A New Mathematical Model for a Multi-product Supply Chain Network with a Preventive Maintenance Policy

A. Fatehi-Kivi, E. Mehdizadeh, R. Tavakkoli Moghaddam*<c,d>

Abstract

The supply chain network design (SCND) implicates decision-making at a strategic level and makes it possible to create an effective and helpful context for managing. The aim of the network is to minimize the total cost so that customer's demands should be met. Preventive maintenance is pre-determined work performed to a schedule with the aim of preventing the wear and tear or sudden failure of equipment components. Unfortunately, there is very little work on the issues of preventive maintenance in the SCND. At first, a mixed integer nonlinear programming model (MINLP) is formulated that maximizes the profit of the network. Since the SCND is an NP-hard problem, we use three meta-heuristic algorithms, namely tabu search, harmony search and genetic algorithm to solve the given problem. Taguchi method is also used to adjust the significant parameters of the forgoing meta-heuristics and select the optimal levels of the influential factors for the better algorithm performance. The results of different numerical experiments endorse the effectiveness of the HS algorithm.

Keywords:
Genetic Algorithm
 Harmony Search
 Preventive Maintenance
 Production-Distribution
 Supply Chain Network Design
 Tabu Search

1. INTRODUCTION

In the current competitive business environment, many factors can influence company’s performance, but the most important factors are product and service quality, customers’ satisfaction and low production and distribution costs. During the past decades there have been some interesting studies in the literature concerning the network design problem.


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Taxakis and Papadopoulos [10] proposed two models. The first model is a mixed-integer linear programming model which is concerned with the SCN design problem, whereas the second operational model is a mixed-integer non-linear programming model in respect to the production–distribution and inventory planning problem in a supply chain network. Ardalan et al. [11] presented supply chain networks design with multi-mode demand satisfaction policy. In multi-mode demand satisfaction policy, some modes are defined by the customers and one of those must be satisfied by the network. The major advantages of this policy rather than prefixed demand are outstanding performance in facility capacity usage, increasing the profit of the network and market share preserving. Also they developed a new iterative Lagrangian relaxation based heuristic.

Preventive maintenance has many different variations and is subject of various researches to determine best and most efficient way to maintain equipment. Preventive maintenance (PM) has the following meanings: (1) The care and servicing by personnel for the purpose of maintaining equipment and facilities in satisfactory operating condition by providing for systematic inspection, detection, and correction of incipient failures either before they occur or before they develop into major defects. (2) Maintenance, including tests, measurements, adjustments, and parts replacement, performed specifically to prevent faults from occurring [12]. Israel et al. [13] proposed a method, which aims to integrate information provided by Intelligent Maintenance Systems into the operational planning of a spare parts supply chain.

The multi-stage logistic network considered in this paper consists of three stages: plants, distribution centers and retailer locations. The problem deals with determining the optimal transportation network with preventive maintenance in order to satisfy the retailer multi-mode demands of several products by using several kinds of vehicles with the maximum profit. Its assumed that there are p vehicle types for transportation with a limited budget for purchasing or hiring them. The capacity of vehicles and their fixed travel cost are taken into consideration. The capacity of plants and distribution centers and cost of production product i on machines are taken into consideration too.

This paper considers the problem of the four-echelon supply chain network design (SCND) with a multi-mode demand satisfaction policy of retailers for multiple products and preventive maintenance with the maximum profit are defined. To this end, firstly the problem is defined with a mixed-integer non-linear programming model (MINLP) for integrated transportation and production in a supply chain. Then, three meta-heuristic algorithms, with a special chromosome structure is expanded to solve the problem.

The remaining of this article is organized as follows. Section 2 the problem is described and a mathematical model is presented. The solution approaches for solving the proposed model introduced in section 3. Taguchi method for tuning the parameters and computational experiments is presented in section 4. The conclusions and suggestions for future studies are included in section 5.

