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Optimization of Urban Distribution Centres: A Multi-Stage Dynamic Location Approach

Liying Yan [1], Manel Grifoll [2], Hongxiang Feng [3], Pengjun Zheng [3,*] and Chunliang Zhou [4]

1 College of Business Administration, Ningbo Polytechnic, Ningbo 315800, China; 2021035@nbpt.edu.cn
2 Barcelona Innovation in Transport (BIT), Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya (UPC-BarcelonaTech), 08003 Barcelona, Spain; manel.grifoll@upc.edu
3 Faculty of Maritime and Transportation, Ningbo University, Ningbo 315806, China; fenghongxiang@nbu.edu.cn
4 College of Finance & Information, Ningbo University of Finance & Economics, Ningbo 315175, China; zhouchunliang@nbufe.edu.cn
* Correspondence: zhengpengjun@nbu.edu.cn

Abstract: Customer demand is dynamic and changeable; thus, optimality of the enterprise's initial location cannot be guaranteed throughout the planning period in order to minimize site selection cost and maximize service reliability in the whole operation cycle. The enterprise planning period is divided into different stages, and a static location model is established at the fixed stage. In addition, a multi-stage dynamic location model is established by introducing the transfer cost between adjacent stages. To reduce the difficulty of solving the dynamic location model, first, we determined the optimal site selection and allocation strategy for each stage. Second, we designed a novel method that transforms the multi-stage dynamic location problem into the shortest path problem in graph theory. Finally, the Dijkstra algorithm was used to find the optimal dynamic location sequence so that its cumulative cost was the lowest in the whole planning period. Through a case study in China, we compare the costs of static and dynamic locations and the location cost under different objectives. The results show that this dynamic location generates more income (as it reduces cost) in comparison to the previous static location, and different location objectives have a substantial influence on location results. At the same time, the findings indicate that exploring the problem of enterprise location from a dynamic perspective could help reduce the operating cost and resources from a sustainable development perspective.

Keywords: distribution centre; dynamic location; city logistics; shortest path

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Citation: Yan, L.; Grifoll, M.; Feng, H.; Zheng, P.; Zhou, C. Optimization of Urban Distribution Centres: A Multi-Stage Dynamic Location Approach. *Sustainability* **2022**, *14*, 4135. https://doi.org/10.3390/su14074135

Academic Editors: Giada La Scalia and Ripon Kumar Chakrabortty

Received: 19 January 2022
Accepted: 14 March 2022
Published: 30 March 2022

1. Introduction

With the sustainable development of the social economy, improved living standards, and fast pace of life, peoples' consumption of all kinds of goods continues to increase, presenting a "multi-variety, multi-batch, small-batch" consumption pattern [1]. How to quickly distribute a large variety of food to where it is needed represents a new logistics challenge, which has stimulated and promoted the rapid development of urban logistics. Considering that customer demand is dynamic and variable, distribution services need to constantly improve in the pursuit of sustainable development.

Where to locate urban distribution centres (UDCs) is one of the most important decision-making problems for logistics enterprises [2–6]. Deciding where to locate UDCs represents a strategic decision problem. The initially optimal locations of UDCs will no longer be optimal at some point in the future, given the development of economies and the need for real-time decisions, changes in urban distribution quantity in accordance with customer demand, distribution cost, and changes in related governmental policies. Therefore, logistics enterprises should comprehensively consider the variable factors that may change over time when choosing the location of UDCs. Dynamic location of UDCs refers to determining location layouts in a time-varying manner to ensure that optimal locations are used to the extent possible at all times. With the increased availability of third-party logistics, enterprises can rent and outsource their distribution centres, which greatly reduces the cost of opening or closing distribution centres and provides convenience and the possibility of timely adjustment of the entire logistics system. Facilities can be put to reasonable use, waste can be avoided, and sustainable development of society can thus be promoted. A reasonable selection of the location and number of distribution centres of the logistics system will provide advantages in ensuring the operation of the logistics system, reducing logistics cost and loss of goods, and accelerating turnover, among other advantages. Additional benefits on distribution centres analysis may be found in the literature linked with sustainability perspective such as emergency materials dispatching [7,8] or logistics distribution networks [9–11]. In the framework of sustainability, our work focuses on two specific points: (i) sustainable economic development and business management, (ii) Sustainable supply chains, logistics, and transportation.

After the Introduction (Section 1), this paper is organised as follows. Section 2 introduces a comprehensive literature review on the location. Sections 3 and 4 present the model formulation and solution method, respectively. Section 5 details the case description and data acquisition. The proposed method is used in Section 6 to solve the dynamic location problem of the Chinese Tianjin port X company and the computational results are discussed. Finally, Section 7 provides a conclusion and identifies future areas for research.

2. Literature Review

The study of the theory of location and distribution formally started with Weber [12] and was subsequently extended by Hakimi [13]. Over the last few decades, the theory of location and distribution has become an important research topic in operations research and management science. Location theory has been used in the real world with respect to hospitals [14], schools [15], public facilities [16], retail establishments [17], urban facilities [18], distribution centres [19], and so forth. Although these location problems involve different entities, the problem is essentially the same in each case. The focus is on how to choose the number and location of facilities to optimally provide services to end-users.

Facility location has been considered using qualitative and quantitative models [19]. Qualitative models primarily include analysis of hierarchical processes [20,21], fuzzy evaluation [2], grey relational degree evaluation [22], or models constructed by synthesising several evaluation methods [23]. The basic principle underlying qualitative methods is to evaluate and rank alternative schemes and select the one with the highest score as the final location scheme. However, these methods are influenced by practitioners and evaluation indexes so that bias can occur in location. Quantitative determination of location is primarily obtained by constructing facility location models, which can be divided into various forms according to decision-makers' goals and spatial characteristics of the problem. Owen et al. [24] divided the facility location problem into static facility location, random facility location, and dynamic facility location. At present, studies have primarily focused on the improvement of static facility location models and methods [25–28]. However, in any application, both actual point demand quantity and demand characteristics may change with time. Therefore, the location should be adjusted according to the actual situation.

