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A DEVELOPED NON-LINEAR MODEL FOR THE LOCATION-ALLOCATION AND TRANSPORTATION PROBLEMS IN A CROSS-DOCKING DISTRIBUTION NETWORK

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The paper addresses the location-allocation and transportation problems in designing a cross-docking distribution network that consists of suppliers, cross-docks, and plants. A developed mixed-integer non-linear model is proposed for a post-distribution cross-docking strategy with multiple cross-docks and products that cross-docks can be connected. The objective function is to minimise the total cost comprising the cost of established cross-docks and transportation costs. To obtain this model, first, two models are introduced and compared (basic non-linear model 1 and non-linear 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 model 1. Then, 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 to evaluate the model accuracy.

Keywords: *cross-docking, location-allocation, transportation problem, mixed-integer non-linear model, consolidation*

1. Introduction

Nowadays, due to competition between companies and complex distribution networks in a supply chain with numerous original and destination nodes, designing a fast and economical distribution network is challenging for researchers. Also, it needs more notice in perishable products supply chains, such as agri-food supply chains, to design a suitable distribution network for preventing waste foods. According to Muriana [1], almost 30% of food products are wasted in all stages of food supply chains globally, and approximately 10% of wasted foods in many developing countries in Asia and Africa are in the distribution stage because of warm and humid climate.

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One of the fast and economical transportation logistics is cross-docking which has been paid attention to more recently. 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 [2–4]. Some companies such as Walmart, Amazon, United Parcel Service (UPS), and Toyota reported successful applications of the cross-docking strategy in their supply chain to achieve competitive advantages by decreasing inventory holding costs and transportation costs [5].

Subject to decision levels in making a decision environment, cross-docking models are classified into operational, tactical, and strategic levels [6]. Scheduling, dock door assignment, transhipment problem, and vehicle routing are generally discussed and modelled at the operational level. For tactical and strategic levels, research is mainly related to the layout and network design of cross-docking, respectively. Cross-docking network design includes problems such as determining 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). When original nodes (suppliers) are far from destination nodes (customers), satisfying customers' demand in the fastest possible time with the least possible cost is a significant problem for companies to obtain a competitive advantage. So, although the cross-docking strategy is a suitable transportation system, it needs to be developed, and linking between cross-docks can be a possible way to deal with the mentioned problem.

The contribution of this research is to develop a cross-docking distribution network by considering cross-dock linking, product consolidation, and using homogeneous trucks simultaneously, which has not been studied before. To obtain this goal, first, two non-linear models (model 1 without cross-docks linking and model 2 with the possibility of cross-docks linking) will be proposed and compared. Finally, a developed non-linear location-allocation model is formulated to design a cross-docking distribution network with the possibility of cross-docks linking for distributing consolidated products by homogeneous trucks in a supply chain. The remainder of this paper is organised 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, to compare 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 operational, tactical, and strategic decision-making levels, the following articles are essential in reviewing many papers about cross-docking models. Agustina et al. [6], Belle et al. [3], Buijs et al. [2], and Sheikholeslam and Emamian [7] provide a literature review of cross-docking models in all of the decision-making levels. Boysen et al. [8] and Ladier and Alpan [4] study cross-docking models only at the operational level.

At this level, truck scheduling and vehicle routing problem has recently brought more attention of such authors as Hasani Goodarzi et al. [9], Theophilus et al. [10], Yu et al. [11], Shahabi-Shahmiri et al. [12], Castellucci et al. [13]. The first paper about the location of cross-docks was written by Sung and Song [14]. The authors present 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 [15] propose an integer programming model in which goods are transported from a central plant to distribution centres and then moved to the customers via cross-docks. Gumus and Bookbinder [16] consider direct shipments and multiple products and provided a mixed-integer programming model. Sung and Yang [17] extend the model of Sung and Song [14] and improve the tabu search algorithm. Bachlaus et al. [18] study a multi-echelon supply chain network to determine the optimal number and location of suppliers, plants, distribution centres, cross-docks, and material flow throughout the supply chain. To achieve this goal, they propose a multi-objective optimisation model that minimises the total cost and maximises the plant and volume flexibility. Finally, for solving the model, a variant of particle swarm optimisation is presented.

Ross and Jayaraman [19] address the cross-docking location-distribution problem and examine the results of two new heuristic solutions (including TABU-SA and RESCALE-SA). They conclude that integrating simulated annealing with tabu search improves the results and needs less CPU time. Yan and Tang [20] develop analytical models for distribution strategies and compare the cost of pre-distribution and post-distribution cross-docking with the cost of a traditional distribution centre 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 will be increased at the cross-dock. Their study shows 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. [21] present a very similar model to the model of Sung and Song [14] and propose an ant colony optimisation to solve the problem.

Marjani et al. [22] address the cross-docking distribution planning problem with linking between cross docks and present a bi-objective mixed-integer model for simultaneously minimising total costs and tardiness. They apply a hybrid metaheuristic procedure (variable neighbourhood search (VNS), tabu search (TS), and simulated annealing (SA)) to solve the problem.