2. MATHEMATICAL MODEL

The logistics network discussed in this paper is a three stage logistics network including plants, distribution centers and retailers. The capacity of the sources and depots, the capacity of the vehicles, and the limited number of the vehicles are considered in this network. Mechanical, process or control equipment failure can have adverse results in both human and economic terms. Preventive maintenance, therefore, is a very important ongoing accident prevention activity, which you should integrate into your operations/ product manufacturing process.

2.1 Assumptions

In this section, we present a MINLP model for the Multi-Product Multi-Stage Supply Chain Network with Preventive Maintenance. The assumptions of the model are as follows:

- The location of retailers and their demand modes are known in advance.
- One of these demand’s mode for each retailer has to be satisfied by the distribution centers.
- The locations of plants and distribution centers are not predetermined and chosen from candidate options.
- Plants and distribution centers are capacitated.
- If maintenance is not performed in period t, the cost of maintenance will not apply to the model, the failure costs will be considered in period t+1 instead, and downtime will be deducted from available machine capacity.
- Transportation costs are based on the transportation cost of the products and using vehicles to carry products.
- The capacity of the vehicles, and the limited number of the vehicles are considered in this network.

2.2 Parameters and Indices

- $i$ index of product, $i = \{1, 2, \ldots, I\}$.
- $j$ index of distribution centers, $j = \{1, 2, \ldots, J\}$.
- $k$ index of retailers, $k = \{1, 2, \ldots, K\}$.
- $m$ index of mode satisfaction, $m = \{1, 2, \ldots, M\}$.
- $t$ index of periods, $t = \{1, 2, \ldots, T\}$.
- $n$ index of machines, $n = \{1, 2, \ldots, N\}$. 
\( f \) index of plants, \( f = \{1, 2, \ldots, F\} \)

\( p \) index of vehicle, \( p = \{1, 2, \ldots, P\} \)

\( Pr_{ci} \) Sale price of each unit of product \( i \) in period \( t \).

\( Vcp_{in} \) Variable production cost of product \( i \) on machine \( n \) in period \( t \).

\( D_{ikt}^m \) amount demand of product \( i \) by retailer \( k \) in mode \( m \) and in period \( t \).

\( CCP_{fi} \) Fixed costs of establishing plant \( f \) in period \( t \).

\( CCDC_{pj} \) Fixed cost of establishing distribution center \( j \) in period \( t \).

\( CP_{fi} \) Capacity of plant \( f \) to production of product \( i \) in period \( t \).

\( CW_{ji} \) Capacity of distribution center \( j \) of product \( i \) in period \( t \).

\( CB_{ni} \) Failure cost of machine \( n \) in period \( t \).

\( CM_{ni} \) Cost of service to maintenance of machine \( n \) in period \( t \).

\( CB_{pj} \) Failure cost of vehicle \( p \) in period \( t \).

\( CM_{pj} \) Cost of service to maintenance of vehicle \( p \) in period \( t \).

\( M_{in} \) Time capacity of machine \( n \) in period \( t \).

\( M_{pt} \) Time capacity of vehicle \( p \) in period \( t \).

\( E_{in} \) Time required for the machine \( n \) to produce a unit of product \( i \).

\( M \) A large number

\( MT_{ne} \) Time of maintenance on machine \( n \) in period \( t \).

\( MT_{pe} \) Time of maintenance on vehicle \( p \) in period \( t \).

\( K_{ne} \) Percentage of the capacity of machine \( n \), lost during period \( t \) (due to lack of maintenance in the previous period) due to failure.

\( K_{pe} \) Percentage of the capacity of vehicle \( p \), lost during period \( t \) (due to lack of maintenance in the previous period) due to failure.

\( a_p \) Distance traveled by the vehicle \( p \) per hour.

\( C_{i} \) Cost of carrying each product \( i \) during period \( t \) per unit of distance.

