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158. A Supply Chain Network Design and Decision Approach and Minimizing Carbon Monoxide Emission to the Environment

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Abstract

This paper submits realistic evidence from a descriptive case study in an industry at the supplier-plant, plant-warehouse and warehouse-customer interfaces. The lead time from the first step to the last is long and it comprises of many levels. Product distribution accounts for a substantial portion of the logistical costs of a product. Distribution activities are repetitive in nature and they influence the delivery lead time to consumers. A well designed fully flexible supply chain network can significantly minimize these costs and lead times. The current study presents a supply chain network design and decision approach for the distribution of products by identifying the supplier, plant and warehouse location and customer allocation. Grade of the product and capacity of the warehouse to satisfy the required customer demand, are solved for optimum solution. Solving the problem for feasible routes to deliver products to customers minimizes the carbon-monoxide emission from vehicles to the environment. The selection of shortest route with minimum hurdles increases the responsiveness, minimizes the transportation cost and CO emission to the environment. A case study is solved to explain the proposed heuristic. At the end, concluding remarks and recommendations for further research are presented.

Keywords: Network design; Traffic factor; CO emission; Green Supply Chain.

1. Introduction

Supply chain managers frequently come across location and allocation problems at the design phase of a supply chain that involves determining the number of suppliers, plants, warehouses and assigning of customers. It appears imperative to treat the location and allocation decisions simultaneously. But due to the complexity of the problem, a breakdown into levels (level-1, level-2 and level-3) helps to manage the complexity of large sized problems. The location decision involves substantial investment. Since it can't be changed frequently, therefore, it has long term implications. The suppliers, plants and warehouses' locations acts as prelude to the overall process of supply chain network design with far reaching effects on the performance of the logistics and distribution system. On the other hand, the allocation decision is more dynamic in nature as these assignments need to be reviewed and changed from time to time as the supply chain grows. This is especially true for the steel, petroleum, cement, etc. products' distribution in Pakistan and other developing countries as well, where the retail outlets and customer buying stations for such products are expanding at an increasing rate.

The work presented is mainly concerned with location of warehouses covering all customers and allocation of customers to the warehouses and minimizing the number of warehouses while satisfying customer demand. We have also incorporated the inter-warehouse distances, thereby further improving the product distribution. Another feature of our approach is to incorporate the traffic factor based on which the route for product delivery to the customers is decided. Some constraints must be imposed during the customer demand delivery associated to a warehouse. Minimizing the number of warehouses increases the load per unit warehouse and thus warehouses must be built with sufficient capacities. Customers are assigned to a warehouse based on the capacity of the warehouse. The procedure developed determines all the feasible routes for the delivery of products to customers from a warehouse through a shortest feasible route. The required grade of the product is also incorporated in this study which further improves the solution.

A supply chain comprises of suppliers, manufacturers, distributors, traders and consumers. A supply chain delivers products with quickest distribution to the customers and at most reasonable price. A supply chain is no longer a single chain but a network tied with many chains, called supply chain network. It is realistically believed that the study of supply chain network has more real-world significance than the study of traditional supply chain [1]. Supply chain networks are worldwide networks with suppliers, manufacturers, distribution centers, traders and customers. The supply chain networks perform the functions of locating of raw materials, conversion of those into intermediate and completed products, the distribution of completed products to consumers and its key objective is to fulfill the consumer requirements. In old-style supply chain networks, the objective is to balance the benefits among the firms involved, to enhance the operating efficiency throughout the services, to maximize the profitability of the procedures and to generate value for the consumers [2]. Supply chain network management is a progressively applied policy for companies. Supply chain network management is an integration of main business procedures from suppliers to end customers. Hence, a supply chain network management system can only be effective if it supports all the main business procedures [3]. Having an effective and efficient supply chain network offers a marketing zone for enterprises in the worldwide business atmosphere. Determining locations, quantity of product flow and reducing transportation costs are handled as a network design problem in supply chain management. Items that include the supply chain are highlighted to provide customer satisfaction and to get competitive advantage in process between raw material suppliers and end customers [4]. A global economy and a growth in consumer expectations concerning costs and services have forced manufacturers to increase their business practices particularly within their supply chains. A supply chain is a network of business entities mutually responsible for moving a product from supplier to consumer. It contains such interconnected activities as the supply of raw materials for manufacturing, customer order, management of inventory, production scheduling and transporting goods to consumers. Supply chain management covers the management of these activities in a smooth way [5]. The processes in product supply chain and logistics are part of today's greatest important economic activities. The ever-growing size of transportation of products has its own concerns, particularly those relating to the environment. Transportation activities are significant causes of air pollution having harmful effects on human health and also responsible for global warming. These matters have raised concerns on reducing the volume of emissions worldwide. In this respect, many countries have set strict targets on minimizing their carbon emissions in the near future [6].