Ma et al. [23] formulate an integer linear model to distribute a single product from suppliers to customers directly or via cross docks. They consider a new shipment consolidation and time windows in the model and minimise the total cost, including transportation and inventory costs. Finally, the genetic algorithm is designed for solving the model. Javanmard et al. [24] study multi-product distribution planning in a cross-docking network. At first, they present a mixed-integer linear model minimising the holding and transportation cost. Then, an efficient heuristic procedure is offered to obtain an initial solution, and finally, the imperialist competitive algorithm is applied to improve the solution. Hosseini et al. [25] develop 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 is suggested for solving the problem. The results demonstrated that the solving approach is better than GAMS/CPLEX due to reducing the total transportation cost and computational time for large-size problems.

Seyedhoseini et al. [26] design a mixed-integer model to optimise the cross-docks network design. This paper aims to minimise 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 tracks. Yu et al. [27] formulate an integer programming model to solve a multi-period cross-docking distribution problem. The author considers multiple products, consolidation of customer orders, and time windows. The model's objective function is to minimise transportation, inventory, and penalty costs simultaneously. They show that the problem is NP-complete and develop a particle swarm optimisation algorithm with multiple social learning terms.

Goodarzi and Zegordi [28] study 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 is proposed to optimise the location of the cross-docks and the allocation of suppliers and plants to them.

Behnamian et al. [29] propose a two-phased programming model for solving a location-allocation and scheduling of inbound and outbound trucks problem. At the first stage, an integer programming model is formulated to obtain the best location of cross-docks and the best allocation of suppliers and customers to established cross-docks. At the second stage, a mixed-integer programming model is proposed to solve the scheduling of inbound and outbound trucks problem. For solving the mentioned problem, the results of several meta-heuristic algorithms are first compared, and finally, simulated annealing is selected as the best algorithm. Bhangu et al. [30] formulate a mixed-integer linear model to design a cross-docking distribution network that decreases transportation costs. Finally, the Lagrangian relaxation method is applied for solving the model. Table 1 shows the similarities and differences between the reviewed literature and the current paper in solving the problem of designing a cross-docking distribution network.

Table 1. Comparing the topics of the current paper with literature

Reference	Modelling					6	7	Vehicles		Method of solution
	1	2	3	4	5			8	9	
[14]	✓								✓	tabu search
[15]	✓									simulated annealing
[16]		✓					✓	✓		exact
[18]	✓				✓					particle swarm optimisation
[21]		✓						✓		ant colony optimisation
[23]		✓		✓			✓	✓		heuristic
[22]		✓		✓	✓	✓				variable neighbourhood search – tabu search – simulated annealing
[25]	✓						✓	✓		harmony search – simulated annealing
[24]		✓		✓				✓		imperialist competitive algorithm
[26]		✓				✓				exact
[27]		✓					✓	✓		particle swarm optimisation
[28]			✓					✓		exact
[29]		✓						✓		simulated annealing
[30]		✓								Lagrangian relaxation
Our study			✓			✓	✓	✓		exact

1 – Integer linear programming, 2 – Mixed-integer linear programming, 3 – Mixed-integer non-linear programming, 4 – dynamic programming, 5 – Multi-objective programming, 6 – Cross-docks linking, 7 – Consolidation, 8 – Homogeneous modelling, 9 – Heterogeneous modelling.

According to Table 1 and the literature review, in designing a cross-docking distribution network, lots of researchers consider homogeneous trucks and products consolidation as a significant activity in a cross-dock, and only two researchers present their study about cross-docks linking. However, none of them uses both in their model simultaneously. So, the clear gap of the current literature is to consider products consolidation, using homogeneous trucks for transhipment, and linking between cross-docks simultaneously. This paper will aim to fill the mentioned gap by introducing a non-linear model for designing a cross-docking distribution network.

In this study, the problem of designing a cross-docking distribution network with multi-product is addressed where the primary goal is to answer the following key questions:

• Where should cross-docks be located? Which candidate distribution centres should be selected as a cross-dock?

• What is the optimum allocation of suppliers and plants to selected cross-docks?

• Can cross-docks linking decrease the total transportation cost, and, if so, which cross-docks are linked?

• What is the optimum flow of products between nodes?

• What is the optimum number of homogeneous trucks in each route?

To answer the abovementioned questions and to design a developed cross-docking distribution network, two models (1 and 2) without and with cross-docks linking will be presented and examined, whether linking between cross-docks can decrease transportation costs. Then, products consolidation and transhipment by using homogeneous trucks will be added to model 2 and formulated a developed model.

3. Problem statement

This paper considers a three-echelon cross-docking supply chain network in which multi-products are transferred from suppliers to plants (as customers) through multiple cross-docks by homogeneous trucks. Cross-docks act as distribution centres without long-term storage, and products are stored only for a short time (less than 24 hours) due to the integration process as referred by literature [6, 3, 9]. It means that in each cross-dock, received multi-products are unloaded from inbound trucks, sorted and consolidated, and loaded immediately into outbound trucks for sending to final destinations. So, inventory variables and related costs are not considered in this study. This cross-docking network uses the post-distribution strategy because the exact demand of plants is unknown in suppliers and should be determined in cross-docks. So, the cross-docks can be linked to compensate for their shortages and satisfy plants' demand allocated to them without connecting to suppliers again.

