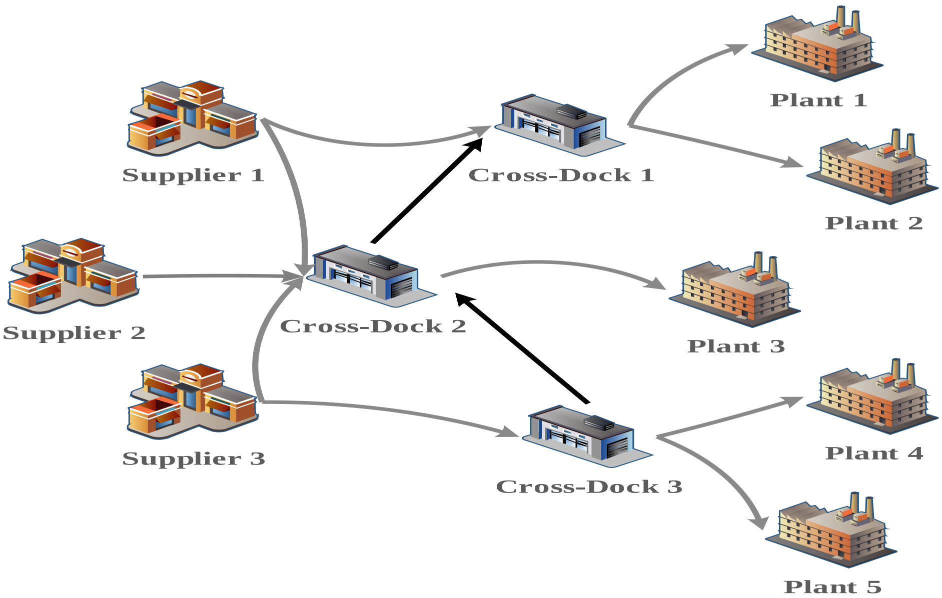

Fig 1. Three-echelon cross-docking network with connections between cross-docks

3-1-Mathematical modelling

The sets, parameters, and variables employed in the models are defined as follows:

Sets

I	The set of suppliers, $i = 1,\ldots,I$
J	The set of cross-docks, $j = 1,\ldots,J$
K	The set of plants, $k = 1,\ldots,K$
L	The set of product families, $l = 1,\ldots,L$

Parameters

F_j	Fixed cost of establishing cross-dock j
c_{ij}	Transportation cost of per unit product transferred from supplier i to cross-dock j
$c_{jj'}$	Transportation cost of per unit product transferred from cross-dock j to cross-dock j' $(j \neq j')$

c_{jk} Transportation cost of per unit product transferred from cross-dock j to plant k

u_j Capacity of cross-dock j

d_{kl} The demand of plant k for product l

h The minimum amount of transported product from each supplier to each cross-dock

Continuous variables

p_{ijl} The amount of product l transferred from supplier i to cross-dock j

$r_{jj'l}$ The amount of product l transferred from cross-dock j to cross-dock j' $(j \neq j')$

Binary variables

z_j 1 if cross-dock j is to be established and 0 otherwise

y_{ij} 1 if the supplier i is assigned to cross-dock j and 0 otherwise

y_{jk} 1 if the plant k is assigned to cross-dock j and 0 otherwise

b_{jk} 1 if the plant k can be covered by cross-dock j (the distance between cross-dock j and plant k is less than covering radius) and 0 otherwise.

3-1-1- Basic nonlinear model (model 1)

- **Objective function**

$$Min \sum_{j\in J} F_j z_j + \sum_{i\in I}\sum_{j\in J}\sum_{l\in L} c_{ij}\, p_{ijl} + \sum_{\substack{j\in J\\ j\neq j'}}\sum_{j'\in J}\sum_{l\in L} c_{jj'}\, r_{jj'l} + \sum_{i\in I}\sum_{j\in J}\sum_{l\in L} c_{jk}\, d_{kl}\, y_{jk} \tag{1}$$

The objective function (1) is to minimize the total cost and includes the fixed cost of establishing cross-docks, transportation cost from suppliers to cross-docks, from cross-docks to each other, and from cross-docks to plants.

