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Solving a Two-Level Location Problem with Nonlinear Costs and Limited Capacity: Application of Two-Phase Recursive Algorithm Based on Scatter Search

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Abstract. This study examines the issue of distribution network design in the supply chain system. There are many production factories and distribution warehouses in this issue. The most efficient strategy for distributing the product from the factory to the warehouse and

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from the warehouse to the customer is determined by solving this model. This model combines location problems with and without capacity limits to study a particular location problem. In this system, the cost of production and maintenance of the product in the factory and warehouse is a function of its output. This increases capacity without additional costs, and ultimately does not lose customers. This algorithm is a population-based, innovative method that systematically combines answers to obtain the most accurate answer considering quality and diversity. A two-phase recursive algorithm based on a scattered object has been developed to solve this model. Numerical results show the efficiency and effectiveness of this two-phase algorithm for problems of different sizes.

Keywords: Mixed integer programming, nonlinear costs, scattered search algorithm, two-tier location.

1. Introduction

In some form or another, facility location models have existed for hundreds of years. The contexts in which these models are built and used differ from case to case. However, their main objective has always been the same: placing one or more facilities within an area containing a number of customers based on the value of an objective function [1-5]. Being the basis of permanent investment in buildings and equipment, facility location tends to be a key decision for both public and private sector entities [6,7]. Any decision to invest in new plant or equipment (or reinvest in old plants or equipment) can be considered a facility location decision [8,9]. Even a business with a single production facility must decide whether to invest in the existing facility or open a new facility [10,11].

Each prospective investment location holds its own set of benefits and drawbacks in terms of production costs [12-14]. This brings about a novel kind of facility location model: a model in which per unit production costs change in proportion to the amount of product produced at the location. Actually, that proposed model is a combination of capacitated and uncapacitated facility location models. The distinctive feature of this model is that the output of each facility is unlimited, but it will cost more to raise the output by a certain amount [15-17]. This can be viewed as applying a soft capacity constraint to the problem. Unravished capacity constraints and soft capacity constraints allow the producer to exceed the defined production limit, but receive a penalty in the objective function [18-20]. If the penalty is small, the problem becomes similar to uncapacitated facility location problems. However, if the penalty is significant, it becomes more like a capacitated facility location problem [21-23].

The location of facilities and the allocation of demand have been studied by many researchers. In its modern form, the location problem was introduced by Weber in 1909 [15]. Pirkul and Jayaraman developed a heuristic method based on Lagrangian relaxation to solve the capacitated location problem with multiple product types in 1998 [13]. In 1997, Holmberg and Ling expanded the location model for a staircase cost function and solved the resulting model with a heuristic solution method [9,18].

Holmberg formulated the location problem with concave production costs and used various techniques including Benders decomposition to solve it [8].

In a 2001 study by Dasci and Verter, they expanded the uncapacitated location model to integrate several types of products and technologies. In this expanded model, the cost of using a technology increases concavely with total production. These researchers also provided a heuristic method for solving small-scale instances of this model [2].

In 2003, Harkness and ReVelle proposed and compared four formulations for a single-level location model where production costs vary with the production output [7].

In 2006, Wu, Zhang, and Zhang developed a capacitated location model with general setup cost functions for cases where multiple facilities can be constructed simultaneously in several locations. In this model, the setup cost is a function of facility size. This model was solved by a metaheuristic method based on Lagrangian relaxation [17].

In a study by Wollenweber, this problem was expanded for staircase costs and commodity splitting. This article also provided a two-phase algorithm utilizing Variable Neighborhood Descent (VND) and Variable Neighborhood Search (VNS) for solving the developed model [16].

Goli and Malmir developed a model for location-routing with covering tours and used a VNS-based metaheuristic algorithm to solve it [5].

In a 2021 study by Pahlevan et al., they developed a model for location, distribution, and production optimization in a multi-level supply chain. In this model, certain capacity levels were defined for warehouses and the cost function was considered to be linear. These researchers used the red deer algorithm to solve this problem [12].

Assuming that all of the existing models with nonlinear costs are of the single-level type and also the solutions proposed for these models are not applicable to larger problem instances, in this study, we use the model of Harkness and Revelle [7] as the foundation to build a novel two-level p-median model with nonlinear costs in the second-level facilities (warehouses). Since facility location at two levels is done simultaneously (plants and warehouses), we propose a two-phase recursive algorithm based on scatter search for solving the model. This model is a population-based, innovative method systematically combining answers to acquire a more accurate and precise answer, considering diversity and quality, compared to other conventional methods.

