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Benders Decomposition for Distribution Networks with Cross-docking Centre

Manpreet Singh, Divya Aggarwal* and Vijay Kumar

Computer Science and Engineering Department, Thapar University, Patiala, India

ABSTRACT

This paper proposes the Benders Decomposition approach for modelling distribution networks with cross-docking centres. The cross-docking centre eliminates the requirement for inventory stores. The mathematical formulation of the proposed model is also presented, and the latter consists of plants, cross-docking centres and distribution centres. The Bender Decomposition approach is utilised to solve the proposed model which is tested on 15 different characteristics of test instances. The effect of plants, and cross-docking centres are also investigated. The experimental results reveal the proposed formulation provides promising solutions with reasonable computation time.

Keywords: Benders Decomposition, Cross-docking, Dual Sub-Problem, Master Problem, Mixed Integer Programming

INTRODUCTION

There is an increasing need to develop an effective supply chain that provides better service to customers' demand and minimise the investment cost. Therefore, the selection of facility location is an important factor in the supply chain. The cost of opening and setting a new facility can greatly affect profits. Therefore, an efficient warehousing strategy is required to reduce the distribution cost. Hence, the cross-docking concept is introduced in the distribution network. The main concept behind cross-docking is the delivery of goods from suppliers to customers through intermediate cross-docking centres where the materials are not stored for long time, generally less than 24 hours.

Cross-docking system facilitates the rapid movement of materials by eliminating storage. It improves organisations' response time and reduces transportation cost. Therefore, cross-docking has become a great distribution strategy as it can speed up the flow of goods

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E-mail addresses:
manibhangu92@gmail.com (Manpreet Singh)
aggarwaldivya2593@gmail.com (Divya Aggarwal)
vijaykumarchahar@gmail.com) (Vijay Kumar)
*Corresponding Author

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which would eventually lower the transportation cost. If locations of cross-dock centres are chosen carefully, then the transportation cost can be reduced to a great extent. The Cross-Dock technique can eventually reduce the distribution costs while satisfying customer demand (Kellar et al., 2015; Mousavi et al., 2014).

The main contribution of this paper is to incorporate the cross-docking concept in the supply chain. A novel model is proposed that utilise the concept of cross-docking. The mathematical formulation of proposed model has been introduced. The Bender Decomposition approach has been used to optimise transportation and fixed costs. The performance of proposed model has been tested on 15 different test instances. The results have been compared with IBM CPLEX.

The reminder of this paper is organised as follows. Section 2 presents the related work done in the field of facility location problem while Section 3 describes the proposed model. The proposed solution methodology is described in Section 4 and Section 5 presents the experimental setup, results and discussions. Finally, the paper is concluded in Section 6.

RELATED WORK

Over the last few decades, the issue of facility location had gained attention of researchers (Melo et al., 2009; Erengüç et al., 1999). The main focus of these researches are on determining which site location should be selected for establishing new facilities from the available set of potential sites while satisfying the constraints. Hindi and Basta (1994) proposed a structure of problem inspired by Geoffrion and Graves (1974) which is a branch and bound approach as solution. Uster et al. (2007) studied a distribution system design problem that has a fixed number of capacitated facilities and suggested various metaheuristics to solve this problem. Cintron et al. (2010) proposed a multi-criterion problem. They solved the problem using Mixed Integer Programming (MIP). Sun and Wang (2015) proposed strategic distribution network design problem of bulk materials considering different distribution modes before and after an intermediate unloading in the distribution centres. They solved mixed- integer model by using the Benders Decomposition (BD).

Cross-docking (CD) is a relatively new strategy in logistics (Van Belle et al., 2012). The various well-known companies, such as Toyota, UPS, Wal-Mart, Kodack Co, Good Year, etc. have successfully implemented Cross-docking in their distribution system. Ross and Jayaraman (2008) suggested a solution approach with the combination of Simulated Annealing and Tabu Search to solve linear programming model of supply chain. The supply chain includes potential retailers, cross-docking centres, and regional warehouses. Dondo and Cerda (2012) considered pickup and delivery problem in a cross-docking system known as Vehicle Routing Problem with Cross-docking (VRPCD). They worked on a monolithic formulation which determined the truck scheduling at the cross-docking centre and routes. It involved a solution strategy based on sweep heuristic which can solve big problems within reasonable CPU time.