- **Location-allocation constraints**

$$\sum_{j\in J} z_j \geq 1 \tag{2}$$

$$y_{ij} \leq z_j \qquad \forall i, j \tag{3}$$

$$\sum_{j\in J} y_{ij} \geq 1 \qquad \forall i \tag{4}$$

$$\sum_{j\in J} y_{jk} = 1 \qquad \forall k \tag{5}$$

$$y_{jk} \leq z_j \qquad \forall j, k \tag{6}$$

$$\sum_{j\in J} b_{jk} z_j \geq 1 \qquad \forall k \tag{7}$$

$$y_{jk} \leq b_{jk} \qquad \forall j, k \tag{8}$$

Constraint (2) ensures that at least one cross-dock should be established. Constraint (3) ensures that the allocation of suppliers to a cross-dock can be performed only when the cross-dock was established. Constraint (4) expresses that each supplier can be allocated to one or several cross-docks. Constraint (5) ensures that each plant should be allocated to only one cross-dock. Constraint (6) ensures that each plant can be allocated to a cross-dock if the cross-dock was established. Nonlinear constraint (7) states the coverage of each plant by at least one cross-dock if the corresponding cross-dock was established. Constraint (8) ensures that each plant can be allocated to a cross-dock if that plant was covered by the cross-dock.

- **Constraints of network flows**

$$\sum_{l \in L} p_{ijl} \leq y_{ij}\, u_j \qquad \forall i, j \tag{9}$$

$$h\, y_{ij} \leq \sum_{l \in L} p_{ijl} \qquad \forall i, j \tag{10}$$

$$\sum_{i \in I} p_{ijl} \leq z_j\, u_j \qquad \forall j, l \tag{11}$$

$$\sum_{i \in I} \sum_{j \in J} p_{ijl} = \sum_{k \in K} d_{kl} \qquad \forall l \tag{12}$$

$$\sum_{i \in I} p_{ijl} = \sum_{k \in K} d_{kl}\, y_{jk} \qquad \forall j, l \tag{13}$$

$$p_{ijl} \geq 0 \tag{14}$$

$$z_j, y_{ij}, y_{jk}, b_{jk} \in \{0,1\} \tag{15}$$

Constraint (9) ensures that if a supplier is not allocated to a cross-dock, any products should not be transferred. Constraint (10) ensures that if a supplier is allocated to a cross-dock, at least h unit product should be transferred. Constraint (11) states that an established cross-dock receives each product from all of the suppliers subject to its capacity. Constraint (12) says that the total quantity of each transferred product from suppliers to cross-docks is equal to the overall demand of plants for that product. Constraint (13) states that the total amount of each product transferred from all suppliers to a cross-dock should be equal to the total demand of plants allocated to the cross-dock for that product. Constraints (14) and (15) define continuous and discrete decision variables of the model.

3-1-2- A nonlinear model with considering connections between cross-docks (model 2)

In the previous mentioned model, the cross-docks can't have any connections with each other. In this section, a nonlinear model with the possibility of having connections between cross-docks is presented to decrease the total cost.

$$Min \sum_{j \in J} F_j z_j + \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} c_{ij} \; p_{ijl} + \sum_{\substack{j \in J \\ j \neq j'}} \sum_{j' \in J} \sum_{l \in L} c_{jj'} \, r_{jj'l} + \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} c_{jk} \, d_{kl} \, y_{jk} \quad (16)$$