The problem studied in this paper is related to the determination of all the required warehouses in order to satisfy a set of customers' demand. Various industrial constraints are involved and studied in the planning and operating processes. The procedure developed leads to considerable improvement in terms of minimizing the number of warehouses and selecting the feasible routes. The solution procedure is based on linear programming model which is solved by the Network Simplex algorithm. LP_Solve_5.5.2.0_IDE and MATLAB R2009a predefined functions and formulae are used to achieve the required final integer optimal solution.

2. Literature Review

A. Gill presented a supply chain network design method for the delivery of petroleum products by recognizing the locations of warehouses and allocations of gas stations. Supply chain supervisors often come across location of warehouse and allocation of gas station problems at the design stage of a supply chain that includes determining the number of warehouses and assigning of consumers to warehouses [7]. Supply chain networks offer the structure for the manufacturing, storage, and delivery of products like pharmaceuticals, steel, vehicles, cements, computers, furniture, and clothing, throughout the world. A. Nagurney developed a modeling and analytical framework for the design of sustainable supply chain networks. A network optimization modeling framework and a procedure are presented, which is then applied to calculate results to a variety of numerical sustainable supply chain design cases in order to exemplify the method [8]. In the competitive trade world, today, industrialists face the continuing task to frequently calculate and design their production and delivery systems and policies to offer the desired consumer service at the lowermost possible cost. Long-range existence for manufacturing companies will be very tough without highly optimized strategic systems. Savings in the range of 5–10% can be attained by using strategic and calculated logistics models and it can significantly affect the profitability of the firm [9].

J.F. Campbell presented the problems of location of discrete hubs. Hubs serve as transshipment and switching points for traffic between identified origins and destinations. A non-negative flow is linked with every origin-destination pair and an attribute such as distance or cost is associated with each movement.

The word cost is used throughout the study which represents the element of interest [10]. Supply chain network design deals with a variety of decisions i.e. determining number of products, capacity and location of facilities and may include decisions such as product distribution and transportation to customers. It may also include operational decisions e.g. satisfying customers demand [11]. The management of supply chain has been considered as the most significant activity in several organizations. In supply chain management, the goal has been to send required products from one level to another, in order to fulfill customer demands such that sum of the costs is minimized [12]. In integrated supply chain design, the decision makers need to consider inventory and distribution costs when the number and localities of the facilities (warehouses) are determined. The goal is to minimize the overall cost that comprises location and inventory costs at the distribution centers, and supply costs in the supply chain [13].