Models in which the location decisions are revisited in each time period due to a change in demand are called dynamic models. The dynamic location model was first stated by Ballou [29] when discussing how enterprises select a warehouse to maximize profits during the planning period. Sweene et al. [30] proposed an improved method based on Ballou [29], which included constraints on the state space of the dynamic programming to improve the quality of the solution. Although both approaches allowed facility relocation, they did not consider the time required for facility construction or relocation cost in the objective function. Wesolowsky [31] studied the dynamic location of a single facility in limited planning and introduced relocation cost into the objective function. Farahani et al. [32] studied the single-facility dynamic location model. Tapiero [33] and Canel et al. [34] studied the location–allocation problem with multiple facilities and multiple cycles and used a myopic algorithm and dynamic programming method to solve the problem respectively. Melo et al. [35] analysed the dynamic location problem with the capacity limitation of multiple commodities and discussed the similarities and differences between the established model and the existing model. Dias et al. [36] studied the dynamic location problem with a minimum and maximum two-layer capacity constraint for facility opening, closing, and reopening, and solved the model using a primal–dual heuristic algorithm. Zhou et al. [37] established a dynamic location model of a logistics centre with multiple facilities and cycles and designed a genetic algorithm to solve the model. However, none of these studies simultaneously considered multi-facility locations and transfer costs. The algorithms for solving models are generally approximate and heuristic in nature. Emirhuseyinoglu et al. [25] studied a two-tier facility location problem with a quantity discount of goods and established a mixed-integer programming model; two heuristic algorithms were designed to solve the model.

In view of all this, the objective of this contribution was to develop a multi-stage dynamic location model for a three-level supply chain logistics network considering the reliability of distribution service and transfer costs. In order to reduce the difficulty in developing the solution to the model involved, first, based on the static location model of each phase, we determined the optimal location and its scheduling scheme. Second, we transformed the dynamic location problem into the shortest path problem using graph theory. In this stage, the Dijkstra algorithm was used to find the optimal dynamic location sequence, so that its cumulative cost was the lowest in the whole planning period. Finally, the suitability of the method was demonstrated by applying the model to X enterprise of Tianjin port in the Beijing-Tianjin-Hebei (BTH) city cluster.

3. Model Formulation

3.1. Problem Statement

We investigated a logistics distribution network consisting of m supply points, n_1 candidate distribution centres and k discrete demand points (Figure 1). The demand for some demand points changed within stated periods. The intention was to formulate a long-term location (multi-stage location) plan to select P distribution centres among n_1 candidate distribution centres, providing services for k demand points in each stage. This aimed to minimize the total cost of the distribution system and maximize the reliability of the distribution centres' service throughout the planning period.

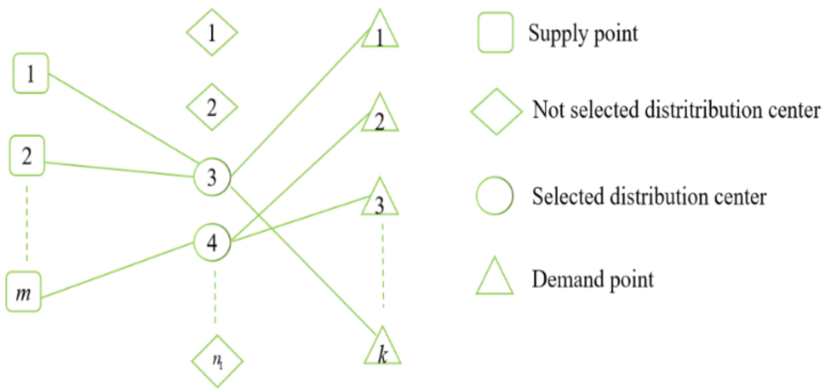

Figure 1. Strategy of location in a supply–distribution–demand system.

3.2. Symbols and Variables

The main symbols and variables used in the analysis are shown in Table 1. Additionally, intermediate variables are defined when they first appear in the paper.

Table 1. Symbols and variables.

Symbols and Variables	Meaning
i	Index of supply points
j	Index of potential distribution centres
k	Index of demand points
t	Index of planning cycles
K	Set of demand points of the goods
M	Set of supply points of the goods
N	Set of the alternative distribution centres
T	Set of planning cycles
d_{ij}	The distance between the supply point i and the distribution centre j
d_{jk}	The distance between the distribution centre j and demand point k
c_1	The transportation cost per unit from the supply point of goods to the distribution centre
c_2	The transportation cost per unit from the distribution centre to the demand point
gd_j	The fixed cost of distribution centre j
P	The number of rental distribution centres
G	Infinite positive number
MN_j	The maximum capacity of the distribution centre j
d_k^t	The demand quantity of demand point k in stage t
tc_j^t	Transit operating cost per unit product of distribution centre j in stage
β	The number of deliveries in each stage
x_{ij}^t	Quantity of goods supplied from the supply point i to the distribution centre j in stage t
y_j^t	If the distribution centre j is selected in stage t, equals to 1; otherwise, it is 0
x_{jk}^t	Quantity of goods supplied from the distribution centre j to the demand point k in stage t

3.3. Service Reliability Calculation for Distribution Centres

The reliability of distribution centres' service is the logical combination (i.e., series connection, parallel connection) of the reliability of several interrelated logistics operation units within distribution centres [38]. Considering the scope of this study, we assumed that the reliability of other logistics operation units (such as picking, collecting, and loading), except delivery, would be perfect, defined as a value of 1. The reliability of logistics service provided by distribution centres for a customer was defined as the probability of delivering products within the time limit required by the customer. The reliability was expressed by the following formula [39]:

$$P_{jk}^t = P(t_{jk} \le t_k) = P(\frac{d_{jk}}{v_{jk}} \le t_k) = P(v_{jk} \ge \frac{d_{jk}}{t_k}) = 1 - F_{v_{jk}}(\frac{d_{jk}}{t_k}) \tag{1}$$

From Equation (1), the reliability of the whole system in stage t was obtained as follows:

$$\tau^t = \beta \frac{\sum\limits_{j \in N} \sum\limits_{k \in K} d_k^t y_j^t P_{jk}^t}{\sum\limits_{k \in K} d_k^t} \tag{2}$$

where t_k denotes the lower limit of service time window required by customers, t_{jk} denotes transportation time from distribution centre j to demand point k, P_{jk}^t denotes the reliability of distribution centre j to provide customers k with logistics services in stage t, v_{jk} denotes vehicle travel speed from distribution centre j to demand point k and $F_{v_{jk}}$ denotes the vehicle travel speed distribution function from distribution centre j to demand point k.