2. Materials and Methods

As explained in the previous section, in the location model of this study, the problem is the optimal location of a predetermined number of plants and warehouses in which production and inventory holding costs vary with the production output.

2.1. Problem description

In the location model of this study, it is assumed that the costs of producing the product and storing it in the plant or warehouse increase with the production output. Figure (1) shows the general form of the cost function assumed for each plant or warehouse.

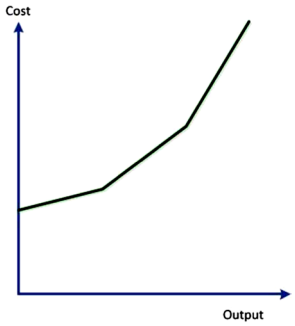


Figure 1. General form of plant/warehouse cost functions

To make the problem easier to formulate, we assume that each segment of the above curve is a straight line. With this assumption, each segment has a slope, which represents the per-unit cost, and a y-intercept (where the line crosses the cost axis), which represents the fixed setup cost. That is to say, each linear segment can be viewed as equivalent to a virtual facility with its own linear cost function. As a result, we must consider for each potential site as many virtual facilities as there are segments in the cost function. It must be remembered that upon selecting a potential site, only one of these virtual facilities can be active at a time, as the cost is dictated by the production output [5].

Figure (2) shows how the equivalent costs of virtual facilities are derived from the original cost function.

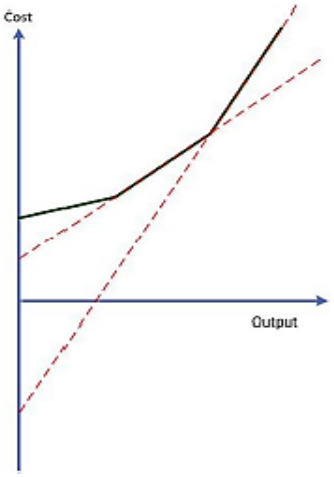


Figure 2. Cost function with virtual facilities replacing the original facility

2.2. Notations

The problem parameters and variables are as follows.

a: Index of the terms of the cost function that are related to after the arrival of the product at the warehouse

l: Index of the terms of the cost function that are related to before the arrival of the product at the warehouse

f_{il}: Cost of setting up virtual plant l at site i

u_{ja}: Cost of setting up virtual warehouse a at site j

c_{ijl}: Cost of supplying the demand of warehouse j from plant i in segment l of the cost function

c'_{jka}: Cost of supplying the demand of customer k from warehouse j in segment a of the cost function

d_k: Demand of customer k

$s_{i,l}$: Production capacity of plant i in segment l of the cost function

$s'_{j,a}$: Storage capacity of warehouse j in segment a of the cost function

y_{il}: A binary variable, =1 if site i is selected for setting up a plant with the output level of segment l of the cost function, =0 otherwise

z_{ja}: A binary variable, =1 if site j is selected for setting up a warehouse with the output level of segment a of the cost function, =0 otherwise

x_{ijl}: Fraction of the output of plant i that is supplied to warehouse j at the cost dictated by segment l of the cost function

x'_{jka}: Fraction of the demand of customer k that is supplied from warehouse j at the cost dictated by segment a of the cost function.

2.3. Problem formulation

With the above-described assumptions and introduced parameters and variables, the problem is formulated as follows:

$$\min \sum_i \sum_l f_{il}\, y_{il} + \sum_i \sum_a u_{ja}\, z_{ja} + \sum_i \sum_j \sum_l c_{ijl}\, s_{i,l} x_{ijl} + \sum_j \sum_k \sum_a c'_{jka}\, d_k x'_{jka} \tag{1}$$

$$\text{Subject to} \sum_j \sum_a x'_{jka} \geq 1 \qquad \forall k \in K \tag{2}$$

$$\sum_k d_k x'_{jka} \leq s'_{j,a} z_{ja} \qquad \forall j \in J, \forall a \in A \tag{3}$$

$$\sum_k d_k x'_{jka} \geq s'_{j,a-1} z_{ja} \qquad \forall j \in J, \forall a \in A \tag{4}$$