Arabani et al. (2010) suggested a cross-docking scheduling problem in which product delivery should have a pre-determined time schedule. Moreover, penalties are considered for any late delivery. Three solution approaches namely Differential Evolution (DE), Genetic Algorithm (GA), and Particle Swarm Optimisation (PSO) were developed to solve this problem. Lee et al. (2006) considered a cross docking system in supply chain. They developed a mathematical model for vehicles. Tabu search algorithm was used to optimise the developed mathematical model.

The above-mentioned researchers missed BD approach for modelling the distribution network with cross-docking centres tracking flow of materials. The concept of cross-docking centres is utilised in this paper and a model is proposed that involves single-sourcing constraints which ensures that each distribution centre is exclusively served by a single cross-docking or merge-in-transit centre. Here, single-period, single-product, and multi-echelon are considered in a deterministic situation to understand the fundamental concepts of cross-dock planning problem. This approach increases the utilisation of warehouse and prevents the construction of links and location of the warehouse with low utilisation.

Moreover, when the problem is considered with large instances, it does not provide optimal solutions. Hence, the BD approach is used to solve mathematical formulation of the given problem. The problem is decomposed into two sub-problems. Figure 1 shows the two-stage classical distribution network where supply is made between the distribution centres and facility location, and customer locations and distribution centre. Figure 2 describes the distribution network with intermediate Cross-dock.

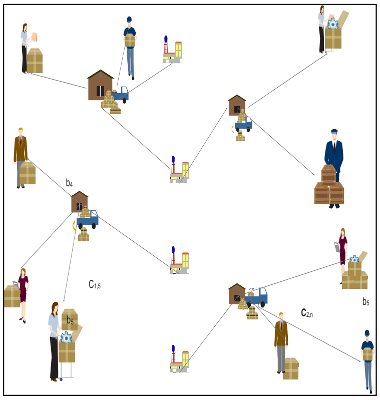

Figure 1. Two-stage distribution network

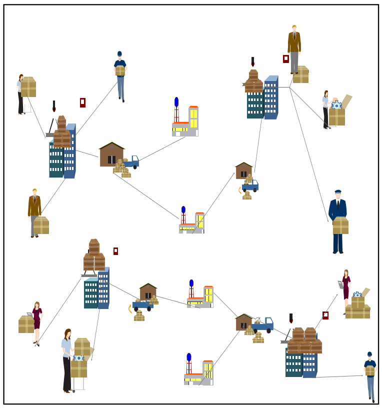

Figure 2. Cross-dock distribution network

MATHEMATICAL FORMULATION

Figure 3 shows the three-stage graph network that considers facility location problem with cross-docking centres. It consists of plants, warehouses and distribution centres which are represented by nodes and relationship between these nodes are represented by links. The model considers two binary variables for opening the cross-docking and allocating to distribution centres. The flow of products from manufacturing plants to operating cross-docks centres are considered in this model.

The following notations, parameters and decisions variables have been used in mathematical formulation of mixed-integer programming model.