3.4. The Location Model of Stage t

The location model of stage t was defined as follows:

$$\text{Objective function} \quad \text{Max} \quad \tau^t = \beta \frac{\sum\limits_{j \in N} \sum\limits_{k \in K} d_k^t y_j^t P_{jk}^t}{\sum\limits_{k \in K} d_k^t} \tag{3}$$

$$\text{Min} \quad Z_t = \beta(F_1 + F_2 + F_3) \tag{4}$$

$$F_1 = \sum_{j \in N} y_j^t g d_j \tag{5}$$

$$F_2 = \sum_{i \in M} \sum_{j \in N} c_1 d_{ij} x_{ij}^t + \sum_{j \in N} \sum_{k \in K} c_2 d_{jk} x_{jk}^t \tag{6}$$

$$F_3 = \sum_{j \in N} tc_j^t x_{jk}^t y_j^t \quad k \in K \tag{7}$$

$$\text{Subject to} \quad \sum_{i \in M} x_{ij}^t = \sum_{k \in K} x_{jk}^t \quad j \in N \tag{8}$$

$$\sum_{i \in M} x_{ij}^t \le G y_j^t \quad j \in N \tag{9}$$

$$\sum_{k \in K} x_{jk}^t y_j^t \le MN_j \quad j \in N \tag{10}$$

$$\sum_{j \in N} y_j^t = P \tag{11}$$

$$y_j^t \in \{0,1\} \quad j \in N \tag{12}$$

$$x_{ij}^t \ge 0 \quad i \in M, j \in N \tag{13}$$

$$x_{jk}^t \ge 0 \quad j \in N, k \in K \tag{14}$$

The objective function (3) maximises the reliability of distribution centres' service. The objective function (4) minimises the total system cost, which includes the fixed cost (5), the transportation cost (6), and the transit operating cost (7). Constraint (8) ensures flow balance among distribution centres. Constraint (9) ensures that the flow of goods in unselected distribution centres is zero. Constraint (10) represents the capacity limitation of distribution centres. The number of selected distribution centres is represented by constraint (11). Constraint (12) ensures that y_j^t varies is 0 or 1. Constraint (13) ensures that x_{ij}^t greater than or equal to zero. Constraint (14) ensures that x_{jk}^t is greater than or equal to zero.

3.5. Transformation of Multi-Objective Model

In this study, the established model utilised dual objectives optimisation. Because there is no unique optimal solution for multi-objective optimisation problems, there are one or more non-inferior solutions. To solve the multi-objective optimisation problem, in general, multi-objective optimisation is converted to single-objective optimisation [40]. The dimensions of the two objective functions are different in a model, so we used the improved weighting average method to carry out multi-objective transformation [41]. The reliability of distribution centres' service was assigned a coefficient. This is understood as a cost that enterprises need to pay to improve the service reliability of the distribution centres. Thus, the multi-objective programming problem was transformed into a single-objective programming problem as follows:

$$\text{Objective function Min } Z' = Z_t + \alpha \tau^t \tag{15}$$

Subject to (8)~(14)

3.6. Dynamic Location Model of the Urban Distribution Centres

In the single-stage location model, the transfer costs of two adjacent stages are introduced. We can get the dynamic location model as follows:

$$\text{Objective function Min } Z = \sum_{t \in T} (Z_t + \alpha \tau^t) + \sum_{t \in T} C_{(t,R_i)(t+1,R_j)} \tag{16}$$

Subject to (8)~(14)

The objective function (16) minimises the total cost, which includes the fixed cost, the transportation cost, and operating cost of distribution centres; the cost of enterprises improving the service reliability of the distribution centres, and the transfer cost between stages.

4. Model Solution

4.1. Solution Idea

First, the location planning period for the distribution centres was divided into several stages according to the time sequence. Second, the optimal static locations of distribution centres in a specific stage were obtained via Mixed-Integer Programming (MIP) using the software Lingo 11.0 and, at the same time, calculating the location cost when the static location point was taken as the location in the other stages. The transfer cost between adjacent stages was calculated using Matlab 2018b. The multi-stage location problem was treated as a multi-stage decision problem in the given periods. Finally, the multi-stage decision-making problem was transformed into a shortest path problem in graph theory. The Dijkstra algorithm was used to find the shortest path. That is, a time-varying dynamic location decision sequence was obtained. Figure 2 shows a flow chart with the main steps involved in the multi-stage location of urban distribution centres.

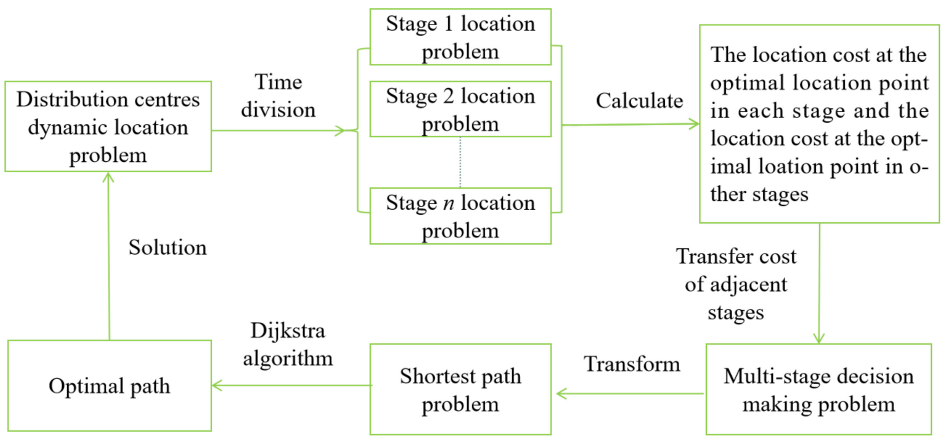

Figure 2. Flow chart showing the main steps in the multi-stage location of urban distribution centres.