The purpose of this paper is to develop a cross-docking distribution network in which cross-docks linking, products consolidation, and using homogeneous trucks are considered simultaneously. So, a developed non-linear model that addresses location-allocation and transportation problems for designing a developed cross-docking network will be proposed. The methodology of our research for formulating the developed location-allocation and transportation model to design a cross-docking network is presented as follows:

• a basic location-allocation and transportation model, named model 1, is formulated subject to literature in which there exist no connections between cross-docks;

• the possibility of cross-docks linking will be added to model 1 to create model 2; so, the only difference between models 1 and 2 is the cross-docks linking;

• some problems are simulated and solved by models 1 and 2, and results will be compared to observe whether linking between cross-docks can decrease the total cost (is model 2 more efficient than model 1?);

• model 2 is developed by considering products consolidation and homogeneous trucks to formulate the developed model;

• the developed model will be validated by solving simulated problems with short, medium, and large sizes.

Also, the following assumptions are considered:

• the products are transported from suppliers to plants via at least one cross-dock;

• each supplier can be allocated to one or several cross-docks to transfer one or several types of various products;

• each plant is allocated to only one cross-dock;

• the cross-docks have their covering radius to serve the plants;

• plants' demand should be satisfied;

• the cross-docks can be linked (the connection between cross-docks);

• the cross-docks never keep any inventories, meaning that the total quantity of products transported from suppliers should equal the amount that plants receive.

Concerning the abovementioned assumptions, a sample of cross-docking networks with three suppliers, three cross-docks, five plants, and linking between cross-docks is shown in Fig. 1.

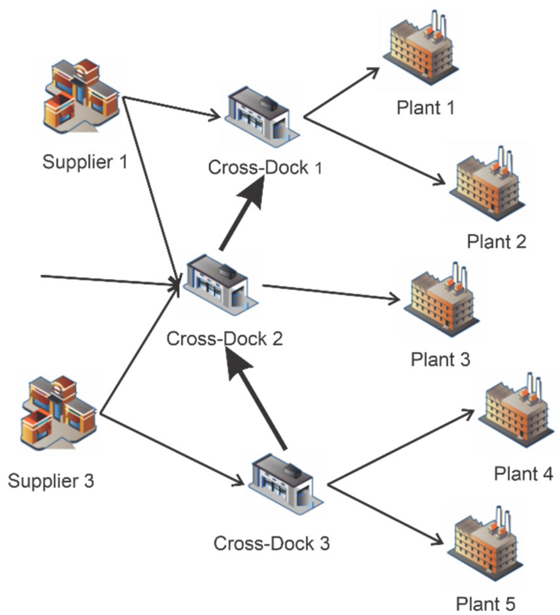

Fig. 1. Three-echelon cross-docking network with linking between cross-docks

Products are transferred from suppliers to plants indirectly through at least one cross-dock, which means no direct shipping from suppliers to plants. Linking between cross-docks is shown by dark arrows. Suppliers 1 and 3 are allocated to more than one cross-dock. Also, each plant is assigned to only one cross-dock. For example, plants 1 and 2 are only allocated to cross-dock 1, and plants 4 and 5 are only assigned to cross--dock 3.

4. Mathematical modelling

In this section, two models are formulated. In model 1, cross-docks linking does not exist, but in model 2, the possibility of cross-docks linking is considered. All models in this paper are non-linear because of coverage constraints. These constraints assure the coverage of each plant by at least one established cross-dock, which is formed by multiplying two binary variables of plant coverage and cross-dock establishment. This kind of coverage constraint has been used in literature.

In the kind of problem under investigation, minimising the total cost, including establishing cross-docks and transportation costs, is the main problem objective used in the literature. So, the objective of the proposed models in this research is to minimise the mentioned total cost.

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

Sets

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

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 $v_{jjcc}jj$
$c_{jj'}$ – 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 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 – equals 1 if cross-dock j is established and 0 otherwise
y_{ij} – equals 1 if the supplier i is assigned to cross-dock j and 0 otherwise
y_{jk} – equals 1 if the plant k is assigned to cross-dock j and 0 otherwise
b_{jk} – equals 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

4.1. A basic non-linear model without considering cross-docks linking (model 1)

In this section, according to the literature, model 1 is formulated for designing a cross-docking distribution network. In this model, cross-docks are located, suppliers and plants are allocated to the established cross-docks, and multi-products are distributed in each route. Also, linking between cross-docks is not allowable. The objective function, location-allocation constraints, and constraints of network flows are explained as follows:

The objective function minimises the total cost and includes the fixed cost of establishing cross-docks, transportation cost from suppliers to cross-docks, and from cross-docks to plants.

$$\min \sum_{j\in J} F_j z_j + \sum_{i\in I}\sum_{j\in J}\sum_{l\in L} c_{ij} p_{ijl} + \sum_{i\in I}\sum_{j\in J}\sum_{l\in L} c_{jk} d_{kl} y_{jk} \tag{1}$$

Location-allocation constraints are as follows

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

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

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

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

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

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

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

Constraint (2) ensures that at least one cross-dock should be established. Constraints (3) and (6) state that suppliers and plants cannot be allocated to a cross-dock that has not been established. Subject to constraint (4), each supplier can be assigned to one or several cross-docks. Constraint (5) ensures that each plant should be allocated to only one cross-dock. Non-linear 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 the cross-dock covers that plant.