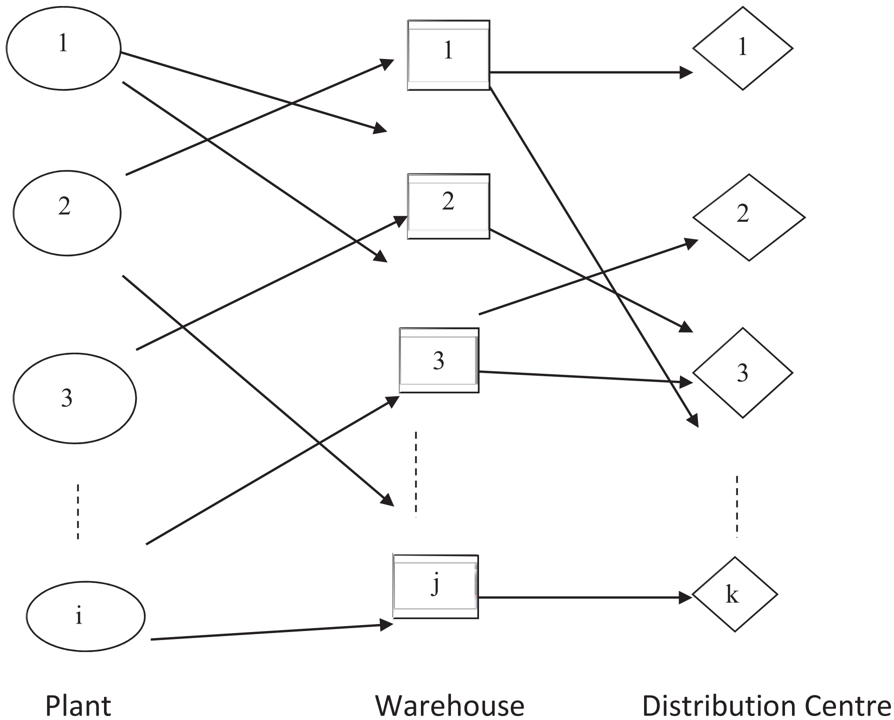

Figure 3. Distribution network incorporate Cross-docking centres

Notations

1. I : set of manufacturing Plants, indexed by i, $\forall i \in I$
2. J : set of Cross-docking warehouses, indexed by j, $\forall j \in J$
3. K : set of Distribution Centres, indexed by k, $\forall k \in K$

Constants

1. C_i : Capacity of Plant i.
2. W_j : Capacity of Cross-docking warehouse j.
3. F_j : Fixed opening cost of cross-docking warehouse in location w.
4. T_{ij} : Transportation cost per unit product from plant i to cross-docking warehouse j.
5. S_{ik} : Shipping cost of product from Cross-dock Warehouse j to distribution centre k.
6. R_k : Request for distribution centre k.

Binary Decision variables

$$X_{jk} = \begin{cases} 1, & \text{if warehouse } j \text{ fulfill demand of distribution center } k \\ 0, & \text{otherwise} \end{cases}$$

$$Y_j = \begin{cases} 1, & \text{if cross-dock warehouse is opend at location } j \\ 0, & \text{otherwise} \end{cases}$$

Q_{ij} : Amount of product sent from plant i to the cross-dock j

The mathematical formulation of the problem is as follows:

$$\min Z = \sum_{i\in I}\sum_{j\in J} T_{ij} * Q_{ij} + \sum_{j\in J} F_j * Y_j + \sum_{j\in J}\sum_{k\in K} S_{jk} * R_k * X_{jk} \tag{1}$$

subject to

$$\sum_{j\in J} Q_{ij} < C_i, \forall i \in I \tag{2}$$

$$\sum_{k\in K} R_k * X_{jk} = \sum_{j\in J} Q_{ij}, \forall j \in J \tag{3}$$

$$\sum_{j\in J} X_{jk} = 1, \forall k \in K \tag{4}$$

$$\sum_{k\in K} r_k * X_{jk} = W_j * Y_j, \forall j \in J \tag{5}$$

$$P * Y_j \leq \sum_{k\in K} X_{jk}, \forall j \in J \tag{6}$$

$$P = \min\{R_k\}, \forall k \in K \tag{7}$$

$$Q_{ij} \geq 0, \forall j \in J, \forall i \in I \tag{8}$$

$$Y_j \in \{0,1\}, \forall j \in J \tag{9}$$

$$X_{ij} \in \{0,1\}, \forall i \in I, \forall j \in J \tag{10}$$

The objective function mentioned in Eq. (1) consists of three terms. The first term is the cost of transportation from manufacturing plant i to Cross-dock Warehouse j. The second term describes the fixed cost to open cross-dock warehouse j. The third term includes the amount for achieving demand raised by distribution centre k. The constraint (2) implies that the output of plant i does not violate the capacity of plant i. The constraint (3) confirms the quantity of arrival products to be same as sent from plant *i*. The constraint (4) ensures the demand satisfaction of each distribution centre *k* by a single Cross-docking warehouse *j*. The number of products that can be sent to a distribution centre *k* from an open cross-docking warehouse *j* is confirmed by constraint (5). The constraint (6) guarantees that at least the minimum amount of demand is received by cross-dock warehouse. The constraint (7) ensures that the minimum demand of each distribution centre *k* is considered. The constraints (8), (9), and (10) ensure the non-negative and integrity conditions.