4.2. Transforming the Dynamic Location into the Shortest Path

Step One. The planning period of distribution centre locations was divided into n stages according to the time sequence. The optimal location of distribution centres at each stage was obtained by Lingo 11.0 programming. The optimal location at stage t is represented by $R_t(t = 1, 2, \cdots, n)$. The best location for each stage is schematised in Figure 3.

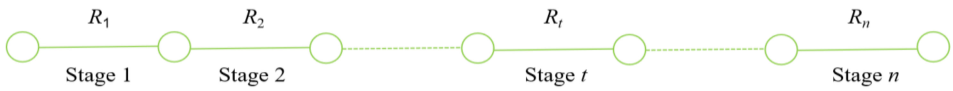

Figure 3. The best location for each stage.

Step Two. The cost of the optimal location strategy at each stage in other stages was calculated. C_{ij} represents the location cost when the optimal location in phase j was used as the location in phase i. For example, C_{j1} represents the location cost when the optimal location strategy R_1 in phase 1 was used as the location strategy in phase j.

Step Three. The location cost of the optimal location strategy in each stage was abstracted. The location cost of each stage represented a point that served as the vertex of each stage; that is, the possible location strategy in this stage. The number of vertices represented the number of possible location schemes in this stage.

Step Four. The cost of state transition between adjacent stages was calculated. $C_{(t,R_i)(t+1,R_j)}$ denotes the transfer cost from strategy R_i in stage t to strategy R_j in stage $t+1$. For example, $C_{(1,R_2)(2,R_3)}$ denotes the transfer cost from strategy R_2 in stage 1 to strategy R_3 in stage 2.

Step Five. Two virtual vertices were constructed: the start point V_0 and the endpoint V_{n+1} of the planning period. The location scheme was represented by a directed connected graph (Figure 3). V is the set of vertices, where V_0 and V_{n+1} indicated that the enterprise did not need to make location decisions, and V_{ij} meant that the optimal site selection of stage j was taken as the site selection of stage i. The set of edges E and the elements in the set represented the distance between two adjacent points. The distance from V_0 to each point in the first phase was equal to the cost in the first phase of the best location in the different phases. The distance from $V_{nj}(j = 1, 2, \cdots, n)$ to the endpoint V_{n+1} was 0, and the distance between the other two adjacent vertices was the sum of step two (location cost) and step four (transfer cost). Through the above five steps, the dynamic location problem was transformed into the shortest path problem shown in Figure 4.

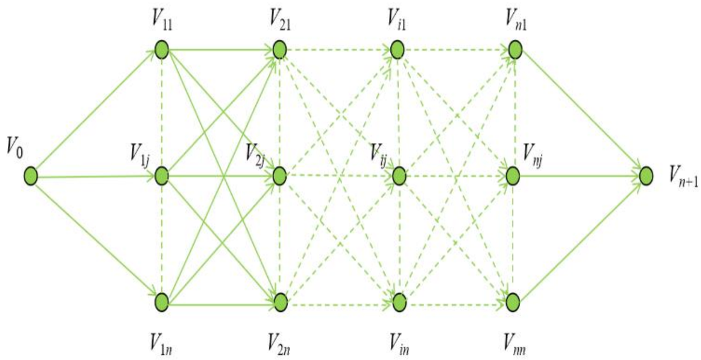

Figure 4. The dynamic location problem transformed into a shortest path graph.

4.3. Shortest Path Algorithm

The Dijkstra algorithm can estimate the shortest path between any two nodes in Figure 4, but the weight of the edges is required to be non-negative. According to the transformation method of the dynamic location shown in the previous section, it may be concluded that the weight of the edges is all non-negative (Step five of Section 4.2) in Figure 4. Hence, the Dijkstra algorithm can be used to obtain the shortest path from V_0 to V_{n+1} in Figure 4, namely, the optimal dynamic location point of the enterprise in the whole site selection planning cycle. The basic steps of the algorithm are as follows [42]:

Step One. Give the starting vertex V_0 the permanent label $U(V_0) = 0$. The other vertices are labelled with Z. At this time, the temporarily labelled set of vertices R is equal to $\{V_{11}, V_{12}, \cdots, V_{1n}, \cdots, V_{1j}, \cdots V_{ij}, \cdots, V_{nj}, \cdots, V_{n+1}\}$ while the permanently labelled set of vertices S is equal to $\{V_0\}$. Arc set $A = \{(V_0, V_{mn}) | V_0 \in S, V_{mn} \in R\}$ represents the set of all lengths from the permanent label point to the temporary label point.

Step Two. Calculate the arc length $L_{(V_0,V_{1i})}(i = 1, 2, \cdots, n)$ from V_0 to its adjacent vertex V_{1i}. Find a vertex V_{1j} such that $L_{(V_0,V_{1j})} = W_{1j} = \min(L_{(V_0,V_{1i})})$ $(i = 1, 2, \cdots, n)$. Change the Z label of V_{1j} to label U. At this time, the permanently labelled set of vertices S is equal to (V_0, V_{1j}), and the temporarily labelled vertex set R is equal to $R \backslash \{V_{1j}\}$.

Step Three. Define $A' = \{(V_{ij}, V_{mn}) \big| V_{ij} \in S, V_{mn} \in R\}$ as the set of new arc segments. When $i = 1$, $A' = \{(V_{1j}, V_{21}), \cdots, (V_{1j}, V_{2j}), \cdots, (V_{1j}, V_{2n})$. Calculate the length of the arc in A'. Find a vertex V_{2k}, such that $L_{(V_0,V_{2k})} = U(V_{1j}) + W_{(1,R_j)(2,R_k)}$. Where, $W_{(1,R_j)(2,R_k)} = \min(L_{(V_{1j},V_{2q})})$ $(q = 1, 2, \cdots, n)$, which represents the weight of the arc between site R_j of Stage One and site R_i of Stage Two.

Step Four. The weights of arc segments from all permanently labelled points to temporary labelled points are compared. Labels Z and U are changed at the endpoint of the arc where the minimum value is located.

Repeat Step Three and Step Four until the procedure is complete.