Ting W and Kaike Z presented a computational study for common network design in multi-commodity supply chains. Their aim was to minimize the cost including location, transportation, and inventory costs [14]. Seval E and Nursel O presented a mathematical model for multi stage and multi period reverse supply chain network, which maximized overall revenue of the network. The suggested model defines warehouse locations and material movements between phases in each period [15]. Tsao YC and Jye-Chye presented a supply chain network design considering transportation cost discounts and developed an algorithm to solve SCM problems using nonlinear optimization techniques [16]. In recent years, the study on supply chain networks has become a main focus. Components and product movement through suppliers, product manufacturers, product distributors, and consumers, is termed as supply chain network. These networks have many applications in manufacturing and distribution, e.g., automobile and electronic industries [17]. Striving for optimal conditions is essential because the current competitive conditions motivate manufacturers to produce faster and inexpensive products with a better quality. Unsuitable process parameter settings may result several manufacturing problems as product defects, longer lead times and higher prices [18]. In the periodic event scheduling problem (PESP), events have to be arranged repetitively over a certain period. It is a complex and well-known problem with many real-world applications [19]. Various methods have been applied for solving linear and nonlinear network flow problems with the aim of examining, improving and understanding the computational efficiency of suggested solutions for lowest cost problems. C.M.S. Machado et al. suggested a network flow linear program model to explain the problem of reducing costs of production and delivering of products to customers [20]. C. A. Colberg et al. [21] presented that the emissions of single road vehicles depend on many factors such as type of engine (two- or four-stroke, gasoline or diesel) and its size, driving conditions (acceleration and speed), road gradient, type of exhaust technology, type of fuel and maintenance. Emission Factors of single vehicles can be measured by dynamometer tests. Imenez-Palacios et al. [22] presented that Vehicle emissions can of course vary with the engine load and with vehicle characteristics. The vehicle specific power (VSP) is a measure for engine load and useful for comparison between different measurement conditions.

3. The Inter-Warehouse Distances

The inter-warehouse distances are incorporated in this study. Table 1 shows the inter-warehouse distances. If warehouse W_1 has sufficient capacity to fulfill the customer demand, then there is no need of installing any other warehouse. If a single warehouse does not have sufficient capacity, then the customer will load some of the required demand from one warehouse and will then go to another nearest warehouse to complete the demand on a shortest possible route. While going to the nearest warehouse, the route will be decided based on the shortest distance, maximum traffic factor value, capacity of warehouse and availability of grade of the required product. Fig. 2 shows a general fully flexible supply chain network.

	W_1					
W_1	0	W_2				
W_2	$D_{2,1}$	0	W_3			
W_3	$D_{3,1}$	$D_{3,2}$	0	W_4		
W_4	$D_{4,1}$	$D_{4,2}$	$D_{4,3}$	0	W_5	
W_5	$D_{5,1}$	$D_{5,2}$	$D_{5,3}$	$D_{5,4}$	0	W_6
W_6	$D_{6,1}$	$D_{6,2}$	$D_{6,3}$	$D_{6,4}$	$D_{6,5}$	0

Table 1. Inter-warehouse distances

Here, $D_{i,j}$ is the distance between i^{th} and j^{th} warehouses for $i \neq j$.

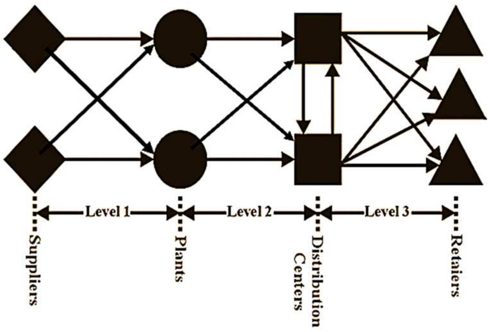

Fig. 1. A general supply chain network

4. Heuristic Solution Approach

The approach is two folds. First, the warehouse locations are chosen from the available sets of warehouses which can cover the customers based on a pre-assigned maximum threshold distance. Then, the customers are allocated to the selected warehouses. The steps of the procedure are as follows:

4.1 Location of warehouses

The location of warehouses involves two steps. First, to construct a binary coefficient matrix so as to identify the potential locations, then selecting the actual locations using a mathematical programming model.

4.1.1 Construction of the binary coefficient matrix for maximum threshold distance

Based on the maximum permissible distance, d_{max}, a binary coefficient matrix [α_{ij}] is prepared, which is to be used as an input to the mathematical model. The relation used to construct the binary matrix is:

$$\alpha_{ij} = 1, \text{ if } d_{ij} \leq d_{max}, \text{ otherwise } 0.$$

Note that:

$$d_{ij} = \frac{D_{ij}}{T_{ij}} \qquad (1)$$

Whereas, d_{ij} is the revised distance, D_{ij} is the actual distance and T_{ij} is the traffic factor value.