$$st: \; \sum_{j \in J} z_j \geq 1 \quad (17)$$

$$y_{ij} \leq z_j \qquad \forall i, j \quad (18)$$

$$\sum_{j \in J} y_{ij} \geq 1 \qquad \forall i \quad (19)$$

$$\sum_{j \in J} y_{jk} = 1 \qquad \forall k \quad (20)$$

$$y_{jk} \leq z_j \qquad \forall j, k \quad (21)$$

$$\sum_{j \in J} b_{jk} z_j \geq 1 \qquad \forall k \quad (22)$$

$$y_{jk} \leq b_{jk} \qquad \forall j, k \quad (23)$$

$$\sum_{l \in L} p_{ijl} \leq y_{ij} \, u_j \qquad \forall i, j \quad (24)$$

$$h \, y_{ij} \leq \sum_{l \in L} p_{ijl} \qquad \forall i, j \quad (25)$$

$$\sum_{i \in I} p_{ijl} + \sum_{j' \in J} r_{j'jl} \leq z_j u_j \qquad \forall j, l, \; j \neq j' \quad (26)$$

$$\sum_{i \in I} \sum_{j \in J} p_{ijl} = \sum_{k \in K} d_{kl} \qquad \forall l \quad (27)$$

$$\sum_{i \in I} p_{ijl} - \sum_{k \in K} d_{kl} \, y_{jk} = \sum_{j' \in J} r_{jj'l} - \sum_{j' \in J} r_{j'jl} \qquad \forall j, l, \; j \neq j' \quad (28)$$

$$p_{ijl}, r_{jj'l} \geq 0 \quad (29)$$

$$z_j, y_{ij}, y_{jk}, b_{jk} \in \{0, 1\} \quad (30)$$

This model is different from the basic model in objective function and constraints (26), (28). In the objective function, the transportation cost from cross-docks to each other has been added. Constraint (26) ensures that an established cross-dock receives each product from all of the suppliers and other cross-docks subject to its capacity. Constraint (28) ensures the connection between cross-docks. If the total amount of each product transferred from all suppliers to a cross-dock is less than the total demand of plants allocated to the cross-dock for that product, so the corresponding cross-dock is connected to other cross-docks for compensating its shortage. Also, if the demand of plants allocated to a cross-dock for a kind of product is less than the amount of that product received by the cross-dock, so it delivers the excess product to other cross-docks.

4-Computational results and comparisons

In this section, to evaluate the accuracy of the proposed models 1 and 2 and compare them, some numerical experiments are prepared. These models aim to determine the minimum number of cross-docks among a set of candidate sites, optimum allocation of suppliers and plants to cross-docks, and optimum distribution of products from suppliers to cross-docks. Besides, model 2 obtains the optimum distribution of products between cross-docks to decrease the total cost.

Five test problems are considered and data (parameters) are generated randomly by integer uniform distribution. Finally, the proposed models 1 and 2 are solved by GAMS optimization software and the results are reported in tables 3 and 4. Also, figure 2 depicts the optimum distribution networks of problems (1-4) resulted from solving model 2. In this figure, connections between cross-docks have been demonstrated by dark arrows.