5. Case Description and Data Acquisition

This case study considered X enterprise of Tianjin port in BTH city cluster; some data were obtained from literature [43]. X company currently provides effective distribution services for 22 regions in BTH of China (Figure 5). To improve transport efficiency and distribution system service reliability, the company intends to select three of 22 demand points as its logistics distribution centres. The enterprise intends to formulate an eight-year plan; every two years is regarded as a stage. The whole planning period is divided into four stages.

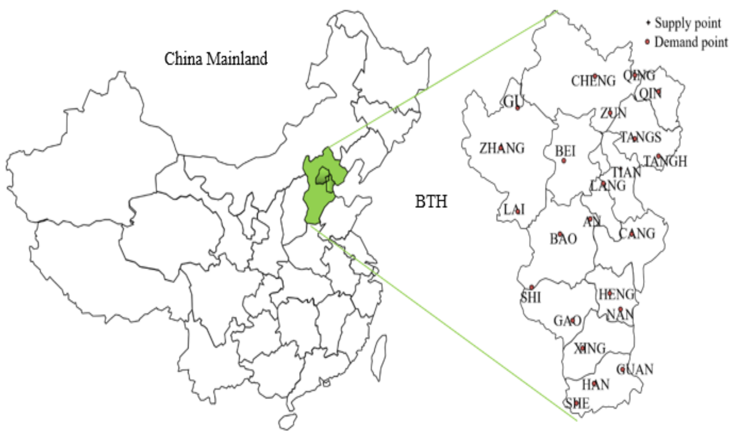

Figure 5. Location of BTH in China and distribution of supply and demand points. The cities correspond to Beijing (BEI), Tianjin (TIAN), Guyuan (GU), Zhangjiakou (ZHANG), Chengde (CHEN), Qinglong (QING), Qinhuangdao (QIN), Zunhua (ZUN), Tangshan (TANGS), Tanghai (TANGH), Laiyuan (LAI), Anxin (AN), Langfang (LANG), Baoding (BAO), Cangzhou (CANG), Shijiazhuang (SHI), Hengshui (HENG), Gaoyi (GAO), Nantong (NAN), Xingtai (XING), Guantao (GUAN), Handan (HAN), and Shexian (SHE).

The distance between Tianjin and the cities and the distances among these cities are shown in Appendix A. The fixed cost and unit operating cost of each demand point in Stage One are shown in Table 2. In the following stages, the operating cost and the fixed cost increased by 8% and 6%, respectively, compared with the previous stage. The demand points in stages 1, 2, 3, and 4 are shown in Table 3, given $t_k = 8$, $c_1 = 2$ Yuan/km, $v_{jk} \sim N(70, 10^2)$, $c_2 = 1.8$ Yuan/km, $MN_j = 60t$ $(j \in N)$, $\beta = 100$, $\alpha = 1000$, and $P = 3$.

Table 2. Fixed cost and unit operating cost of each demand point (in Yuan).

Site	Fixed Cost	Unit Operating Cost	Site	Fixed Cost	Unit Operating Cost
BEI	207,000	125	BAO	121,500	65
GU	52,800	45	AN	40,500	25
ZHANG	64,800	45	GUAN	33,750	18
CHENG	81,000	53	CANG	67,500	35
QING	42,000	18	SHE	36,000	25
QIN	70,200	81	HAN	54,000	30
ZUN	90,000	48	NAN	33,750	18
TANGH	54,000	35	XING	78,750	45
LANG	142,500	72	GAO	45,000	24
TANGS	135,000	75	HENG	67,500	35
LAI	45,000	26	SHI	123,750	65

Table 3. Demand quantity of demand points at different stages (units in tons).

	Site										
	BEI	**GU**	**ZHANG**	**CHENG**	**QING**	**QIN**	**ZUN**	**TANGH**	**LANG**	**TANGS**	**LAI**
stage 1	6	4	2	7	7	4	6	2	2	3	6
stage 2	10	4	8	7	2	7	5	3	7	8	6
stage 3	4	3	3	2	5	6	5	6	2	7	5
stage 4	8	4	8	7	2	7	5	5	7	8	6
	Site										
	BAO	**AN**	**GUAN**	**CANG**	**SHE**	**HAN**	**NAN**	**XING**	**GAO**	**HENG**	**SHE**
stage 1	4	8	5	2	4	6	6	5	3	5	6
stage 2	6	7	3	7	2	7	4	6	5	7	8
stage 3	5	7	7	8	5	6	8	5	5	6	8
stage 4	3	7	3	2	3	2	3	2	6	1	8

6. Results and Discussion

6.1. Optimal Dynamic Location and Comparison with Static Solution

First, through Lingo 11.0 software programming, the optimal location and distribution strategy of each stage was obtained (Figure 6). The optimal location point of each stage differed, as follows: ZUN, AN, CANG → TANGH, LANG, CANG → TANGH, AN, CANG → TANGH, LANG, AN.

At the optimal site, the reliability of the distribution centre service is more than 98%, so the service satisfaction is high.

Second, the total location cost of each stage was calculated for the optimal location point, and the total location cost for the optimal location point in other stages was also calculated (Table 4). The cost at other location points outweighed the cost at the optimal location point for a given stage; the maximum difference was 455×10^3 Yuan and the minimum difference was 36×10^3 Yuan.