4.1.2 Construction of the binary coefficient matrix for the capacity of warehouses

Based on the capacity C_j of the set of warehouses X_j, a binary coefficient matrix [β_{ij}] is prepared, which is to be used as an input to the mathematical model. The relation used to construct the binary matrix is:

β_{ij} = 1, if sum of capacities of all the warehouses is greater or equal to the sum of total customer demand, otherwise 0.

4.1.3 Construction of the binary coefficient matrix for grade of the required product

Based on the grade of the products, a binary coefficient matrix [γ_{ij}] is prepared, which is to be used as an input to the mathematical model. The relation used to construct the binary matrix is:

γ_{ij} = 1, if a set of warehouses Xj has grade of the products demanded by customer i, otherwise 0.

4.1.4 Route existence

A route between the two nodes will exist if:

$$\alpha_{ij}\beta_{ij}\gamma_{ij} = 1 \tag{2}$$

and a route between the two nodes will not exist if:

$$\alpha_{ij}\beta_{ij}\gamma_{ij} = 0 \tag{3}$$

$i = 1,2,..., m$ and $j = 1,2,..., n$

Whereas, m is the number of customers, n is the number of sets of warehouses.

4.1.5 Network simplex method mathematical model

Network simplex method is composed of nodes and arcs. The locations of warehouses and customers are represented by nodes and the distances between them are represented by arcs (routes).

Minimize:

$$Z = \sum_{pq} d_{pq} Y_{pq} \tag{4}$$

Subject to:

$$A_{p,qr} Y_{pq} \geq R_p \tag{5}$$

$$A_{p,qr} = \begin{cases} -1 & if \;\; p = q, \\ +1 & if \;\; p = r, \\ 0 & Otherwise. \end{cases} \tag{6}$$

Whereas, A is a matrix indexed by the set of nodes and is incidence matrix of a network. And p is the number of nodes, d_{pq} is the distance from node p to node q, Y_{pq} is the required amount of products to ship from node p to node q through distance d_{pq}. Negative value of R_p means capacity of warehouse (source), and positive value of R_p means customer demand (destination).

A customer may be facilitated directly from a single warehouse. However, when a single warehouse has not sufficient products as demanded by the customer, then two or more than two warehouses jointly can satisfy a customer. Fig. 3 shows all the feasible routes to approach a customer. A customer C may be directly facilitated from warehouse 1 or may be facilitated from two warehouses i.e. starting from warehouse 1 (origin) and passing through warehouse 2 and then reaching customer C. Similarly, a customer C may be facilitated from three warehouses i.e. starting from warehouse 1 (origin), passing through warehouses 2 and 3 and then reaching customer C and so on.

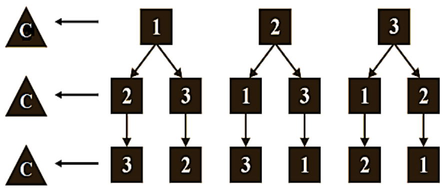

Fig. 2. Warehouse-customer feasible routes

5. Case Study

The production plants produce unlimited products and then store the products in the warehouses. Table 2 shows the capacity of each warehouse. A single warehouse may or may not have sufficient capacity to fulfill the total customer demand. If a single warehouse cannot satisfy customer demand, then two or more than two warehouses (set of warehouses) jointly satisfy the customer demand. It is preferred that a warehouse be constructed with sufficient capacity. The customer demands are shown in Table 3.

Table 2. Warehouse capacity

Warehouse	Capacity
1	500
2	700
3	400

Table 3. Customer demand

Customer	Demand
C_1	390
C_2	350
C_3	250
C_4	380

The example solved explains the proposed procedure. Table 4 shows the inter-warehouse distances. The distance between warehouse 1 and warehouse 2 is 60 km. The distance between warehouse 1 and warehouse 3 is 70 km and similarly the distance between warehouse 2 and warehouse 3 is 45km.

Table 4. Inter-warehouse distances

	W_1		
W_1	0	W_2	
W_2	60	0	W_3
W_3	70	45	0

The warehouse-customer distances are shown in Table 5. The distance between warehouse 1 and customer 1 is 110km and the distance between warehouse 2 and customer 1 is 60km and so on.