$$\sum_a z_{ja} \leq 1 \qquad \forall j \in J \tag{5}$$

$$\sum_{j}\sum_{a} z_{ja} = q \tag{6}$$

$$\sum_{k}\sum_{a} d_k x'_{jka} \le \sum_{i}\sum_{l} s_{i,l} x_{ijl} \qquad \forall j \in J \tag{7}$$

$$\sum_{j} s_{i,l} x_{ijl} \le s_{i,l} y_{il} \qquad \forall i \in I, \forall l \in L \tag{8}$$

$$\sum_{j} s_{i,l} x_{ijl} \ge s_{i,l-1} y_{il} \qquad \forall i \in I, \forall l \in L \tag{9}$$

$$\sum_{l} y_{il} \le 1 \qquad \forall i \in I \tag{10}$$

$$\sum_{i}\sum_{l} y_{il} = p \tag{11}$$

$$0 \le x_{ijl}, \quad x'_{jka} \le 1 \qquad \forall i \in I, \forall j \in J, \forall k \in K, \forall l \in L \tag{12}$$

$$y_{il}, z_{ja} \in \{0,1\} \qquad \forall i \in I, \forall j \in J, \forall k \in K, \forall l \in L \tag{13}$$

The first term of objective function (1): the total fixed cost of setting up virtual plant *l* at site *i*

The second term of objective function (1): The total fixed cost of setting up virtual warehouse *a* at site *j*

The third term of objective function (1): The total cost of supplying the demand of warehouse *j* from plant *i* in segment *l* of the cost function

The fourth term of objective function (1): The total cost of supplying the demand of customer *k* from warehouse *j* in segment *a* of the cost function

Constraint (2): The demand of all customers must be met.

Constraints (3) and (4): The fraction of the demand of customers that is supplied from warehouse *j* in segment *a* of the cost function should not exceed the capacity of that warehouse.

Constraints (5) and (10): Only one virtual plant can be set up at site *i* and only one virtual warehouse can be set up at site *j*.

Constraint (7): The output of each warehouse must be less than or equal to its input.

Constraints (8) and (9): The fraction of the demand of warehouses that is supplied from plant *i* in segment *l* of the cost function should not exceed the capacity of that plant.

Constraints (6) and (11): Specify that the number of plants (warehouses) that are to be set up should be p (q).

Constraints (12) and (13): Determine the type of variables (discrete or continuous) and their domain (discrete binary or continuous between 0 and 1).

2.4. Solution method

As proven by Mirchandani and Francis [11], all capacitated location problems are NP-hard [6]. Therefore, we also propose a two-phase meta-heuristic method based on scatter search for solving the model presented in the previous section. With the problem formulation, parameters and variables and the proposed model covered in the previous section, this section

provides a description of the solution method and the next section will present the numerical results obtained applying the method to a number of problem instances.

2.5. Scatter search

Scatter search is a meta-heuristic method that searches the solution space by evolving a set of reference points. It is an evolutionary method that operates on a small set of solutions and makes limited use of randomization methods to inject diversity in the search for the global optimum. Scatter search is highly flexible and allows for the development of alternative implementations with varying degrees of complexity [3,19,20]. From an algorithmic point of view, scatter search essentially performs its operations iteratively on a set of good solutions called the reference set. It should be noted that, here, the "goodness" of solutions refers to not only their quality but also the diversity that they bring to the set.

After creating an initial set of solutions, this algorithm starts an iterative process comprised of three steps: 1- Diversification Generation, 2- Improvement, and 3- Reference Set Update. In the following, we first describe the five main components of the algorithm and then explain how they interact with each other.

1- Diversification Generation Method: this component produces a diverse set of trial solutions by using one or multiple arbitrary seed solutions as input.

2- Improvement Method: this component improves the trial solutions to one or more enhanced trial solutions. While input and output solutions need not be feasible, this is preferable for output solutions. If an input trial solution cannot be improved, its enhanced version will be considered to be the same as the input solution.

3- Reference Set Update Method: this component builds and maintains a set of b best solutions ever created by the algorithm (b is typically small rarely exceed 20). Many different criteria can be defined for adding or removing solutions from the reference set.

4- Subset Generation Method: this component produces a subset of the reference set, which will later be used to generate combined solutions. The method most commonly used for this purpose is to generate pair combinations of all solutions in the reference set (subsets of size 2).

5- Solution Combination Method: this component takes a subset of solutions produced by the Subset Generation Method as input and transforms it into one or more combined solutions [3].