Constraints of network flows are given by the following equations

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

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

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

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

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

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

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

Constraint (9) ensures that any products are not transferred if a supplier is not allocated to a cross-dock. Constraint (10) ensures that if a supplier is allocated to a cross-dock, at least h unit product should be sent. Constraint (11) states that an established cross-dock cannot receive a product more than 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 equal the total demand of plants allocated for that product. Constraints (14) and (15) define continuous and discrete decision variables of the model.

4.2. Non-linear model considering the possibility of cross-docks linking (model 2)

In model 1, the cross-docks cannot have any connections with each other. This section presents a non-linear model with the possibility of linking between cross-docks to decrease the total cost. So, model 2 is formulated and improved by adding cross-docks linking as follows:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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 is added. Constraint (26) ensures that an established cross-dock receives each product from all suppliers and other cross-docks subject to its capacity. Constraint (28) ensures the connection between cross-docks. If the total amount of each received product by a cross-dock is less than the total demand of allocated plants, the corresponding cross-dock compensates its shortage by linking to other cross-docks. Also, if the demand of plants allocated to a cross-dock for a kind of product is less than the amount received by the cross-dock, it delivers the excess product to other cross-docks.

5. Computational results and comparisons

In this section, some numerical experiments are prepared to evaluate the accuracy of the proposed models 1 and 2 and to compare them. 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.

Fifteen test problems with short, medium, and large sizes are considered. Their sizes, including the number of suppliers, potential cross-docks, and plants, are presented in Table 2. Table 3 reports the data generated randomly by integer uniform distribution.

Table 2. Sizes of test problems

Problem	No. of suppliers	No. of potential cross-docks	No. of plants	No. of products
1	3	2	3	2
2	4	3	5	2
3	6	3	8	3
4	7	3	10	3
5	9	4	12	3
6	12	4	15	3
7	15	5	20	4
8	22	7	22	4
9	30	10	25	4
10	35	12	30	5
11	37	15	32	5
12	40	17	35	6
13	45	20	38	7
14	50	22	40	8
15	60	25	45	10

Table 3. Sources of random generation of data for test problems (integer uniform)

Problems	Parameters						
	F_j	c_{ijl}	$c_{jj'l}$	c_{jkl}	u_j	d_{kl}	h
1	(1000, 2000)	(100, 200)	(40, 60)	(20, 100)	(200, 300)	(20, 70)	(10, 40)
2	(1200, 2400)	(80, 220)	(30, 50)	(10, 80)	(250, 400)	(30, 100)	(30, 50)
3	(1500, 2500)	(100, 250)	(20, 90)	(40, 120)	(350, 550)	(50, 120)	(20, 30)
4	(500, 1500)	(100, 150)	(50, 120)	(50, 170)	(400, 800)	(20, 80)	(15, 35)
5	(2000, 3000)	(150, 300)	(10, 100)	(25, 140)	(500, 600)	(40, 150)	(40, 70)
6	(1600, 2900)	(90, 280)	(25, 75)	(60, 160)	(800, 1300)	(10, 90)	(25, 35)
7	(3500, 5000)	(250, 400)	(50, 150)	(100, 200)	(600, 900)	(80, 180)	(50, 80)
8	(800, 1400)	(300, 450)	(15, 25)	(250, 450)	(1500, 2000)	(65, 105)	(17, 27)
9	(2200, 3200)	(200, 300)	(100, 200)	(150, 250)	(1000, 2500)	(15, 55)	(35, 45)
10	(2500, 4500)	(230, 470)	(170, 330)	(220, 340)	(2000, 3000)	(75, 135)	(28, 37)
11	(1700, 3500)	(60, 550)	(45, 350)	(70, 400)	(700, 2200)	(85, 110)	(65, 75)
12	(3700, 5700)	(70, 500)	(5, 115)	(80, 650)	(550, 1800)	(25, 45)	(45, 55)
13	(700, 5500)	(120, 320)	(220, 450)	(130, 350)	(1900, 4000)	(100, 200)	(85, 125)
14	(2800, 4800)	(50, 650)	(70, 250)	(35, 550)	(2500, 5000)	(55, 250)	(100, 200)
15	(4500, 6500)	(110, 850)	(35, 135)	(115, 750)	(1700, 3500)	(35, 65)	(47, 68)

The simulated problems are solved by models 1 and 2 in GAMS software using Baron solver, and the results are reported in Tables 4–8. The optimal values of problems 1–3, 5, and 7 for two models are given in Tables 4–7.