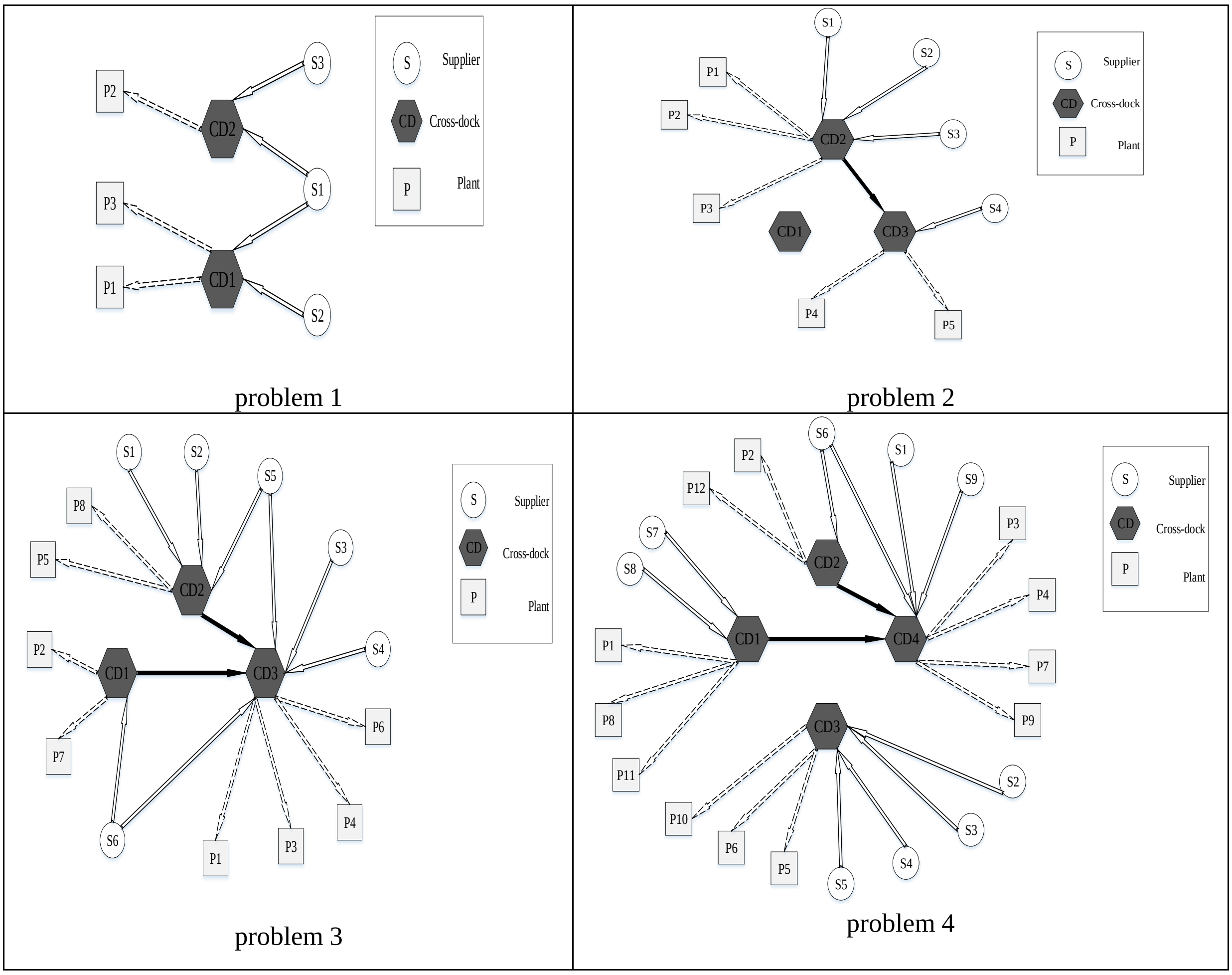

Fig. 2. The optimum distribution networks of problems (1-4)

Table 1. Optimization values of simulated problems

		Problem 1	Problem 2	Problem 3	Problem 4	Problem 5
Optimal Objective	Model 1	57050	101032	387694	770134	3964024
	Model 2	57050	100493	385059	769904	3964024

According to table 1, the optimization objective values of models 1 and 2 in problems 1 and 5 are equal because there aren't any linkages between cross-docks but the total cost of model 2 in problems 2, 3, and 4, which cross-docks are connected, is less than model 1 (basic model). In other words, when cross-docks connect for transferring products, the total cost is decreased.