Table 5. Warehouse-customer distances

	W_1	W_2	W_3
C_1	110	60	45
C_2	70	95	80
C_3	25	90	95
C_4	95	40	75

X_1, X_2,…, X_{15} are the maximum feasible number of sets of warehouses fulfilling the customer demand. Table 6 shows the maximum number of feasible sets of warehouses for satisfying the customer demand.

Table 6. Sets of warehouses

Set	Members	Set	Members	Set	Members
X_1	W_1	X_6	W_2 W_1	X_{11}	W_1 W_3 W_2
X_2	W_2	X_7	W_2 W_3	X_{12}	W_2 W_1 W_3
X_3	W_3	X_8	W_3W_1	X_{13}	W_2 W_3 W_1
X_4	W_1 W_2	X_9	W_3W_2	X_{14}	W_3 W_1 W_2
X_5	W_1 W_3	X_{10}	W_1 W_2W_3	X_{15}	W_3 W_2 W_1

Table 7 (Appendix A) shows the warehouse-customer distances. In the set X_1 of warehouses, the direct distance from warehouse W_1 to customer C_1 is 110km. In the set X_4 of warehouses, the total distance, starting from warehouse W_1 (origin), passing through W_2 and reaching customer C_1 (destination) is 120km. Similarly, in the set X_{10} of warehouses, the total distance starting from warehouse W_1 (origin), passing through W_2 and W_3 and reaching customer C_1 (destination) is 150km and so on.

The traffic factor values for the designed routes are given in Table 8. For the set of warehouses X_4, the distance between W_1 and W_3 is 70km and traffic factor value is 1. The distance between W_3 and C_3 is 95km and traffic factor value is 0.9. The total distance of the route starting from W_1 passing through W_3 and reaching C_3 is 165km. So, the overall traffic factor value for this route will be 0.94. Mathematically:

$$\frac{[70+95]}{\left[\frac{70}{1}\right]+\left[\frac{95}{0.9}\right]} = 0.94^* \qquad (7)$$

The route starting from W_2 passing through W_1 and reaching C_1, has a traffic factor value 1 between W_2 and W_1 and has a traffic factor value 0 between W_1 and C_1. This route will be discarded because there is no overall traffic flow possible from warehouse W_2 to customer C_1. Hence, the overall traffic factor value is 0^+ (zero) for this designed route.

The actual distances divided by the traffic factor value gives us revised distance d. When the traffic factor value is zero, then either there is no route from the warehouse to customer or the route is closed. Table 9 shows the revised distances from the sets warehouses to the customers.

∞ means that either the distance is too large or there is no access possible from origin to destination. Based on the maximum permissible distance, d_{max}, a binary coefficient matrix $[\alpha_{ij}]$ is prepared. In Table 10, the binary coefficient matrix is shown. The following relation can be used to construct the binary matrix.

$$\alpha_{ij} = 1, \text{ if } d_{ij} \leq d_{max}, \text{ otherwise } 0.$$

$$d_{max} = 100km \text{ (In this case)}$$

Based on the capacities of the sets of warehouses, a binary coefficient matrix $[\beta_{ij}]$ is prepared. The following relation is used to make the binary matrix for the capacities of the sets of warehouses. β_{ij} =1, if sum of capacities of all the warehouses is greater or equal to the sum of total customer demand, and 0 otherwise. Table 11 shows that each set of warehouses has sufficient capacity.

Based on the grade of the products, a binary coefficient matrix $[\gamma_{ij}]$ is prepared. The following relation is used to construct the binary matrix. γ_{ij} = 1, if a set of warehouses X_j has products of the required grade demanded by customer i, and 0 otherwise. Table 12 shows the binary coefficient matrix $[\boldsymbol{\gamma}_{ij}]$ for the grade of the required products.

Multiplying the corresponding binary coefficients α_{ij}, β_{ij} and γ_{ij} evaluated in Table 10, 11 and Table 12 respectively. Using Eqs. 2 and 3, the corresponding values are shown in Table 13.