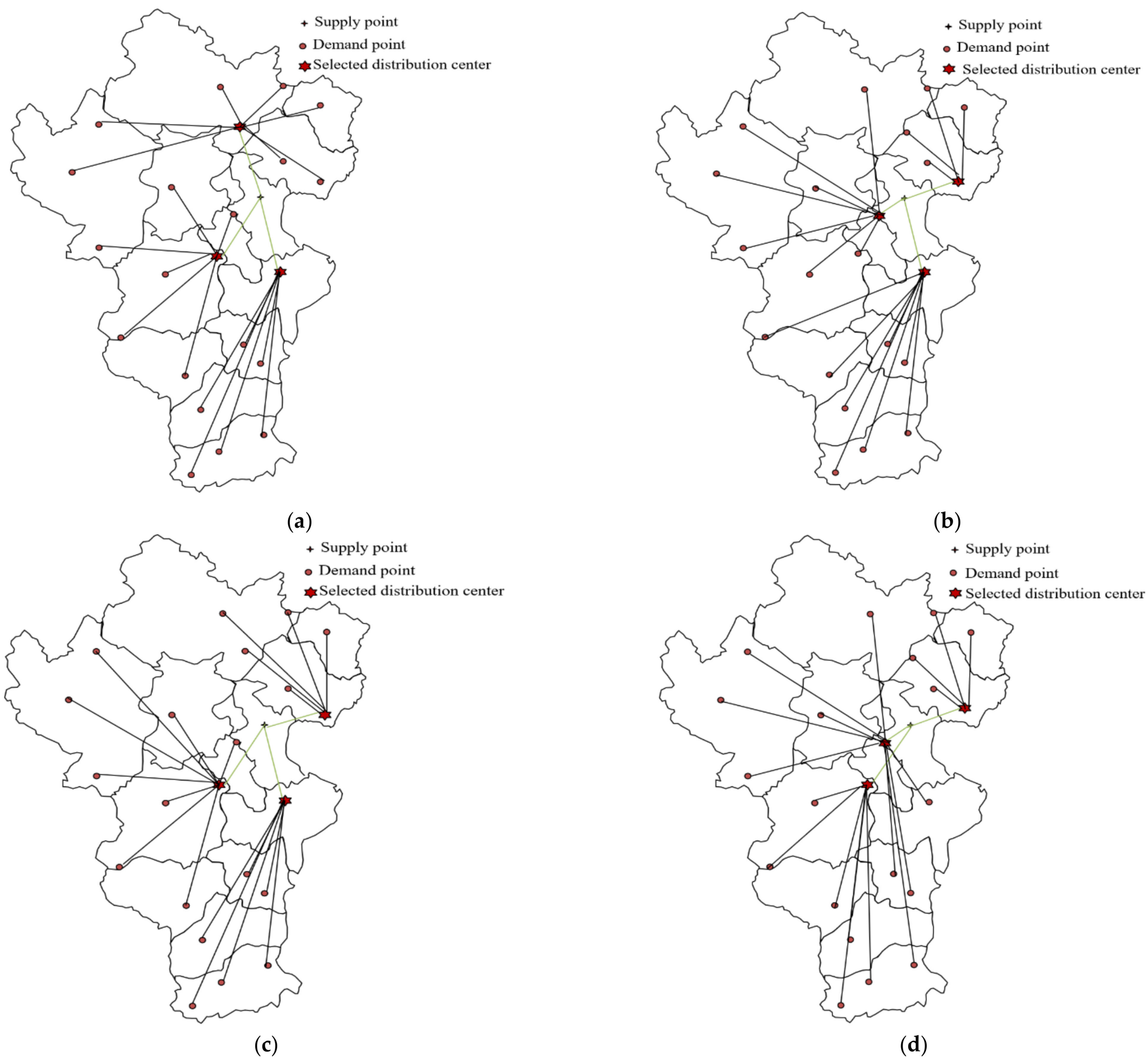

Figure 6. Optimal location and distribution in different stages. The names of the cities are listed in Figure. (**a**) The optimal location and allocation of stage one. (**b**) The optimal location and allocation of stage two. (**c**) The optimal location and allocation of stage three. (**d**) The optimal location and allocation of stage four.

Table 4. Location cost of different stages (units in 10^3 Yuan).

Site	Cost			
	Stage One	Stage Two	Stage Three	Stage Four
ZUN, AN, CANG	**6460**	7934	7251	6916
TANGH, LANG, CANG	6496	**7561**	7257	6689
TANGH, AN, CANG	6579	7924	**7124**	6850
TANGH, LANG, AN	6667	7800	7579	**6578**

Third, transfer cost was determined, as follows:

- If the location points remained unchanged, the transfer cost was 0.
- If the location points change, transfer costs are related to the fixed cost of the changed location point. Specifically, the transfer cost from phase one to phase two was equal to 0.5 times the fixed cost of the location point in stage two, the transfer cost from phase two to phase three was equal to 0.8 times the fixed cost of the location point in stage three, and the transfer cost from phase three to phase four was equal to 1.2 times the fixed cost of the location point in stage four.

- If the fixed capacity of the location point was exceeded in any stage, the transfer cost was equal to the excess tonnage multiplied by two times the operating cost of the site. The transfer cost between different stages was calculated, as shown in Table 5.

Table 5. Transfer cost between stages (in 10^3 Yuan).

		ZUN, AN, GANG	**TANGH, LANG, CANG**	**TANGH, AN, CANG**	**TANGH, LANG, AN**
Transfer cost from stage one to stage two	ZUN, AN, CANG	0	65.5	180	65.5
	TANGH, LANG, CANG	43.5	0	13.5	13.5
	TANGH, AN, CANG	30	47.5	0	47.5
	TANGH, LANG, AN	52.5	22.5	22.5	0
Transfer cost from stage two to stage three	ZUN, AN, CANG	0	104.8	28.8	104.8
	TANGH, LANG, CANG	69.6	0	21.6	21.6
	TANGH, AN, CANG	48.1	76	0	76
	TANGH, LANG, AN	84	36	36	0
Transfer cost from stage three to stage four	ZUN, AN, CANG	0	157.2	43.2	157.2
	TANGH, LANG, CANG	104.4	0	32.4	32.4
	TANGH, AN, CANG	72	114	0	114
	TANGH, LANG, AN	126.2	54	54	0

Finally, the optimal multi-stage location decision sequence was determined. The distance was the sum of the transfer cost and location cost between different stages (Table 6). Using the Dijkstra algorithm, the optimal multi-stage location decision sequence was obtained for TANGH, LANG, CANG → TANGH, LANG, CANG → TANGH, AN, CANG → TANGH, LANG, AN. The total cost of the whole planning period was 27.723×10^3 Yuan. Furthermore, the single-stage optimal location sequence was not the optimal location sequence for the whole planning period.

Table 6. Distance between vertices (in 10^3 Yuan).