4-1-A developed nonlinear model with considering connections between cross-docks

In this section, a developed model of model 2 is presented for considering consolidation assumption and obtaining the number of trucks used between nodes. So, integer variables $v_{ij}, v_{jj'}, v_{jk}$ and parameter w are defined as follow,

v_{ij} Number of trucks used between supplier i and cross-dock j

$v_{jj'}$ Number of trucks used between cross-docks j and j' $(j \neq j')$

v_{jk} Number of trucks used between cross-dock j and plant k

w Truck capacity

Subject to the abovementioned definitions, three kinds of below constraints are added to model 2 to take into account the assumption of consolidation.

$$\sum_{l \in L} p_{ijl} \leq w\, v_{ij} \qquad \forall i, j \tag{31}$$

$$\sum_{l \in L} r_{jj'l} \leq w\, v_{jj'} \qquad \forall j, j',\ j \neq j' \tag{32}$$

$$\sum_{l \in L} d_{kl}\, y_{jk} \leq w\, v_{jk} \qquad \forall j, k \tag{33}$$

Also, the objective function of model 2 is changed according to the new variables and finally, the developed model is written as follows,

$$Min\ \sum_{j \in J} F_j z_j + \sum_{i \in I} \sum_{j \in J} c_{ij} v_{ij} + \sum_{\substack{j \in J \\ j \neq j'}} \sum_{j' \in J} c_{jj'} v_{jj'} + \sum_{i \in I} \sum_{j \in J} c_{jk} v_{jk} \tag{34}$$

$$st: \quad Constraints\ (17) - (28)$$

$$Constraints\ (31) - (33)$$

$$p_{ijl}, r_{jj'l} \geq 0 \tag{35}$$

$$z_j, y_{ij}, y_{jk}, b_{jk} \in \{0,1\} \tag{36}$$

$$v_{ij},\ v_{jj'},\ v_{jk}\ are\ integer \tag{37}$$

This model has $\{(I \times J) + J \times (J-1) + (J \times k)\}$ integer variables and constraints more than model 2 which causes spending more time to solve it (assume that there are I suppliers, K plants, and J established cross-docks). This means that metaheuristic methods and some exact algorithms can be used for solving the developed model in large sizes with many nodes.

4-2-Computational results of the developed model

To evaluate the accuracy of the developed model, five test problems are considered in different sizes. Table 2 shows the sizes, optimization objective values, and elapsed time for solving each problem by GAMS software. Parameters values are selected randomly by integer uniform distribution. Reported results in table 2 demonstrate that the execution time of each problem is increased when its sizes are enlarged.

Table 2. Sizes of test problems and their results

Problem No.	No. of suppliers	No. of potential cross-docks	No. of plants	No. of products	Optimization objective	Elapsed Time(second)
1	3	2	4	2	2254	1.048
2	5	2	6	2	3541	1.077
3	8	3	9	3	5926	6.123
4	10	4	12	3	6116	30.930
5	15	5	17	4	8552	1001.098

5- Conclusion and future research

In this paper, to address the location-allocation and distribution problem in the cross-docking networks, first, a basic mixed-integer nonlinear model was formulated. Second, to deal with post-distribution cross-docking strategy, this nonlinear model was changed to consider connections between cross-docks for satisfying products shortage or surplus in them. Third, for evaluating the accuracy and comparing the two mentioned models, five problems in short sizes were simulated randomly and the results were reported. The results demonstrate that the proposed model 2 has optimization objective values equal to or less than model 1. So, model 2 is more efficient than model 1 and can be used to solve the location-allocation and distribution problem of cross-docking networks. Fourth, model 2 was developed by considering constraints of orders consolidation and truck number variables. Finally, some problems in different sizes were generated randomly and the developed model was used to solve them. Results confirmed the accuracy of the developed model.

For future research, the uncertainty can be added to the developed model. For example, plants' demands can't be deterministic in many cases. So, stochastic programming can be used to take into account the uncertain demand. Considering the multi-period cross-docking distribution problem and time window constraint in the model is another recommendation for future research. Another extension is to integrate several problems such as location-allocation and scheduling of inbound and outbound trucks in one approach simultaneously. Also, parameters of cross-docks and trucks capacity can be considered as variables in the model to be optimized and obtained another realistic model. Finally, suitable metaheuristic algorithms can be used or extended for solving the developed model in large sizes.

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