The network flow diagram for this example is shown in Fig. 4. There are three warehouses and four customers. The total nodes are 7. Negative value inside the node shows source (warehouse) and positive value inside the node shows destination (customer demand). Y_{15} is the units of product required to shift from warehouse 1 (node1) to customer 2 (node 5) and d_{15} is the corresponding actual distance (70 km). Using Eq. 6, binary coefficients of Y_{ij} are shown in Table 14.

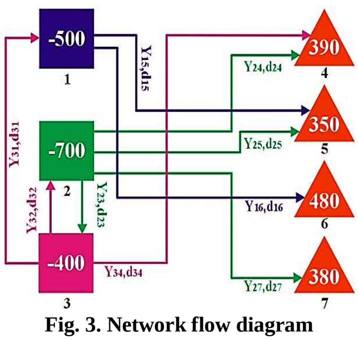

Fig. 3. Network flow diagram

$$d_{ij} = [d_{15}\ d_{16}\ d_{23}\ d_{24}\ d_{25}\ d_{27}\ d_{31}\ d_{32}\ d_{34}] \qquad (8)$$

From Eq. 8, the distance matrix is:

$$d_{ij} = [70\ 25\ 45\ 60\ 95\ 40\ 70\ 45\ 45] \tag{9}$$

$$Y_{pq} = \begin{bmatrix} Y_{15} \\ Y_{16} \\ Y_{23} \\ Y_{24} \\ Y_{25} \\ Y_{27} \\ Y_{31} \\ Y_{32} \\ Y_{34} \end{bmatrix} \tag{10}$$

$$B = \begin{bmatrix} -500 \\ -700 \\ -400 \\ +390 \\ +350 \\ +480 \\ +380 \end{bmatrix} \tag{11}$$

From Eq. 4, the objective is:

Minimize: $Z = 70Y_{15} + 25Y_{16} + 45Y_{23} + 60Y_{24} + 95Y_{25} + 40Y_{27} + 70Y_{31} + 45Y_{32} + 45Y_{34}$

And from Eq. 5, the constraints are:

$$-Y_{15} - Y_{16} + Y_{31} \geq -500$$
$$-Y_{23} - Y_{24} - Y_{25} - Y_{27} + Y_{23} \geq -700$$
$$Y_{23} - Y_{31} - Y_{32} - Y_{34} \geq -400$$
$$Y_{24} + Y_{34} \geq 390$$
$$Y_{15} + Y_{25} \geq 350$$
$$Y_{16} \geq 480$$
$$Y_{27} \geq 380$$

The problem is solved with the data provided in the tables. The model comprises of 7 constraints and 9 variables with an objective to minimize the total cost and minimizing the CO emission. All instances were solved using lp_solve version 5.5.2.0 for 32 bit OS, with 64 bit REAL variables, 2.00 GB of RAM and Intel® Core™ i3 CPU 2.53 GHz processor. Time to load data was 0.001 seconds; presolve used 0.006 seconds, 0.020 seconds in simplex solver, in total 0.027 seconds.

$Y_{15}=30$	$Y_{24}=0$	$Y_{31}=10$
$Y_{16}=480$	$Y_{25}=320$	$Y_{32}=0$
$Y_{23}=0$	$Y_{27}=380$	$Y_{34}=390$

The optimum solution is: Z = 77950

The sub-network of Fig. 4 is given in Fig. 5.

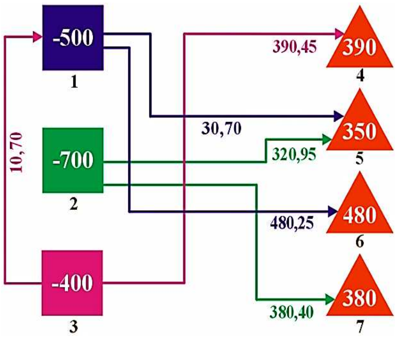

Fig. 4. Product supply to demand locations

In this case study, the total demand is equal to total capacity of the three warehouses. If we increase the capacities of the warehouses as shown in Fig. 6, then less number of warehouses will fulfill the required demand from customers. For example, if we increase the capacities if warehouse 1, 2 and 3 to 800, 900 and 700 respectively then only two warehouses (warehouse 1 and 2) will be enough to fulfill the total customer demand. There will be no need of warehouse 3.