PROPOSED SOLUTION APPROACH

The BD approach is used to solve the mathematical model mentioned above. Figure 4 shows the flowchart of BD which consists of following steps:

- Compute the Sub-Problem (SP) from given problem by fixing integer variables.
- Compute Dual Sub-Problem (DSP) which provides lower-bound (*LB*) of the problem.
- Compute Master Problem (MP) which provides upper bound (*UB*) of the problem.
- Compute *LB* and *UB* repeatedly until $UB - LB < \varepsilon$. Here, ε is a very small constant.

Steps of Algorithm

1. Initialise the parameters of BD approach. The lower bound (*LB*) and upper bound (*UB*) are set to -∞ +∞ respectively. The values for X_{ij} and Y_j are initialised.
2. Compute DSP which gives LB.

   $Max_u \{(\beta^t \bar{y} + \Omega - b\bar{y})^T u \mid \alpha^T u \leq C, u \geq 0\}$
3. *If* LB is unbounded

   Get unbounded Ray $\bar{u}$.

   Add cut $(\Omega - by)\ \bar{u} \leq 0$ to MP

   Else

   Get extreme point $\bar{u}$

   Add cut $Z \geq \beta^T y + (\Omega - by)^T \bar{u}$ to MP

   Set UB to Min $\{UB, \beta^T \bar{y} + (\Omega - b\bar{y})^T \bar{u}\}$

   End If
4. Solve MP which gives upper bound.
5. Repeat Steps 2-6 until $UB - LB < \varepsilon$

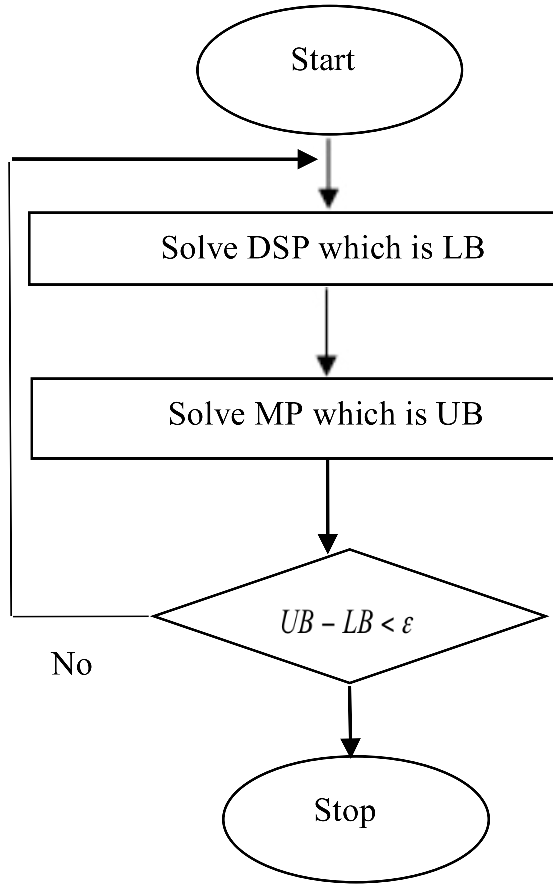

Figure 4. Flow chart of Benders Decomposition

Solving the BD Problem

The given SP is decomposed into two sub-problems such as DSP and MP. The mathematical representation of the sub-problem is given below:

