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Original

The design of a liquefied natural gas (LNG) distribution network of a company operating in Mexico

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Abstract: This paper presents a modification of the Multi Depot Multi Period Vehicle Routing Problem with heterogeneous fleet (MDMPVRPHF) to consider capital expenditures and operating expenses (MDMPVRPHFMR). The aim is to design a product distribution network and minimize the total delivery cost. The MDMPVRPHF only considers transportation costs with transportation restrictions. In this paper, the purpose is to solve a real-life freight distribution problem that considers capital expenditures and operations expenses. The MDMPVRPHFMR is formulated as a mixed integer programming model. The results of the application of both models to a real case of study demonstrate the advantages presented by the MDMPVRPHFMR over the MDMPVRPHF. Hence, management restrictions must be considered when designing a real-life freight distribution problem. The study case is to develop a liquefied natural gas distribution model based on a real company operating in Mexico.

Keywords: Vehicle routing problem; freight distribution; supply chain management; heterogeneous fleet; multi depot; multi period

1. INTRODUCTION

This paper presents a real-life problem for the design of an opening hazardous material production and distribution network by optimizing capital expenditures (CAPEX) and operating expenses (OPEX). The problem presents a high degree of complexity, mostly because both CAPEX and OPEX play a major role in the feasibility of the venture. CAPEX includes buying machinery, acquiring permits, and investment in transport vehicles (fleet size), whereas OPEX involves a hazardous material to the customers (truck drivers and truck fuel) and the raw material costs.

The problem considers that a company has evaluated several locations on which to install the processing of a product and distribute from there to different customer's locations. The transportation is considered as in-house, reason why the fleet size and vehicles capacities are a decision of the owners or investors of the company. The company business model requires the customers to sign a take-or-pay off contract in which it is obligated to pay for a specific amount of product independent on whether it is consumed or not. This business model allows for the planning of the whole contract period by the selection of supply stations, machinery and transport routes.

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In this paper, a new version of the Multi Depot Multi Period Vehicle Routing Problem with heterogeneous fleet (MDMPVRPHF) is proposed. In this version, CAPEX are included to the MDMPVRPHF model as a set of restrictions that must be considered to design a better freight distribution network. We called this model the Multi Depot Multi Period Vehicle Routing Problem with heterogeneous fleet and management restrictions (MDMPVRPHFMR).

The MDMPVRPHF and the MDMPVRPHFMR are variants of the vehicle routing problem (VRP). The VRP is introduced by Dantzig and Ramser (1959). It is the generalization of the Traveling Salesman Problem (TSP) presented by Flood (1956). The classic VRP aims to design a network by minimizing distances, travel times or transportation costs. The network is defined on a graph $G = (V, \mathcal{E}, C)$, where $V = \{V_0, ..., V_n\}$ is a set of vertices, $\mathcal{E} = \{(V_i, V_j) \,|\, (V_i, V_j) \in V^2, i \neq j\}$ is the arc set; and $C = (C_{ij})_{(Vi, Vj) \in \mathcal{E}}$ is a cost matrix defined over $\mathcal{E}$. The depot is vertex V_0 and the customers to be served are represented by the remaining vertices V (Pillac, Gendreau, Guéret, & Medaglia, 2013). The classic VRP consists in designing a network by finding a set of routes for a fleet of vehicles with the same capacity, customer´s demands are known and supplied by only one vehicle (Archetti & Speranza, 2008).

Different VRP variants have been developed. The most studied are the Capacitated VRP (CVRP), the VRP with time Windows (VRPTW), the VRP with Pick-up and Delivery (PDP), the Split Delivery Vehicle Routing Problem (SDVRP), and the Heterogeneous fleet VRP (HVRP).