	V_{11}	V_{12}	V_{13}	V_{14}
V_0	6460	6596	6579	6667
	V_{21}	V_{21}	V_{23}	V_{24}
V_{11}	7934	7626	7942	7866
V_{12}	7977	7561	7938	7814
V_{13}	7964	7608	7924	7848
V_{14}	7986	7583	7947	7800
	V_{31}	V_{32}	V_{33}	V_{34}
V_{21}	7251	7362	7153	7684
V_{21}	7321	7257	7146	7601
V_{23}	7299	7333	7124	7656
V_{24}	7335	7293	7160	7579
	V_{41}	V_{42}	V_{43}	V_{44}
V_{31}	6916	6846	6893	6735
V_{32}	7021	6689	6882	6610
V_{33}	6988	6803	6850	6692
V_{34}	7000	6725	6886	6578
	V_{41}	V_{34}	V_{43}	V_{44}
V_5	0	0	0	0

In a static location method, once locations are determined, they will not change during the whole planning period. We used the location decision of stage one as the location decision for the entire planning cycle. In this case, the total cost of the four stages, including fixed cost, transfer cost, transportation cost, and the cost of improving the service reliability of the distribution centres was 28.561 × 10^3 Yuan (Table 4), which was 2.93% more than the dynamic location cost (Table 4).

6.2. Optimal Location and Cost Analysis Given Different Objectives

As can be seen from Figure 7, using the shortest distance as the objective function, the location strategy was TANGS, LANG, and CANG. When the objective function minimised the total cost, at least one of the best sites was LANG or CANG in each stage (Figure 6). However, TANGS did not appear in any stage, primarily due to the high fixed and operating cost of TANGS, which increased the total cost. Table 7 shows that when the objective function minimised distance, transportation cost was lower than when using the minimum total cost as the objective function. In contrast, operation costs and fixed costs exhibited the opposite pattern to transportation costs.

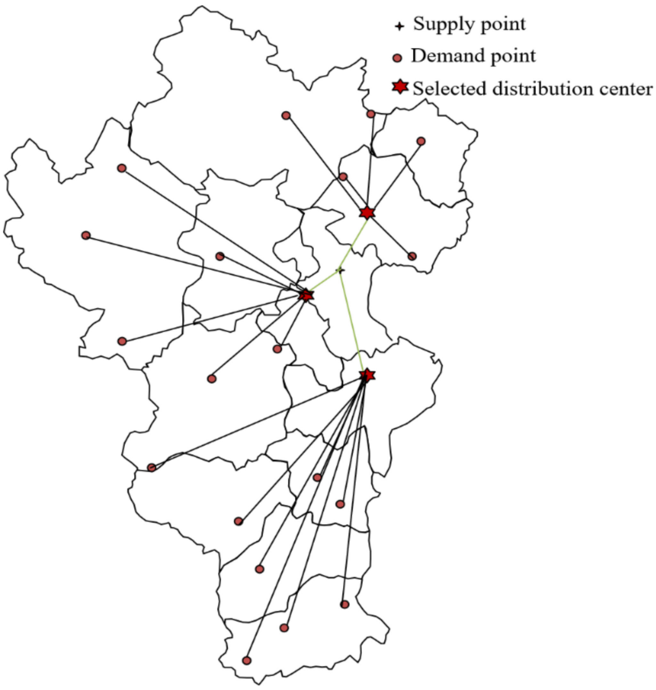

Figure 7. Optimal location and distribution with the shortest distance as the objective function. The names of the cities are shown in Figure 5.

Table 7. Location cost given different objectives (in 10^3 Yuan).

	Objective Function	Transportation Cost	Operating Cost	Fixed Cost	Total Cost
stage 1	shortest distance	5249	595	690	6534
	minimum cost	5599	371	396	6366
stage 2	shortest distance	6055	818	731	7604
	minimum cost	6195	707	560	7462
stage 3	shortest distance	5756	752	775	7283
	minimum cost	6229	433	364	7026
stage 4	shortest distance	5022	844	822	6688
	minimum cost	5254	661	565	6480

6.3. Discussion of the Results

From the perspective of enterprises, it is necessary to determine the distribution cost associated with third-party logistics to improve the competitiveness of the enterprise [44,45]. For enterprises and additional stakeholders, it is necessary to consider various factors that may affect costs, measure the relationship among costs and employ third-party logistics companies consistent with the objectives of the enterprise. In this sense, the location of UDCs is a multi-stage dynamic decision-making problem. Based on experience, Chinese city clusters (e.g., BTH) are developing rapidly and peoples' demand for goods is constantly changing. The initial optimal site selection of UDCs will not necessarily continue to be the optimal site selection in later stages. Hence, a static UDC selection method contradicts the enterprise's pursuit of profit maximisation. Furthermore, customer satisfaction is a key factor in the development of enterprises, as we considered in the current study. This represents a step forward in comparison to previous studies [22,25,46,47] because we introduced explicitly service reliability into the location model, building a multi-objective and multi-stage dynamic location model.

The multi-objective problem has no optimal solution; rather, there only exists a set of pareto solutions [40]. Thus, to obtain the optimal solution to the problem, it is necessary to transform the multi-objective problem into a single-objective model. However, in the model described in this paper, the unit of measurement of cost differed from the unit of measurement of distribution reliability. Therefore, a traditional linear weighting method was not feasible; hence, we used an improved weighting average method to implement multi-objective transformation [41]. This method converts the reliability of the distribution system into a distribution cost by introducing a constant. The method can not only eliminate differences in units and orders of magnitude among multiple objectives but can also permit dynamic adjustment according to the requirements of the problem. An alternative is also the use of the theory of multi-objective optimization such as hierarchical sequence method, efficiency coefficient method, purpose planning method among others [41].

Exact algorithms are likely to generate more realistic and accurate results in comparison to hybrid heuristic algorithms [37,48]. However, it is difficult to solve the dynamic location model established herein using an exact algorithm. In order to obtain the exact solution of the dynamic location model, a new method was proposed. The advantage of our method lies in its versatility because it decomposes and transforms the multi-stage dynamic location problem thus making it easier to solve. The key of the method is that we transformed the multi-stage dynamic location problem into a shortest path problem. Then, the Dijkstra algorithm of graph theory was used to obtain the shortest path. Consequently, the Dijkstra algorithm solved a problem noted previously in the literature [49,50]. The BTH application example demonstrated that the proposed method is simple and feasible for solving the multi-stage dynamic location problem.