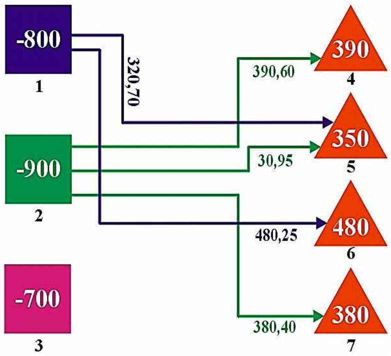

Fig. 5. Final network flow diagram

6. Conclusion

The present paper evaluates product distribution strategy of a company with a view to improve its distribution network for better area coverage and to identify its major warehouse locations and allocation of customers to the selected warehouses. The capacity issue is important as the company has a practice of frequently reviewing its supply chain decisions. The required grade of product is included in the current analysis and the inter-warehouse distances further optimized the solution. Traffic factor is incorporated in the mathematical modeling and has an important impact in the route selection for the supply of products. The problem is solved for feasible routes to deliver products to the end customers, which minimized the carbon-monoxide emission from vehicles to the environment.

It is envisioned that the scope of the analysis could further include issues such as criteria for sequencing and scheduling, precedence relations, preemption and Gantt charts. The sequencing and scheduling criteria issue was omitted from current analysis based on the assumption that customers have sufficient waiting time for loading of the required products. Secondly, for the existing four customers, sequencing and scheduling, precedence relation and preemption had never been a problem.

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Appendix A

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
C_1	110	60	45	120	115	170	90	180	105	150	175	175	225	190	215
C_2	70	95	80	155	150	130	125	140	140	185	210	210	185	225	175
C_3	25	90	95	150	165	85	140	95	135	200	205	225	140	220	130
C_4	95	40	75	100	145	155	120	165	85	180	155	205	210	170	200

Table 7. Warehouse-customer distances

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
C_1	0	1	1	1	1	0^+	1	0	1	1	1	1	0	1	0
C_2	1	1	0	1	0	1	0	1	1	0	1	0	1	1	1
C_3	1	1	0.9	1	0.94^*	1	0.93	1	1	0.95	1	0.96	1	1	1
C_4	1	1	0	1	0	1	0	1	1	0	1	0	1	1	1

Table 8. Traffic factor values for the designed routes

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
C_1	∞	60	45	120	115	∞	90	∞	105	150	175	175	∞	190	∞
C_2	70	95	∞	155	∞	130	∞	140	140	∞	210	∞	185	225	175
C_3	25	90	105	150	175	85	150	95	135	210	205	235	140	220	130
C_4	95	40	∞	100	∞	155	∞	165	85	∞	155	∞	210	170	200

Table 9. Revised warehouse-customer distances

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
C_1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0
C_2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
C_3	1	1	0	0	0	1	0	1	0	0	0	0	0	0	0
C_4	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0

Table 10. Binary coefficient matrix [α_{ij}]

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
C_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
C_2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
C_3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
C_4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 11. Binary coefficient matrix [β_{ij}]

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
C_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
C_2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
C_3	1	0	1	0	1	0	0	1	0	0	0	0	0	0	0
C_4	0	1	1	0	0	0	1	0	1	0	0	0	0	0	0

Table 12. Binary coefficient matrix [γ_{ij}]

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
C_1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0
C_2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
C_3	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
C_4	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0

Table 13. Existence of routes

	Y_{qr}	Y_{15}	Y_{16}	Y_{23}	Y_{24}	Y_{25}	Y_{27}	Y_{31}	Y_{32}	Y_{34}
Number of nodes (i)	1	-1	-1	0	0	0	0	+1	0	0
	2	0	0	-1	-1	-1	-1	0	1	0
	3	0	0	+1	0	0	0	-1	-1	-1
	4	0	0	0	1	0	0	0	0	+1
	5	+1	0	0	0	+1	0	0	0	0
	6	0	+1	0	0	0	0	0	0	0
	7	0	0	0	0	0	+1	0	0	0

Table 14. Coefficients of Y_{ij}