Table 4. Optimisation values for simulated problems No. 1 and 2

Variable	Problem No. 1		Problem No. 2	
	Model 1	Model 2	Model 1	Model 2
z_j	$z_1 = z_2 = 1$	$z_1 = z_2 = 1$	$z_2 = z_3 = 1$	$z_2 = z_3 = 1$
y_{ij}	$y_{11} = y_{12} = 1$ $y_{21} = y_{32} = 1$	$y_{11} = y_{12} = 1$ $y_{21} = y_{32} = 1$	$y_{12} = 1$ $y_{22} = y_{23} = 1$ $y_{32} = y_{43} = 1$	$y_{12} = y_{22} = 1$ $y_{32} = y_{43} = 1$
p_{ijl}	$p_{111} = 28$ $p_{122} = 40$ $p_{211} = 105,\ p_{212} = 103$ $p_{321} = 27,\ p_{322} = 1$	$p_{111} = 28$ $p_{121} = 27,\ p_{122} = 13$ $p_{211} = 105,\ p_{212} = 103$ $p_{322} = 28$	$p_{121} = 44$ $p_{221} = 48, = 49$ $p_{321} = 101,\ p_{322} = 230$ $p_{431} = 110,\ p_{432} = 141$	$p_{121} = 44$ $p_{221} = 97$ $p_{321} = 101,\ p_{322} = 230$ $p_{431} = 110,\ p_{432} = 141$
$r_{jj'l}$	–	$r_{jj'l} = 0\ \forall j, j', l$	–	$r_{231} = 49$
y_{jk}	$y_{11} = y_{13} = y_{22} = 1$	$y_{11} = y_{13} = y_{22} = 1$	$y_{21} = y_{22} = y_{23} = 1$ $y_{34} = y_{35} = 1$	$y_{21} = y_{22} = y_{23} = 1$ $y_{34} = y_{35} = 1$
Objective function	57 050	57 050	101 032	100 493

Table 5. Optimisation values for simulated problem No. 3

Variable	Model 1	Model 2
z_j	$z_1 = z_2 = z_3 = 1$	$z_1 = z_2 = z_3 = 1$
y_{ij}	$y_{11} = y_{22} = y_{31} = 1$ $y_{43} = y_{52} = y_{53} = 1$ $y_{61} = y_{63} = 1$	$y_{12} = y_{22} = y_{33} = 1$ $y_{43} = y_{52} = y_{53} = 1$ $y_{61} = y_{63} = 1$
p_{ijl}	$p_{111} = 26$ $p_{221} = 201,\ p_{222} = 174,\ p_{223} = 120$ $p_{311} = 25,\ p_{431} = 25$ $p_{523} = 31,\ p_{531} = 292,\ p_{531} = 215$ $p_{611} = 108,\ p_{612} = 195,\ p_{613} = 204$ $p_{632} = 143,\ p_{633} = 365$	$p_{121} = 25,\ p_{222} = 111,\ p_{223} = 384$ $p_{331} = 25,\ p_{431} = 25$ $p_{521} = 267,\ p_{522} = 228$ $p_{531} = 172,\ p_{533} = 336$ $p_{611} = 43$ $p_{631} = 120,\ p_{632} = 388$
$r_{jj'l}$	–	$r_{211} = 116,\ r_{212} = 195,\ r_{213} = 204$ $r_{231} = 34$
y_{jk}	$y_{12} = y_{17} = 1$ $y_{23} = y_{28} = 1$ $y_{31} = y_{34} = y_{35} = y_{36} = 1$	$y_{12} = y_{17} = 1$ $y_{25} = y_{28} = 1$ $y_{31} = y_{33} = y_{34} = y_{36} = 1$
Objective function	387694	385059

Table 6. Optimisation values for simulated problem No. 5

Variable	Model 1	Model 2
z_j	$z_1 = z_2 = z_3 = z_4 = 1$	$z_1 = z_2 = z_3 = z_4 = 1$
y_{ij}	$y_{14} = y_{23} = y_{33} = y_{43} = y_{53} = 1$ $y_{62} = y_{64} = y_{71} = y_{81} = 1$ $y_{84} = y_{94} = 1$	$y_{14} = y_{23} = y_{33} = 1$ $y_{43} = y_{53} = y_{62} = 1$ $y_{64} = y_{71} = y_{81} = y_{94} = 1$
p_{ijl}	$p_{141} = 47,\ p_{232} = 159,\ p_{233} = 367$ $p_{331} = 165,\ p_{332} = 99,\ p_{431} = 47$ $p_{531} = 47,\ p_{621} = 151,\ p_{622} = 156$ $p_{623} = 186,\ p_{641} = 259,\ p_{642} = 265$ $p_{711} = 308,\ p_{712} = 198$ $p_{812} = 127,\ p_{813} = 332,\ p_{841} = 60$ $p_{942} = 7,\ p_{943} = 445$	$p_{141} = 47,\ p_{232} = 159,\ p_{233} = 367$ $p_{331} = 165,\ p_{332} = 99,\ p_{431} = 47$ $p_{531} = 47,\ p_{621} = 176,\ p_{622} = 156$ $p_{623} = 186,\ p_{641} = 79,\ p_{643} = 445$ $p_{712} = 174,\ p_{713} = 332$ $p_{811} = 343,\ p_{812} = 151$ $p_{941} = 180,\ p_{942} = 344$
$r_{jj'l}$	–	$r_{141} = 35\ ,\ r_{241} = 25$
y_{jk}	$y_{11} = y_{18} = y_{1(11)} = y_{22} = 1$ $y_{2(12)} = y_{35} = y_{36} = y_{3(10)} = 1$ $y_{43} = y_{44} = y_{47} = y_{49} = 1$	$y_{11} = y_{18} = y_{1(11)} = y_{22} = 1$ $y_{2(12)} = y_{35} = y_{36} = y_{3(10)} = 1$ $y_{43} = y_{44} = y_{47} = y_{49} = 1$
Objective function	770 134	769 904