$$\min Z = \sum_{i \in I} \sum_{j \in J} T_{ij} * Q_{ij} + \sum_{j \in J} F_j * \overline{Y}_j + \sum_{j \in J} \sum_{k \in K} S_{jk} * R_k * \overline{X}_{jk} \tag{11}$$

subject to

$$-\sum_{j \in J} Q_{ij} \geq -C_i, \forall i \in I \tag{12}$$

$$\sum_{i \in I} Q_{ij} = \sum_{k \in K} R_k * \overline{X}_{jk}, \forall j \in J \tag{13}$$

$$\sum_{i \in I} Q_{ij} \geq P * \overline{Y}_i \ , \forall i \in I \tag{14}$$

For DSP, three new variables, namely U1, U2, U3 are introduced. The value of these variables is taken as positive. The value of these variables is fixed for MP. The mathematical representation of DSP is given below:

$$\max Z = -\sum_{i\in I} C_i U1_i + \sum_{j\in J}\sum_{k\in K} R_k \overline{X_{jk}} U2_{jk} + \sum_{j\in J} P\overline{Y_j} U3_j \tag{15}$$

subject to

$$-U1_i + U2_{jk} + U3_j \leq T_{ij}, \qquad \forall i \in I, \forall j \in J \tag{16}$$

The mathematical representation of MP is given below:

$$Z \geq \sum_{j\in J} F_j * Y_j + \sum_{j\in J}\sum_{k\in K} S_{jk} * R_k * X_{jk} + -\sum_{i\in I} C_i * \overline{U1_i} + \sum_{j\in J}\sum_{k\in K} R_k * \overline{X_{jk}}\,\overline{U2_{jk}} + \sum_{j\in J} P * \overline{Y_j} * \overline{U3_j} \tag{17}$$

subject to

$$-\sum_{i\in I} C_i * U1_i + \sum_{j\in J}\sum_{k\in K} R_k * \overline{X}_{jk} U2_{jk} + \sum_{j\in J} P * \overline{Y}_j * U3_j \leq 0 \tag{18}$$

$$X_{jk} \in \{0,1\} \tag{19}$$

$$Y_j \in \{0,1\} \tag{20}$$

Computation of Dual Sub-Problem (DSP)

DSP gives lower bound for fixed values of X_{jk} and Y_j. It is computed using the following procedure:

Step 1. Initialise the values of decision variables X_{jk} and Y_j.

Step 2. *If* problem is feasible

Add new optimality cut

Else

Add new feasibility cut

End If

Step 3. Repeat Step 2 until termination condition is not satisfied.

Computation of Master Problem (MP)

MP is used to obtain feasible and optimal solutions. It depends on the results generated by DSP. After solving DSP, the feasible values for X_{jk} and Y_j are obtained which may not be optimal solution for the original problem. It is used to generate feasible and optimal solution which provides an upper bound of given problem. If the new value of *UB* is better than the previous one, then the value of *UB* is updated. This procedure is repeated until the bound gap is reached. If both MP and DSP are not feasible, then the algorithm is terminated.

Termination Conditions

The algorithm will terminate if any of the following conditions are satisfied:

1. Bound Gap: It is reached when difference of UB and LB gets close to zero; i.e., $(UB-LB) < \varepsilon$, ε is very small constant value. Typically, pre-specified value of ε is 0.00001.
2. Iteration limit: When the iteration limit has reached a pre-determined value *maxItrLimt;* i.e., If $n > maxItrLimt$, then processing will terminate. *MaxItrLimt* is typically set to 1000.
3. Step size Limit: When the step size α becomes Negligible (approximately zero); i.e., If $\alpha < minStepSize$, then processing will terminate. *MinStepSize* is typically set to 0.0001.
4. Infeasible Solution: If both DSP and MP give infeasible solution, then no results will be generated for this problem.

PERFORMANCE ANALYSIS

This section validates the performance of the proposed model over 15 test instances and compares it with IBM CPLEX solver.