7. Conclusions

In the near future, with the rapid development of China's economy, indicators related to city distribution, such as customer demand, transportation cost, transit cost, and so on, may change. As such, the original location of UDCs will not be the optimal location at some future time. In this paper, a multi-stage dynamic location of UDCs was established. To reduce the difficulty of solving the model, we used the ideas of decomposition and transformation. Ultimately, we transformed the multi-stage dynamic problem into a multi-stage decision-making problem. The multi-stage decision-making process was regarded as the shortest path problem, which was successfully solved using the Dijkstra algorithm. The effectiveness of the model and algorithm was verified through a case study of a Tianjin port enterprise. Based on the results of the numerical experiments, we present the following conclusions:

When the needs of customers change at different stages of site selection, the optimal UDC site locations also change. Compared to the static optimal location decision, the dynamic optimal location decision can provide cost savings for enterprises in a planning period.

By comparing and analysing the optimal location strategies for different objectives in different stages, we found that the transportation cost was smaller when the objective function minimised distance rather than total cost, however, fixed costs and operating costs demonstrated opposite trends.

In summary, the proposed model can effectively solve the multi-stage dynamic location problem. Moreover, in this contribution, the algorithm used for solving the model was based on decomposition and transformation, which reduced the difficulty of solving the model to a great extent. This may promote urban distribution by developing transitions towards a healthier, greener, and more sustainable direction. Future research could address uncertainty in supply chains. In this case, location optimization of UDCs will be more complicated. Additionally, the proposed method may be eventually improved using advanced pathfinding algorithms for complex networks or high density of nodes (for instance, an A* pathfinding algorithm) and the consideration of other methods for the dynamic location model such as the Epsilon-constraint method [51] or Two-Phase-Method [52]. Future works also include designing a heuristic algorithm to solve the dynamic location model and comparing this with the method presented in this paper to verify the quality of the heuristic algorithm. Future improvements of the work could include improvement of the pathfinding algorithm and establishing a model to determine the optimal location stage of an enterprise.

Author Contributions: All of the authors contributed to the work in the paper. Specifically: Conceptualization, L.Y. and P.Z.; methodology, L.Y.; software, L.Y.; validation, L.Y., M.G. and H.F.; data curation, L.Y.; writing—original draft preparation, L.Y.; writing—review and editing, L.Y. and M.G.; funding acquisition, P.Z. and C.Z. All authors have read and agreed to the published version of the manuscript.

Funding: The research was supported by National Key Research and Development Project (2017YFE9134700); Zhejiang Province Philosophy Planning Project (21NDQN290YB, 21NDJC167Y B); Ningbo Polytechnic Research Project (NZ22007).

Data Availability Statement: The data and material used to support the finding of this study are available from the corresponding author upon request.

Acknowledgments: The authors would like to thank the anonymous reviewers for their helpful and constructive comments, which greatly improved the quality of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Distance between pairs of cities used in the case study.

	TIAN	BEI	GU	ZHANG	CHENG	QING	QIN	ZUN	TANGH	TANGS	LANG	LAI	AN	BAO	CANG	GUAN	SHE	HAN	NAN	XING	HENG	GAO	SHI
TIAN	0	136	529	353	364	241	264	143	135	124	83	257	150	176	120	384	549	460	311	415	256	391	345
BEI	136	0	393	228	221	232	290	182	235	183	58	252	150	147	228	443	619	456	347	399	292	331	285
GU	529	393	0	174	290	493	693	484	585	535	456	399	543	540	622	836	921	849	740	792	685	696	650
ZHANG	353	228	174	0	388	518	513	341	462	412	296	224	379	376	532	689	747	647	599	590	538	522	476
CHENG	364	221	290	388	0	203	403	194	295	254	296	371	387	384	396	660	825	736	587	691	532	568	522
QING	241	232	493	518	203	0	121	107	173	131	259	489	379	382	355	662	851	707	552	650	497	563	517
QIN	264	290	693	513	403	121	0	184	149	122	334	545	440	437	364	628	793	703	555	659	500	635	589
ZUN	143	182	484	341	194	107	184	0	94	68	262	379	272	269	319	550	801	638	454	581	399	513	467
TANGH	135	235	585	462	295	173	149	94	0	50	156	431	385	382	232	542	768	607	446	550	391	566	520
TANGS	124	183	535	412	254	131	122	68	50	0	194	373	318	297	224	488	653	563	415	519	360	495	449
LANG	83	58	456	296	296	259	334	262	156	194	0	231	124	141	170	396	546	449	300	404	245	325	279
LAI	257	252	399	224	371	489	545	379	431	373	231	0	186	144	300	447	472	395	347	338	289	270	224
AN	150	150	543	379	387	379	440	272	385	318	124	186	0	42	151	355	428	351	259	294	204	226	180
BAO	176	147	540	376	384	382	437	269	382	297	141	144	42	0	156	313	386	311	217	246	162	182	130
CANG	120	228	622	532	396	355	364	319	232	224	170	300	151	156	0	264	429	340	191	295	136	271	225
GUAN	384	443	836	689	660	662	628	550	542	488	396	447	355	313	264	0	172	75	94	129	142	198	223
SHE	549	619	921	747	825	851	793	801	768	653	546	472	428	386	429	172	0	97	238	134	301	202	315
HAN	460	456	849	647	736	707	703	638	607	563	449	395	351	311	340	75	97	0	151	65	204	129	181
NAN	311	347	740	599	587	552	555	454	446	415	300	347	259	217	191	94	238	151	0	104	48	89	119
XING	415	399	792	590	691	650	659	581	550	519	404	338	294	246	295	129	134	65	104	0	159	64	116
HENG	256	292	685	538	532	497	500	399	391	360	245	289	204	162	136	142	301	204	48	159	0	129	138
GAO	391	331	696	522	568	563	635	513	566	495	325	270	226	182	271	198	202	129	89	64	129	0	52
SHI	345	285	650	476	522	517	589	467	520	449	279	224	180	130	225	223	315	181	119	116	138	52	0

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