Table 7. Optimisation values for simulated problem No. 7

Variable	Model 1	Model 2
z_j	$z_1 = z_2 = z_3 = z_4 = z_5 = 1$	$z_1 = z_2 = z_3 = z_4 = z_5 = 1$
y_{ij}	$y_{15} = y_{21} = y_{32} = y_{33} = y_{41} = y_{55} = y_{62} = 1$ $y_{71} = y_{81} = y_{91} = y_{(10)4} = y_{(11)4} = y_{(12)3} = 1$ $y_{(13)2} = y_{(14)2} = y_{(14)4}$ $= y_{(15)3} = y_{(15)4} = y_{(15)5} = 1$	$y_{15} = y_{21} = y_{32} = y_{33} = y_{41} = y_{55} = y_{62} = y_{71} = 1$ $y_{81} = y_{91} = y_{(10)4} = y_{(11)4} = y_{(12)3} = y_{(13)2} = 1$ $y_{(14)2} = y_{(14)4} = y_{(15)3} = y_{(15)4} = y_{(15)5} = 1$
p_{ijl}	$p_{151} = 241,\ p_{153} = 35,\ p_{154} = 344$ $p_{212} = 88,\ p_{214} = 759,\ p_{323} = 334$ $p_{324} = 500,\ p_{331} = 116,\ p_{333} = 208$ $p_{334} = 471,\ p_{411} = 93,\ p_{412} = 754 p_{552}$ $= 277,\ p_{553} = 343,\ p_{621} = 50,\ p_{711} = 50$ $p_{811} = 113,\ p_{813} = 734,\ p_{911} = 531$ $p_{(10)41} = 227,\ p_{(10)42} = 330,\ p_{(10)43} = 124$ $p_{(11)41} = 50,\ p_{(12)32} = 510,\ p_{(12)33} = 285$ $p_{(13)21} = 77,\ p_{(13)22} = 465,\ p_{(13)23} = 292$ $p_{(14)21} = 397,\ p_{(14)41} = 183,\ p_{(15)31} = 382$ $p_{(15)42} = 275,\ p_{(15)43} = 406,\ p_{(15)51} = 193$	$p_{151} = 241,\ p_{153} = 35,\ p_{154} = 344,\ p_{212} = 88,$ $p_{214} = 759,\ p_{323} = 334,\ p_{324} = 500,\ p_{331} = 116,$ $p_{333} = 208,\ p_{334} = 471,\ p_{411} = 93,\ p_{412} = 754$ $p_{552} = 277,\ p_{553} = 343,\ p_{621} = 50$ $p_{711} = 50,\ p_{811} = 113,\ p_{813} = 734,\ p_{911} = 531,$ $p_{(10)41} = 227,\ p_{(10)42} = 330,\ p_{(10)43} = 124,$ $p_{(11)41} = 50,\ p_{(12)32} = 510,\ p_{(12)33} = 285$ $p_{(13)21} = 77,\ p_{(13)22} = 465,\ p_{(13)23} = 292,\ p_{(14)21}$ $p_{14(21)} = 397,\ p_{(14)41} = 183$ $p_{(15)31} = 382,\ p_{(15)42} = 275$ $p_{(15)43} = 406,\ p_{15(51)} == 193$
$r_{jj'l}$	–	$r_{jj'l} = 0\ \forall\, j, j', l$
y_{jk}	$y_{11} = y_{14} = y_{18} = y_{1(17)} = y_{1(18)} = y_{1(20)} = 1$ $y_{22} = y_{25} = y_{2(11)} = y_{2(15)}$ $= y_{33} = y_{39} = y_{3(13)} = y_{3(16)} = 1$ $y_{46} = y_{47} = y_{4(10)} = y_{5(12)} = y_{5(14)} = y_{5(19)} = 1$	$y_{11} = y_{14} = y_{18} = y_{1(17)} = y_{1(18)} = y_{1(20)} = 1$ $y_{22} = y_{25} = y_{2(11)} = y_{2(15)} = y_{33} = y_{39}$ $= y_{3(13)} = y_{3(16)} = 1$ $y_{46} = y_{47} = y_{4(10)} = y_{5(12)} = y_{5(14)} = y_{5(19)} = 1$
Objective function	396 4024	396 4024