\( DM_{bj} \) Distance between plant \( f \) and distribution center \( j \).

\( DM_{bk} \) Distance between distribution center \( j \) and retailer \( k \).

\( p_{i} \) The cost of renting vehicle \( p \) in period \( t \).

\( C_{1,pij} \) Fixed cost of using vehicle \( p \) to transport product \( i \) from plant \( f \) to distribution center \( j \) in period \( t \).

\( C_{2,pijk} \) Fixed cost of using vehicle \( p \) to transport product \( i \) from distribution center \( j \) to retailer \( k \) in period \( t \).

\( a_{pi} \) Capacity of vehicle \( p \) to transport product \( i \).

\( p_{phe} \) Cost of renting or purchasing vehicle \( p \) in period \( t \).

\( b_{pe} \) Maximum budget available to buy or rent vehicle \( p \) in period \( t \).

\( X_{ijft} \) Total products \( i \) transported from plant \( f \) to distribution center \( j \) in period \( t \).

\( Y_{ikt} \) Total products \( i \) transported from distribution center \( j \) to retailer \( k \) in period \( t \).

\( R_{m}^{it} \) The binary variable is equal to 1 if the demand for mode \( m \) from product \( i \) is answered by the retailer \( k \) in period \( t \), otherwise it will be 0.

\( P_{fi} \) Binary variable equal to 1 if plant \( f \) is established in period \( t \), otherwise to 0.

\( W_{p} \) Binary variable equal to 1 if distribution center \( j \) is established in period \( t \), otherwise to 0.

\( PM_{ai} \) Binary variable equal to 1 if preventive maintenance decision variable on machine \( n \) in period \( t \), otherwise to 0.

\( PM_{pj} \) Binary variable equal to 1 if preventive maintenance decision variable on vehicle \( p \) in period \( t \), otherwise to 0.

\( B_{1,pijt} \) Binary variable represents the type of vehicle \( P \) chosen for product \( i \) from distribution center \( j \) to retailer \( k \) in period \( t \).

\( B_{2,pijk} \) Binary variable that represents the type of vehicle \( p \) want to move product \( i \) from factory \( f \) to distribution center \( j \).

### 2.3 Mathematical Modeling

The objective of this problem is to maximize the profit, which mathematically is written by:

\[
\begin{align*}
\text{Maximize} \quad Z &= \sum_{i} \sum_{f} \sum_{t} \sum_{n} \left( Pr_{ci} \left( \sum_{m} Vcp_{in} \right) D_{ikt}^m, R_{m}^{it} \right) + \\
& \sum_{f} \sum_{j} \sum_{i} \sum_{t} \left( \sum_{n} \sum_{m} \left( \sum_{p} P_{pij} \right) \right) X_{ijft} + \\
& \sum_{f} \sum_{j} \sum_{i} \sum_{t} \left( \sum_{n} \sum_{m} \left( \sum_{p} CM_{pj} \right) \right) Y_{ikt} + \\
& \sum_{f} \sum_{j} \sum_{i} \sum_{t} \left( \sum_{n} \sum_{m} \left( \sum_{p} CM_{pj} \right) \right) B_{1,pijt} \quad (1)
\end{align*}
\]

s.t.

\[
\sum_{m} R_{m}^{it} = 1 \quad \forall i, k, t \quad (2)
\]
\[
\sum_{i,j,k,t} x_{ijkt} = \sum_{i} \sum_{j} R^m_{ij} D^n_{kt}, \quad \forall i,k,t
\] (3)

\[
\sum_{j} x_{ijjt} \geq \sum_{k} x_{ijkt}, \quad \forall i,j,t
\] (4)

\[
\sum_{k} y_{ijk} \leq CW_{ij} W_{ip}, \quad \forall j,i,t
\] (5)

\[
\sum_{j} x_{ijt} \leq CP_{ij}, P_{jt}, \quad \forall i,t,f
\] (6)