The basic mechanism for generating trial points in the solution space is the weighted linear combination of two points in the reference set. This mechanism is usually used in combination with a rounding mechanism to make sure that generated trial points do not violate the integer-constrained terms of the problem. These mechanisms are intended to give the weighted centers of each subset [10].

This procedure begins with generating a set of P initial solutions and then continues with deriving the reference set from this set. In this diagram, darker circles represent the enhanced solutions obtained from the improvement method.

3. Results and Discussion

We developed a two-phase recursive algorithm based on scatter search for solving the proposed model. In its first phase, this algorithm generates a set of random feasible solutions for setting up plants and uses it as the input of scatter search to find the optimal points for setting up warehouses. In the second phase, the algorithm uses the warehouse setup points obtained in the previous phase as the input of scatter search to find the optimal sites for setting up plants. At the end of the second phase, the algorithm compares the solution of the first phase with that of the second phase. If the solution of the second phase is better than that of the first phase, the algorithm starts redoing the first phase with the new better solution; otherwise, it records the solution of the first phase as the optimal solution. For each problem, we run this two-phase algorithm from the start a certain number of times and record the best solution ever found by the algorithm as the optimal solution to the problem.

In order to evaluate the validity of the model and the capability of the solution method, a number of small and large-sized test problems were designed. It is worth noting that these issues were labeled small or large based on the time it took to solve them. Table (1) demonstrates the profile of the designed small and large-sized problems.

Table 1. Profile of the designed small and large-sized problems

Mean solution time	k	a	q	m	l	p	n	Title	
219.6	21	3	6	13	4	4	8	*SSP*	Small-Sized Problems
2177.4	80	5	15	40	7	5	9	*LSP*	Large-Sized Problems

The designed problems were resolved with the proposed two-phase scatter search-based recursive algorithm. Utilizing MATLAB, the inputs of the algorithm were randomly generated with a uniform distribution on the intervals given in Table (2).

Table 2. Range of randomly generated inputs for the designed problems

Input parameter	For small-sized problems	For large-sized problems
f_{il}	[80, 110]	[90, 130]
s_{il}	[40, 90]	[80,190]
u_{jl}	[80, 100]	[90, 160]
S'_{ja}	[20, 50]	[30, 135]
d_k	[7, 13]	[10, 15]
c_{ijl}	[3.5, 5.5]	[5.5, 8.5]
c'_{jka}	[3.5, 5]	[6, 9]

To acquire statistically reliable and accurate numerical results, each problem was solved 10 times and the best objective function value ever found was recoded as the optimal solution. The results obtained for the first small-scale problem (SSP1) are given in Table (3) as an example.

Table 3. Results obtained from 10 runs of the algorithm for SSP1

	Run	Solution time (s)	Objective function value
SSP1	1	245	1214.3
	2	293	1265.9
	3	296	1205.1
	4	273	1252.6
	5	285	1248.4
	6	287	1258.2
	7	250	1191.4
	8	294	1177.6
	9	246	1245.8
	10	161	1236.9

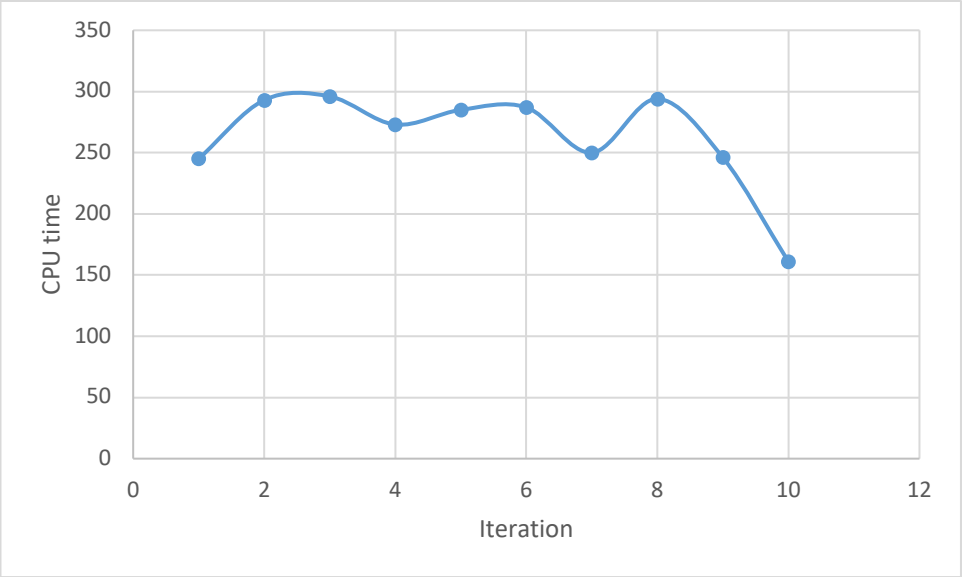


Figure 3. Comparison of solution times in different runs of the algorithm for SSP1