Table 8. Optimal objectives of models 1 and 2

Problem	Optimal objective		Improvement of the objective function	Cross-docks linking
	Model 1	Model 2		
1	57050	57050	–	–
2	101032	100493	0.53%	(2–3)
3	387694	385059	0.68%	(2–1), (2–3)
4	227670	227670	–	–
5	770134	769904	0.03%	(1–4), (2–4)
6	486610	479828	1.39%	(3–1)
7	3964024	3964024	–	–
8	4429544	4416540	0.29%	(1–6), (4–6), (5–6), (7–6)
9	1302549	1302549	–	–
10	7467484	7467484	–	–

Table 8. Optimal objectives of models 1 and 2

Problem	Optimal objective		Improvement of the objective function	Cross-docks linking
	Model 1	Model 2		
11	2670561	2670561	–	–
12	1517460	1499173	1.21%	(1–2), (2–5), (4–11), (8–3), (10–8), (12–14)
13	10544430	10544430	–	–
14	6043049	6043049	–	–
15	5922821	5908212	0.25%	(4–19), (16–3)

Table 8 shows the results of solving test problems by models 1 and 2. For example, after solving problem 15, the optimal objective of model 2 is 0.25% less than model 1, and cross-docks 4 and 16 are linked to cross-docks 19 and 13, respectively.

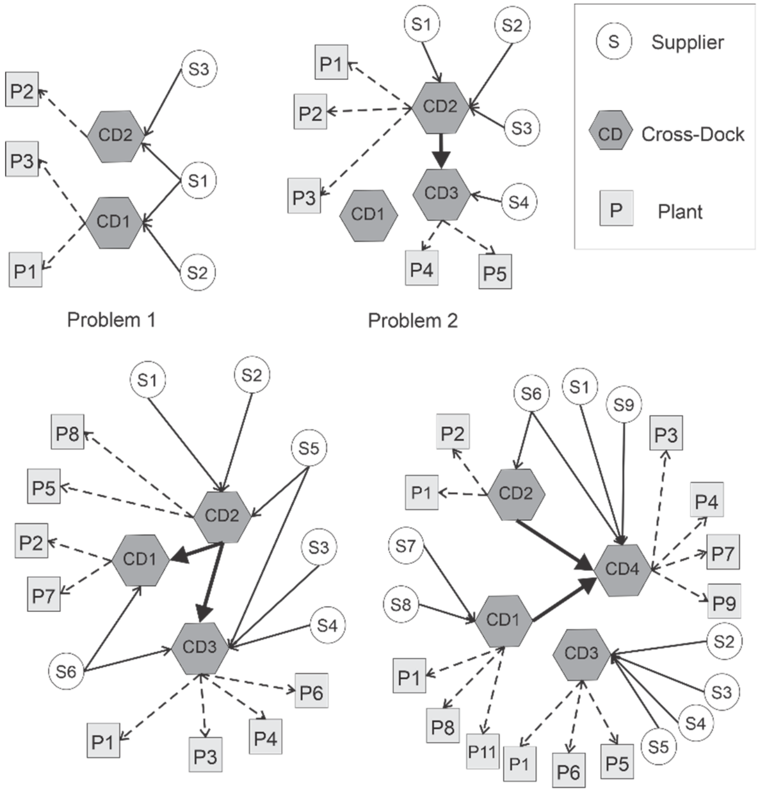

Fig. 2. The optimum distribution networks of problems (1–3, and 5)

The optimal objective values of models 1 and 2 in problems 1, 4, 7 9–11, 13, and 14 are equal because there are not any linkages between cross-docks, but the total cost of model 2 in problems 2, 3, 5, 6, 8, 12 and 15, in 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. These results demonstrated that model 2 is more efficient than model 1 in decreasing the total cost.

Figure 2 shows the optimum distribution networks of problems 1–3, and 5 resulting from solving model 2. In this figure, connections between cross-docks are demonstrated by dark arrows. For example, in the network of problem 5, cross-docks 1 and 2 are linked to cross-dock 4.

6. Developed non-linear model considering the possibility of cross-docks linking and products consolidation with homogeneous trucks

In this section, model 2 is developed by considering product consolidation as the main activity of a cross-dock and transhipment by homogeneous trucks. The novelty and improvement of the developed model rather than other models in the literature is to design a developed cross-docking network in which cross-dock linking possibility, products consolidation, and using homogeneous trucks are considered simultaneously. So, for creating the developed model, integer variables v_{ij}, $v_{jj'}$, v_{jk} and parameters w, c_{ij}, $c_{jj'}$, c_{jk} are defined as follows:

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,
c_{ij} – cost of using a truck for transferring products from supplier i to cross-dock j,
$c_{jj'}$ – cost of using a truck for transferring products from cross-dock j to cross-dock j' ($j \neq j'$),
c_{jk} – cost of using a truck for transferring products from cross-dock j to plant k.

Subject to the abovementioned considerations, three constraints are added to model 2 to consider products consolidation and transhipment by homogeneous trucks

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

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

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

Also, the objective function of model 2 is changed, according to the new variables and cost parameters. Finally, the developed model is formulated as follows

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

s.t.: constraints (17)–(28) and (31)–(33)

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

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

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

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 solving it (assume that there are I suppliers, K plants, and J established cross-docks).