\[
p_{ij} \left( \sum_{i} \sum_{j} B_{1 ij} + \sum_{j} \sum_{k} B_{2 ij} \right) \leq b_{it}, \quad \forall t,p
\] (7)

\[
x_{ijt} \leq M \sum_{p} B_{1 ij t}, \quad \forall i,f,j,t
\] (8)

\[
y_{ijk} \leq M \sum_{p} B_{2 ijkt}, \quad \forall i,j,k,t
\] (9)

\[
\sum_{p} B_{1 ij t} \leq 1, \quad \forall i,f,j,t
\] (10)

\[
\sum_{p} B_{2 ijkt} \leq 1, \quad \forall i,j,k,t
\] (11)

\[
\left( \sum_{i} \sum_{f} \sum_{j} x_{ijt} \right) + PM_{mf} MT_{mt} + (1 - \sum_{i} \sum_{j} \sum_{k} x_{ijkt} - \sum_{i} \sum_{j} \sum_{k} x_{ijkt}) K_{mf} M_{mt} \leq M_{mf}
\] (12)

\[
\left( \sum_{i} \sum_{f} DM_{if} \left( \sum_{j} \frac{x_{ijt}}{a_{it}} \right) B_{1 ij t} \right) + \left( \sum_{i} \sum_{f} DM_{if} \left( \sum_{j} \frac{y_{ijt}}{a_{it}} \right) B_{2 ij t} \right) \leq M_{m}
\] (13)

In the objective Function (1), maximizes total profit of the network. The first term is the total income of satisfied demands. The two subsequent terms are the fixed cost of opening plants and distribution centers, respectively. The third terms is failure and maintenance costs of machines and vehicles, respectively. The forth terms represent the purchasing or hiring cost of vehicles and the travel cost of vehicles to carry products between the related sources and depots.

Constraint set (2) guarantees that for each retailer, one mode of demand satisfaction is selected. Constraint set (3) represents that transported each product from distribution centers to each retailer is equal to satisfied mode of retailer’s demand. Constraint set (4) enforces that the total output of each distribution center is less than its total inputs. Constraint sets (5) and (6) ensure that the distributed products from each of the opened plants and distribution centers do not exceed their capacity limit. Constraint set (7) represents the budget constraints for purchasing or hiring vehicles. Constraint sets (8)-(9) enforce that there should be at least one kind of vehicle to carry products. Constraint sets (10)-(11) require that for each path and each product, only one kind of vehicle should be used. Constraint sets (12)-(13) The total amount of time needed to produce the product in the machine, maintenance time in the system and the reduced time of capacity due to system failure should be less than the available capacity of the machine and vehicle during the course. Constraints (14) and (15) place a binary and non-negativity restriction on the corresponding decision variables.

Defining new variables and adding some extra constraints as follows, non-linearity of the model can be eliminated.

\[
x_{ijjt} \times B_{1 ij t} = Z_{1 ijjt}
\] (16)

\[
Z_{1 ijjt} \geq X_{ijjt} - M (1 - B_{1 ij t})
\] (17)

\[
Z_{1 ijjt} \leq X_{ijjt} + M (1 - B_{1 ij t})
\] (18)

\[
y_{ijkt} \times B_{2 ijkt} = Z_{2 ijkt}
\] (19)

\[
Z_{2 ijkt} \geq Y_{ijkt} - M (1 - B_{2 ijkt})
\] (20)

\[
Z_{2 ijkt} \leq Y_{ijkt} + M (1 - B_{2 ijkt})
\] (21)

3. Solution Concepts

In this section, first the chromosome representation is described, and then metaheuristic algorithms are used to solve the problems. The notable advantage of a metaheuristic algorithm its ability in solving NP-hard problems. A number of authors [14–16] proposed metaheuristics to solve large-sized problems considering their computational time. Due to the NP-hardness of the proposed model, it is necessary to use a meta-heuristic approach to solve the proposed model. In this paper we
use three meta-heuristic algorithms namely harmony search, tabu search and genetic algorithms. Table 1 show the Algorithm components and characters.