In the CVRP, a set of customers have a different demand for a good and the fleet of vehicles have finite capacity (Pillac et al., 2013). The VRPTW designs routes from one depot to a set of dispersed customers who can be supplied once by only one vehicle in a time interval, every route starts and ends at the depot, the total demand transported per route (sum of the demands of all points in a route) cannot exceed the capacity of the vehicle (Braysy & Gendreau, 2005). In the PDP, a specific amount of goods must be picked-up and delivered to customers (Pillac et al., 2013). Contrary to the classical VRP, the SDVRP does not consider the restriction that customers are supplied by only one different capacities and costs is available for the distribution of goods (Baldacci, Battarra, & Vigo, 2008).

In the literature, there are many variations of the HVRP problem with vehicles capacities constraints and with time window constraints to consider multiple depots, multiple trips to be operated by the vehicles, multiple vehicles with different capacities and other operational constraints. These HVRP variations are the Heterogeneous VRP with Fixed Costs and Vehicle Dependent Routing Costs (HVRPFD), the Heterogeneous VRP with Vehicle Dependent Routing Costs (HVRPD), the Fleet Size and Mix VRP with Fixed Costs and Vehicle Depending Routing Costs (FSMFD), the Fleet Size and Mix VRP with Vehicle Dependent Routing Costs (FSMD), the Fleet Size and Mix VRP with Fixed Costs (FSMF), and the Site-Dependent VRP (SDVRP) (Baldacci et al., 2008).

Goel and Gruhn (2008) study the VRP in real-life applications, and they find different difficulties to be considered. In real-life, the VRP must consider a heterogeneous fleet of vehicles, time window restrictions, differing travel times and costs, vehicles capacity, facility capacity, vehicle compatibility with specific orders, multiple pick-ups per order, delivery locations, service locations, orders where a vehicle can start and finish a journey at different locations, and vehicle route restrictions such as maximum sizes and weights. They include these difficulties as restrictions into the classic VRP and therefore, they formulate the General Vehicle Routing Problem (GVRP). Based on the GVRP, Mancini (2016) develops the MDMPVRPHF. In her study, Mancini explains that real-life cargo distribution problems have a high degree of complexity because of multi-dimensional vehicle capacity constraints, characteristics of the vehicles, route lengths and travel times, time windows, the compatibility between products, the compatibility between products and vehicles, the compatibility between customers and vehicles, and objective functions which consider different costs such as transportation costs, inventory costs, opportunity costs, etc.

In this article, the MDMPVRPHFMR recognizes the MDMPVRPHF restrictions and adds and proves that CAPEX and OPEX must be considered to design a freight distribution network much closer to real-life. Therefore, the MDMPVRPHFMR includes CAPEX transport vehicles) and OPEX (raw material cost and transportation of product to the customers such as truck drivers and truck fuel).

This article presents the application of the MDMPVRPHFMR to a real-life problem for the design of an opening liquefied natural gas (LNG) distribution network for a planning time horizon. In this study case, the CAPEX and OPEX information of a real company is used to design its distribution network prior to establishing a contract with the client. The model simultaneously optimizes location allocation, production capacity and vehicle routing decisions. To solve the problem, we present optimal solutions for different random variables small instances using the optimization software *CPLEX* from *IBM*. The customers' demands and the distances between nodes (suppliers and customers) have been generated using Mersenne Twister which is a random number generator. These values are different for each instance and they are presented in Appendix A.

The paper is organized as follows. In Section 2, the MDMPVRPHF and the MDMPVRPHFMR problems are described and the mixed integer linear programming models are presented. In Section 3, the study case is presented together with the computing results of the application of the MDMPVRPHF and the MDMPVRPHFMR models. Section 4 presents the aleatory instances used to test the MDMPVRPHF and the MDMPVRPHFMR models and their computing results. Finally, conclusions and references are included.

2. MDMPVRPHFMR PROBLEM DESCRIPTION AND MATHEMATICAL

2.1 MDMPVRPHFMR PROBLEM DESCRIPTION

The company's business model is to deliver a steady, guaranteed and contractual supply of natural gas to its customers. To produce LNG, a liquefaction plant and access to a natural gas pipeline are needed. Since the natural gas pipeline network in Mexico is not vast, there are industrial plants that do not have access to natural gas via pipeline, and their natural gas consumption must be delivered by truck as compressed natural gas (CNG) or LNG. A typical supply chain of LNG consists of a liquefaction plant that is connected to the natural gas pipeline, terrestrial transport of the LNG via trucks and a vaporization plant that converts the LNG into natural gas to be consumed as fuel in the client's installations. Storage may be added in the liquefaction plant and in the customer's plant as buffer to account for transport eventualities.