IBM CPLEX Solver

The IBM CPLEX is one of the tools widely used to solve combinatorial optimisation problems. It has a concert technology that provides interfaces to C++, C# and Java languages. It is accessible through independent modelling systems, such as AMPL, and TOMLAB. It is also recognised as a constraint solving toolkit suitable for solving optimisation models. It uses inbuilt procedures to solve the mixed integer programming in short time. It can be used to solve a variety of different optimisation problems in a variety of computing environments. The IBM CPLEX is an exact solver that uses mixed integer programming to search the desired solutions.

Test Dataset

The three types of datasets are randomly generated in Table 1. Dataset *X* has large opening cost of cross-dock warehouse, while dataset *Y* has moderate opening cost of cross-dock warehouse with large transportation cost from plant to warehouse and from warehouse to distribution centres. Therefore, the shipping is costlier than opening a new warehouse in *Y* dataset. The instances generated in dataset *Z* are based on small to medium sized organisations. It has moderate transportation and opening cost of cross-dock warehouse. The datasets for problem are randomly generated by keeping realistic characteristics for small and medium sized organisation. Table 1 represents the range of possible values for cost, demand, supply and capacity in each dataset. Here, *U* indicates uniform distribution of numbers over the specified range. The average value of 10 independent simulation runs are reported. Table 2 shows the size and characteristics of test instances.

Table 1
Detail of dataset used

Datasets	*X* (Type 1)	*Y* (Type 2)	*Z* (Type 3)
Cross-Dock Warehouse Opening Cost (F_j)	*U* [1500, 4000]	*U* [500,1250]	*U* [400,2000]
Transportation cost from Plant to *i* warehouse *j* (T_{ij})	*U* [50, 110]	*U* [80, 130]	*U* [75, 130]
Shipping Cost from Cross-Dock warehouse to Distribution centres (S_{jk})	*U* [50, 110]	*U* [80, 120]	*U* [50, 120]
Demand (R_k)	*U* [10,25]	*U* [10, 25]	*U* [20, 45]
Plant's Capacity (M_i)	*U* [15, 45]	*U* [25, 40]	*U* [20, 50]
Warehouse Capacity (N_j)	*U* [10,30]	*U* [25, 60]	*U* [25,75]

Table 2
Characteristics of test instances

Instance	Plants (I)	Warehouse (W)	Distribution Centre (D)	Constraints	Continuous Variables	Binary Variables	Iterations
1	11	17	25	106	385	910	2755
2	15	25	30	115	525	1085	16448
3	28	43	71	185	1204	3096	2253815
4	26	41	53	161	1066	2214	511439
5	17	27	35	138	731	1548	17283
6	22	37	45	141	814	1702	3374
7	37	42	65	186	1554	2772	92978
8	19	63	91	236	1197	5796	2593380
9	22	36	45	139	792	1656	924374
10	21	34	39	128	714	1360	6231
11	32	61	95	249	1952	5856	2753898
12	47	79	127	332	3713	10112	1179933
13	23	61	91	236	1403	5612	1497516
14	21	35	47	138	735	1680	1773725
15	29	43	49	164	1247	2150	51670

Experimental Results

The test instances are checked by decomposing the problem into DSP and MP which give the lower bound and upper bound to the optimal solution respectively.

The optimality gap is calculated to measure performance and is defined as follows:

$$Optimality\ Gap = \frac{UB - LB}{UB} \times 100 \tag{21}$$

Table 3 depicts optimality gap, computation time and mean objective for the various test instances. It is observed from table that the proposed model provides better computational time than CPLEX Solver which solves the problem by computing mixed integer programming. The problem instances are solved in lesser time than CPLEX Solver. The optimality gap obtained from the proposed model is smaller than 0.25. This means that the solution produced by the proposed model is close to an optimal one. The computational test on the random instances with size up to 50 has maximum gap of 0.2%. This shows that the proposed approach is quite promising.