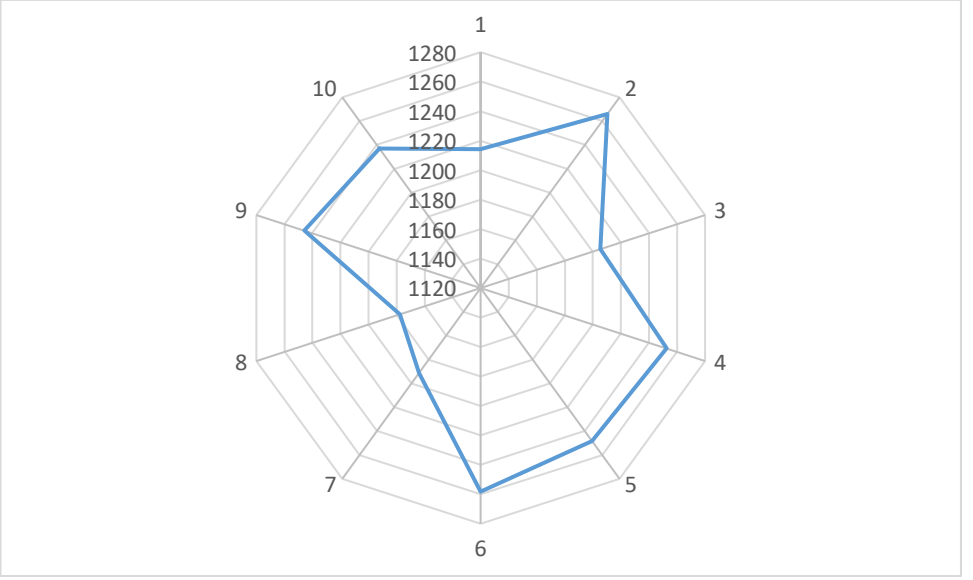


Figure 4. Comparison of objective function values obtained in different runs of the algorithm for SSP1

Based on Figure 3, the algorithm took almost the same amount of time to solve SSP1. Due to the fact that the solution algorithm runs through the same process every time, there is not much variation in calculations from one run to the next. A similar result can also be seen in Figure 4, which illustrates the values obtained for the objective function. According to the results obtained from 10 runs of the algorithm, the solution procedure can consistently and reliably produce optimal solutions. Table (4) presents the objective function values and solution times for all problems.

Table 4. Numerical results obtained by the developed recursive algorithm for the proposed model

Problem No.	Solution method		Problem No.	Solution method	
	scatter search-based recursive algorithm			scatter search-based recursive algorithm	
	Solution time (s)	objective function value		Solution time (s)	objective function value
SSP1	234	1176.1	LSP1	2391.2	6759.7
SSP2	281.5	1447.4	LSP2	2595.2	6764.5
SSP3	190	1326.2	LSP3	2794.5	7460
SSP4	194.3	1424.8	LSP4	2617.7	6259.9
SSP5	230.9	1358.6	LSP5	2877.1	7099.7

SSP6	318.7	1638.1	LSP6	3150.1	6350.4
SSP7	307.1	1620.4	LSP7	3057.6	7345
SSP8	162	1229.7	LSP8	2740.5	6389.6
SSP9	161	1291.8	LSP9	2812.2	6715.2
SSP10	280.7	1583.1	LSP10	3044	6931.5
Mean	236.02	1409.62	Mean	2808.01	6807.55