When a customer quotes a LNG contractual supply, the company has to determine the nearest feasible connections to the natural gas pipeline in which liquefaction plan must be installed and the possible terrestrial routes to deliver the LNG to the client. The investment required for LNG plants is high, therefore a long-term supply take-or-pay contract is signed between the customer and the company, in which the customer is obligated to pay for a specific amount of product independent on whether it is consumed or not. This long-term contract requires the company to consider and minimize the transportation costs, since after five or seven years, the transportation costs may be greater than the initial investment.

The different feasible connections to a natural gas pipeline that the company evaluates to supply LNG to a customer, bring several variables into consideration: land cost, permit costs, natural gas (raw material) cost, and different routes to the customer plant(s). The natural gas cost within the pipelines is not fixed territory wise and therefore dependent on the location. It can be concluded that the location of the processing and distribution plant is correlated with the operation costs, and this presents a high degree of complexity.

Since CAPEX and OPEX are correlated, the model's objective is to minimize both simultaneously. The decisions of the MDMPVRPHFMR problem are to locate a set of supply stations, allocate supply stations to customers, select the distribution routes, manage the fleet, and select the machinery in the supply stations. The aim is to meet customer demand by designing an optimal network for the company for a planning horizon at minimum total cost.

The MDMPVRPHFMR requires solving investment in infrastructure and transport decisions. These former decisions are long-term or strategic decisions (Miranda & Garrido, 2004). The investment in infrastructure decisions are: location of supply stations through time and buying machines for production capacity. These decisions are long-term decisions that require high investment (Current, Ratick, & Revelle, 1997) because of the cost associated with property acquisition and facility construction (Owen & Daskin, 1998). The transport decisions are: the management of the fleet and its size, vehicles capacities (heterogeneous fleet), and routes selection. These decisions are long-term decisions that depend on operation costs, supply, and demand. The product transportation is considered as in-house and the allocation of supply stations to customers can change over time, normally every year (Vidal & Goetschalckx, 1997; Current et al., 1997). The MDMPVRPHFMR considers a multi-period approach and the flexibility for a vehicle to end the route at another supply station. The supply station capacity, vehicle capacity and inventory control introduced by Coelho and Laporte (2012) are restrictions also included in the MDMPVRPHFMR. Besides these restrictions, the MDMPVRPHFMR adds the cost of opening of supply stations (permits, city gate, civil), penalties for service times, machinery selection, raw material costs and fleet size.

A. *Assumptions*

- Costumer demands are independent and location are known.
- Once a supply station is located, they cannot be relocated.
- The company pays a fixed location cost for opening a supply station.
- The company pays a fixed cost for the natural gas in a supply station.
- Once the machines are installed in a supply station, they cannot be moved to another supply station.
- Vehicles capacities are known (heterogeneous fleet).
- The natural gas costs remain the same throughout the optimization period in each supply station.
- The CAPEX are amortized through the optimization period, which usually is equal to the customer's contract period.
- 28.00 standard cubic meters of natural gas [m3] are equal to 1 million of British Thermal Units [mmBtu] of LNG which is the standard unit used in this industry, but for scientific purposes, in this paper we use cubic meters.

B. *Decisions*

- Location, production capacity and allocation decisions: number of supply stations to locate, where to locate them, set their production capacities, and allocate customers to them.
- Fleet size decisions: number of vehicles to use.
- Routing decisions: What routes to operate, Vehicles must start their journey from a supply station and serve their allocated customers. Hence, the solutions include multi-period routes.

The assumptions and decisions are incorporated in a mathematical programming model presented in Section D. Its notation is introduced in Section C.