3. 1. Representation Scheme In this paper, the general structure of the solution representation performed for two products, two retailers, and two modes is shown in Figure 1. All algorithms are compiled in Visual Basic programming language. All computational tests are performed on a Dell not book at Intel Core2 Duo Processor 2 GHz and 2 GB of RAM.

4. COMPUTATIONAL RESULTS

4. 1. Parameter Calibration In this section Taguchi method is employed to tune the parameters of the HS, GA and TS Algorithms, because the values of meta-heuristic algorithms parameters affected on quality of the solution. Taguchi method is a fractional factorial experiment proposed by Taguchi useable as an efficient alternative for full factorial experiments [17]. Table 2 lists different levels of the factors for HS, TS and GA. In this paper according to the levels and the number of the factors, respectively Taguchi method L27 for HS, GA and TS is used for the adjustment of the parameters for algorithms. Figures 2-4 show the S/N ratios.

<table>
<thead>
<tr>
<th>TABLE 1. Three algorithms and their components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorithm</td>
</tr>
<tr>
<td>GA</td>
</tr>
<tr>
<td>HS</td>
</tr>
<tr>
<td>Tabu</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 2. Factors and their levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
</tr>
<tr>
<td>size of the tabu list</td>
</tr>
<tr>
<td>Neighborhood size</td>
</tr>
<tr>
<td>Pitch adjustment rate</td>
</tr>
<tr>
<td>Harmony memory consideration rate</td>
</tr>
<tr>
<td>Harmony memory size</td>
</tr>
<tr>
<td>Stop criteria</td>
</tr>
<tr>
<td>Number of population</td>
</tr>
<tr>
<td>Probability of mutation</td>
</tr>
<tr>
<td>Probability of crossover</td>
</tr>
<tr>
<td>Strongly mutation</td>
</tr>
<tr>
<td>Stop criteria</td>
</tr>
</tbody>
</table>

4. 2. Numerical Results In this paper the test instances are randomly generated based on the features of the integrated production-distribution planning problem. An instance is generated for each number of demand periods. Each instance is executed in ten runs.
instances that can be characterized by the number of products \( n_p \) that are between 2 and 15, plants \( n_m \) that between 2 and 14, retailers \( n_r \) that are between 2 and 11, satisfaction mode \( n_m \) that are between 2 and 12, periods \( n_t \) that are between 2 and 19, machines \( n_m \) that are between 2 and 16, vehicle \( n_v \) that are between 3 and 22. The objective function values listed in Table 3 are the average values in the ten runs for each instance. Table 4 shows the CPU time of three algorithms in each instance. In Tables 5 and 6, according to the values of the survey (or P-Value) we can get the conclusion that the algorithm HS has the best solution quality in each instance between the three algorithms. To clarify the matter, the one-way analysis of variance (ANOVA) was used to compare the performances and CPU time for different sizes have been illustrated in tables and Figures 5 and 6. The objective function value obtained by HS is bigger than that of the other two algorithms in each instance. TS and GA are the second and third best algorithms for solution quality, respectively and for cpu time the incremental sequence is HS, TS and GA according to the computational time.

**Figure 4.** S/N ratio for the tabu search algorithm

Computational experiments are conducted to validate and verify the behavior and the performance of the algorithms to solve the production and supply chain network model with preventive maintenance. Table 3 shows details of computational results obtained by solution methods for all test problems. We define 20