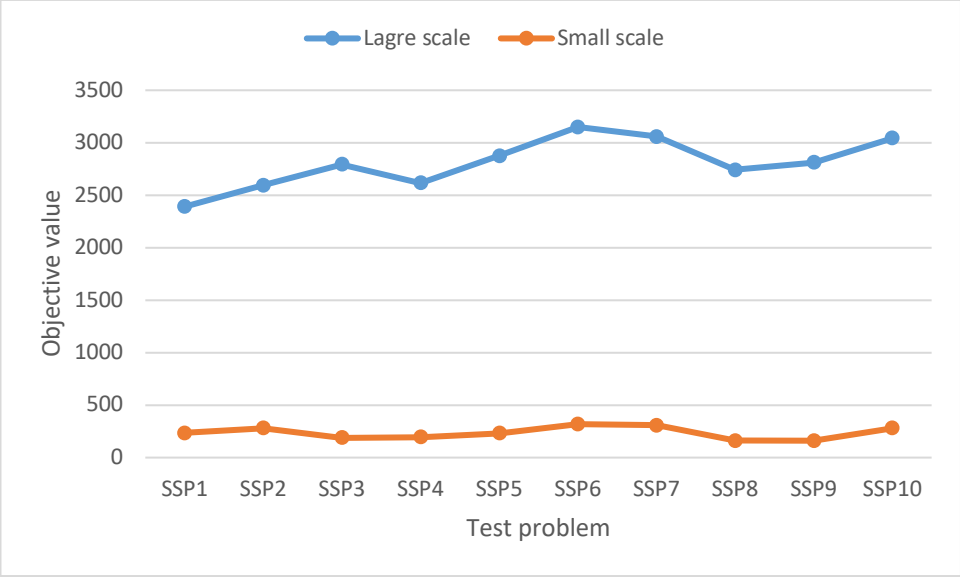


Figure 5. Comparison of objective function values obtained by the algorithm for small and large-sized problems

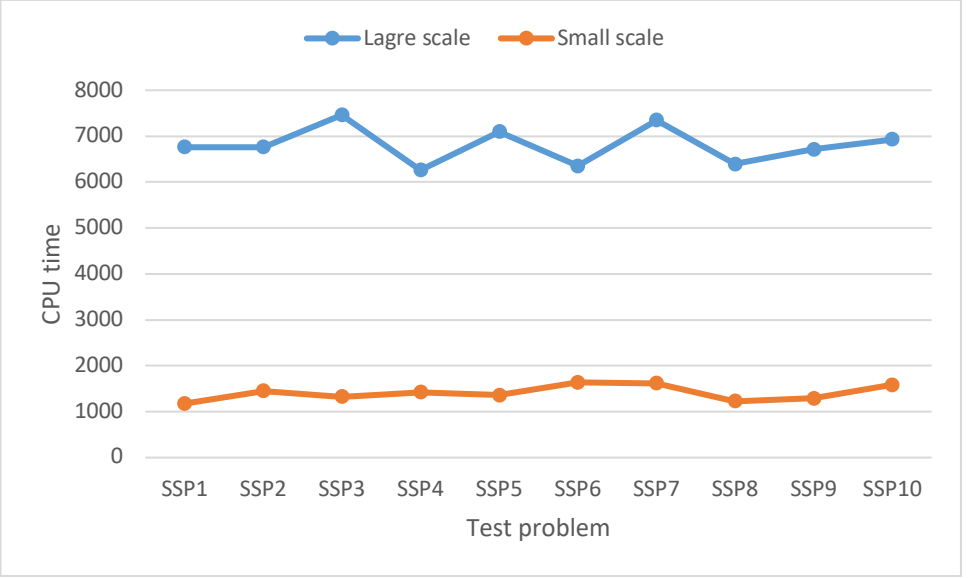


Figure 6. Comparison of solution times of the algorithm for small and large-sized problems

Results presented in Figures 5 and 6 indicate that objective function values obtained for large-sized problems are much larger (less desirable) than those obtained for small-sized problems. There has been an increase in both fixed and variable costs as a result of this. As a result, analyzing the developed algorithm on problem instances of various sizes demonstrated its efficiency and effectiveness in generating precise, and reliable solutions for the modeled problem.

4. Conclusion

The purpose of this study is to develop a model for the location of predetermined numbers of plants and warehouses in which production costs and inventory holding costs vary nonlinearly with production output. For the purpose of solving this model, a recursive algorithm based on scatter search was also developed in a two-phase process. After testing the algorithm that was developed on a number of different problem instances of varying sizes, it was found that it was capable of producing realistic, feasible solutions to the particular problem that was modeled. In terms of future studies, it is suggested to use the results of this study as a starting point for developing much more elaborate models, reflecting the greater complexity of real systems and a more accurate representation of operational features encountered along the supply chain. The model offers a few aspects to consider, primarily its implementation, since it would be interesting to observe how it develops, impacts, and responds to other business environments.

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