7. Computational results of the developed model

For evaluating the accuracy of the developed model, thirteen test problems are considered in different sizes. Table 9 shows the sizes of the problems, and Table 10 presents parameters that have been selected randomly from an integer uniform distribution.

Table 9. Sizes of test problems

Problem	Number of suppliers	Number of potential cross-docks	Number of plants	Number of products
1	3	2	4	2
2	4	2	5	2
3	5	2	6	2
4	6	3	7	2
5	8	3	9	3
6	10	4	12	3
7	12	4	15	3
8	15	5	17	4
9	17	5	18	4
10	20	5	20	4
11	25	7	20	4
12	28	9	23	5
13	30	10	25	6

Table 10. Sources of random generation of data for test problems (Integer Uniform)

Problem	Parameter							
	F_j	c_{ijl}	$c_{jj'l}$	c_{jkl}	u_j	d_{kl}	h	w
1	(600, 2000)	(200, 300)	(150, 250)	(200, 300)	(550, 700)	(40, 140)	(5, 12)	(15, 20)
2	(3000, 4000)	(220, 470)	(100, 300)	(120, 270)	(1200, 2200)	(120, 230)	(17, 22)	(24, 28)
3	(2500, 3500)	(150, 270)	(200, 350)	(250, 350)	(1500, 3500)	(150, 200)	(12, 17)	(18, 24)
4	(1500, 2500)	(250, 450)	(10, 50)	(150, 250)	(400, 600)	(60, 120)	(10, 15)	(20, 25)
5	(1000, 3700)	(300, 400)	(20, 100)	(170, 370)	(450, 900)	(40, 70)	(15, 25)	(25, 30)
6	(2000, 3000)	(40, 90)	(250, 400)	(100, 220)	(900, 1500)	(50, 90)	(18, 26)	(27, 35)
7	(3200, 5200)	(30, 380)	(40, 90)	(60, 200)	(3000, 4500)	(70, 170)	(24, 28)	(30, 36)
8	(700, 2700)	(70, 420)	(50, 150)	(140, 320)	(3500, 5500)	(30, 80)	(25, 30)	(35, 40)
9	(4000, 7000)	(350, 650)	(300, 450)	(270, 550)	(1100, 5000)	(15, 105)	(10, 20)	(30, 40)
10	(2700, 4200)	(270, 530)	(110, 200)	(90, 420)	(2200, 3200)	(25, 65)	(27, 35)	(37, 45)
11	(500, 1500)	(100, 550)	(80, 350)	(220, 390)	(4000, 6000)	(100, 150)	(35, 45)	(50, 60)
12	(1800, 5500)	(120, 750)	(25, 130)	(110, 650)	(2000, 4000)	(45, 85)	(32, 38)	(40, 48)
13	(6000, 8000)	(180, 800)	(15, 85)	(130, 750)	(2500, 7000)	(35, 75)	(7, 27)	(32, 50)

Table 11 reports the established cross-docks, linking between them, optimal objective values, and elapsed time for solving each problem by Baron solver in GAMS software. For example, after solving problem 12, only cross-docks 2, 3, 5, and 7 are established, and cross-docks 3 and 5 are linked to cross-docks 2 and 7, respectively. The reported results in table 11 confirm the validity and accuracy of the developed model.

Table 11. Optimal objective function of the developed model for test problems

Problem	Established cross-docks	Cross-docks linking	Optimal objective	Elapsed time [s]
1	2	–	23 500	0.299
2	2	–	33 596	0.296
3	1	–	44 371	1.023
4	1, 3	(1–3)	49 642	4.669
5	1, 3	(1–3)	33 859	0.446
6	1	–	19 695	2.925
7	1, 3	(1–3)	33 985	37.022
8	3, 5	(3–5)	30453	2.442
9	2, 3	–	109 046	11.880
10	2, 4	(4–2)	35 032	3.928
11	1, 2, 4, 6	–	74547	21.267
12	2, 3, 5, 7	(3–2), (5–7)	53 869	11.310
13	3, 4, 5	(3–4)	127 648	384.618

8. Conclusion

The proposed model designs a cross-docking distribution network that can decrease transportation costs considering cross-dock linking and product consolidation. So, this model can help managers obtain an economical supply chain and a competitive advantage comparing others. Our model can be used in other supply chains, such as automobile and petrochemistry industries, and agri-food supply chains.

A basic mixed-integer non-linear model was first formulated to address the location-allocation and distribution problem in cross-docking networks. Second, to deal with post-distribution cross-docking strategy and undetermined demand conditions, this non-linear model was changed to consider connections between cross-docks for satisfying products shortage or surplus in them. Third, to evaluate the accuracy and to compare 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 optimal objective values equal to or less than model 1. Model 2 is thus more efficient than model 1 and can 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 different-sized problems 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 cannot 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 truck capacity can be considered as variables in the model to be optimised and obtained in another realistic model. Finally, suitable metaheuristic algorithms can be used or extended for solving the developed model in large sizes.

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