**TABLE 3.** Solution qualities of GA, HS and TS for each instance

<table>
<thead>
<tr>
<th>Pro.</th>
<th>Objective function values</th>
<th>HS</th>
<th>TS</th>
<th>GA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>((n_p, n_m, n_r, n_t, n_m, n_v))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>2916</td>
<td>2916</td>
<td>2916</td>
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<tr>
<td>2</td>
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<td>4111.009</td>
<td>4111.009</td>
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<td>26745</td>
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<td>10936.66</td>
<td>10936.66</td>
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<td>7</td>
<td>(4,4,5,6,5,6,3,9)</td>
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<td>12726.4</td>
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<td>12</td>
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<td>23845.2</td>
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<td>26076.15</td>
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<td>40473.32</td>
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<td>44274.81</td>
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<td>19</td>
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<td>77732.40</td>
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<td>49870.75</td>
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**TABLE 4.** CPU time of GA, HS and TS for each instance

<table>
<thead>
<tr>
<th>Pro.</th>
<th>Objective function values</th>
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<th>GA</th>
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<tr>
<td></td>
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<td>977.88</td>
<td>2210.56</td>
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</tr>
<tr>
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<td>(9,7,8,8,13,10,16)</td>
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<td>2402.24</td>
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</tr>
<tr>
<td>15</td>
<td>(10,8,9,9,14,11,17)</td>
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<td>2295.54</td>
<td>2839.21</td>
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<tr>
<td>16</td>
<td>(11,8,10,9,15,12,18)</td>
<td>2348.73</td>
<td>2487.22</td>
<td>2962.41</td>
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<tr>
<td>17</td>
<td>(12,9,10,11,8,16,13,19)</td>
<td>2576.21</td>
<td>3029.66</td>
<td>3727.91</td>
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<tr>
<td>18</td>
<td>(13,9,11,12,10,17,14,20)</td>
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<td>3830.99</td>
</tr>
<tr>
<td>19</td>
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<td>3315.62</td>
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<td>20</td>
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<td>2767.44</td>
<td>3808.59</td>
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network with multiple factories, multiple distribution centers, and multiple retailers and multi-mode demand satisfaction policy with preventive maintenance and decision-making need to determine the optimal routes and vehicles when there is a limited budget for hiring vehicles. In this study, we formulated the problem as a mixed integer nonlinear programming model (MINLP) to maximize the total profit. To solve the proposed model, three meta-heuristic algorithms namely HS, GA and TS was employed. Furthermore, an extensive parameter setting with performing Taguchi method was conducted for selecting the optimal levels of the factors that effect on the algorithm’s performance. The results of the algorithms showed that the HS algorithm had a better performance than the GA and TS in terms of the objective function on 20 generated random problems. The one-way analysis of variance (ANOVA) was used to compare the performances of the HS, GA and TS algorithms statistically but HS had big time than GA and TS. Also, the tendency displayed that HS had better performances in comparison with GA and TS in most problems. Some of the opportunities for future research are as using the other meta-heuristic algorithms and extending the model with probability parameters.

6. REFERENCES

A New Mathematical Model for a Multi-product Supply Chain Network with a Preventive Maintenance Policy

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Keywords: Genetic Algorithm, Harmony Search, Preventive Maintenance, Production-Distribution, Supply Chain Network Design, Tabu Search

Abstract

We present a new mathematical model for designing a multi-product supply chain network (SCN) that requires a strategic decision at one level and the possibility of establishing an effective and reliable maintenance policy. The objective of this network is to optimize the total cost of the system in response to demand. Preventive maintenance and repair activities are considered as performed tasks aimed at preventing failure and emergency breakdowns. Unfortunately, discussions on preventive maintenance have been limited to a few studies. Initially, we formulate a mixed-integer nonlinear programming model with the goal of maximizing profits in the network. The problem is then modeled as a mixed-integer linear programming problem, since it is known that the supply chain problem is NP-Hard. We use three metaheuristic algorithms (Genetic Algorithm, Harmony Search, and Tabu Search) to solve the presented model. Also, the Taguchi method is used to determine the optimal level of the algorithms' parameters. The effectiveness of the Harmony Search algorithm will be confirmed via numerical examples.