Table 3
Performance evaluation on test instances

CPLEX Solver						
Instance	Plants (I)	Warehouse (W)	Distribution Centre (D)	Gap%	CPU Time (in sec)	Mean Objective
1	11	17	25	0.00	1.89	6.849E+3
2	15	25	30	0.00	2.14	8.999E+3
3	28	43	71	0.20	34.13	2.110E+4
4	26	41	53	0.11	24.09	1.510E+4
5	17	27	35	0.12	1.84	8.199E+3
6	22	37	45	0.21	2.05	2.128E+4
7	37	42	65	0.28	10.30	2.153E+4
8	19	63	91	0.32	173.12	2.908E+4
9	22	36	45	0.09	44.71	1.899E+4
10	21	34	39	0.10	1.09	1.265E+4
11	32	61	95	0.20	171.85	3.600E+5
12	47	79	127	0.21	165.20	4.848E+5
13	23	61	91	0.23	126.47	2.935E+4
14	21	35	47	0.02	78.81	2.975E+5
15	29	43	49	0.04	4.11	1.954E+5
Benders Decomposition (Proposed Model)						
Instance	Plants (I)	Warehouse (W)	Distribution Centre (D)	Gap%	CPU Time (in sec)	Mean Objective
1	11	17	25	0.00	1.11	7.438E+03
2	15	25	30	0.00	1.53	1.012E+03
3	28	43	71	0.12	31.34	2.101E+04
4	26	41	53	0.08	20.87	1.635E+04
5	17	27	35	0.00	1.25	1.039E+03
6	22	37	45	0.07	1.34	1.502E+04
7	37	42	65	0.13	7.50	1.963E+04
8	19	63	91	0.15	138.39	2.649E+04
9	22	36	45	0.05	37.57	1.241E+04
10	21	34	39	0.07	0.87	1.182E+04
11	32	61	95	0.15	151.32	2.756E+04
12	47	79	127	0.20	153.87	3.688E+05
13	23	61	91	0.19	122.59	2.641E+04
14	21	35	47	0.00	61.54	1.415E+05
15	29	43	49	0.00	3.21	1.588E+05

Analysis of Parameters Involved

Figure 5 shows the impact of number of plants, cross-docking and distribution centres on the objective function. The horizontal axis gives the approximate objective value when multiplied by 10^3. The bigger the number of plants, warehouses and distribution centres, the greater the objective function. This figure also shows the value of plants, warehouses and distribution centres affect the value of objective function.

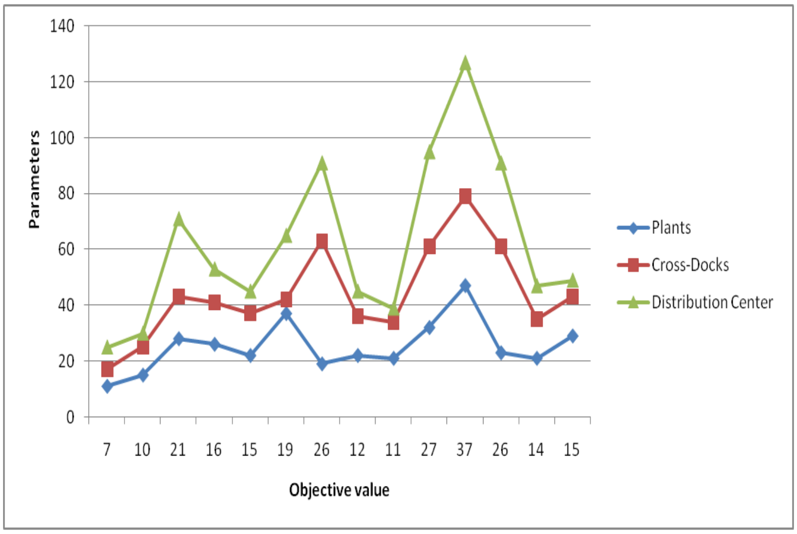

Figure 5. Impact of number of parameters involved in proposed model

CONCLUSION

In this paper, the concept of cross-docking in distribution network was proposed. The model utilised the concept of cross-docking. The mathematical formulation of proposed model was established. The Benders Decomposition was utilised to optimise the proposed model. The proposed model was tested on 15 test instances. The experimental result reveal that the proposed model is found to be superior to the CPLEX solver in terms of computational time, objective function and optimal gap. For future studies, the proposed model can be used in a parallel environment.

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