C. *Definition and notations*

The model works with a set of nodes, a set of supply stations, a set of customers, a set of routes, and a set of vehicles.

— $V = \{1 \dots v\}$ is the set of homogenous vehicles
— $K = \{1 \dots k\}$ is the set of routes
— $I = \{1 \dots i\}$ is the set of supply stations
— $J = \{1 \dots j\}$ is the set of customers
— $M = \{1 \dots m\}$ is the set of machines
— $N = I \cup J = \{1 \dots i\} \cup \{i+1 \dots i+j\}$ is the set of nodes

Therefore, the total number of nodes is $n+m$, where and the maximum number of routes for all vehicles is $k \in$ K.

1) *Variables*

The Boolean variables are:

— $x_{ij_k}^{v}$ is a directed routing variable equal to 1 if arc ij, with $i \in N, j \in N$, is used by a vehicle $v \in V$ in route $k \in K$, 0 otherwise [-]
— $y_{i_k}^{v}$ is equal to 1 if node $i \in N$ is visited by a vehicle $v \in V$ in route $k \in K$, 0 otherwise [-]
— $L_{i_k}^{v}$ specifies if vehicle $v \in V$ starts a journey from the supply station $i \in I$ in route $k \in K$, 0 otherwise [-]
— $Z_{i_k}^{v}$ is equal to 1 if route $k \in K$ for vehicle $v \in V$,

— u^v is equal to 1 if vehicle $v \in V$ is used in the solution, 0 otherwise [-]
— P_i is equal to 1 when node $i \in I$ is used in the solution, 0 otherwise [-]

The integer variables are:

— g_i^m indicates how many machines $m \in M$ are selected for supply station $i \in I$ [-]

The continuous variables are:

— $q_{ij_k}^v$ is the quantity delivered to costumer $j \in J$ by vehicle $v \in V$ in route $k \in K$ departing from $i \in I$ [m3]
— CC_i is the required production capacity for $i \in I$ [m3/h]
— W_k^v is the traveling time of vehicle $v \in V$ in route $k \in K$ [h]
— $T_{i_k}^v$ is the time schedule in which node $i \in N$ is visited by vehicle $v \in V$ in route $k \in K$ [-]

2) *Parameters*

The parameters are:

— α the maximum route duration [h]
— s the vehicles average speed [km/h]
— Θ the planning time horizon is the time per day available to operate [h]
— Q_j daily demand per location $j \in J$ [m3]
— C^v the transport capacity per vehicle $v \in V$ [m3]
— r_{ij} the distance matrix, with $i \in N, j \in N$ [km]
— μ^v the cost of usage per vehicle $v \in V$ [$/km]
— ρ_i the cost of opening a supply station $i \in I$ [$/day]
— ϱ_i the raw material cost in a supply station $i \in I$ [$/m3]
— p^m the cost of machine $m \in M$ [$/day]
— c^m the production capacity of machine $m \in$ M [m3/day]
— δ_j the time to discharge/charge material from vehicles to customers $j \in J$ [h]
— γ a penalty cost in visit times [$]
— β the cost of renting/buying the vehicle [$/day]
— Num_j the number of days in contract with customer $j \in J$ [days]
— fc_j the fuel consumed by customer $j \in J$ during Num_j [m3]
— $margin_j$ the company´s margin for supplying customer $j \in J$ [$/m3]

3) *Costs and Price definitions*

— *CAPEX* is the company capital expenditures [$/day]
— *OPEX* is the company operating expenses [$/day]
— *TRA* is company the daily transport costs [$/day]
— *VEH* is the company the daily vehicle rent costs [$/day]
— *PEN* is the company daily cost for customer time services [$/day]
— *RAW* is the company daily raw material costs [$/day]
— *INV* is the company daily cost for opening a supply station [$/day]
— *MCH* is the company daily machines costs in the supply stations [$/day]
— S_j is the company fuel price to customer $j \in J$ [$/m3]

The cost of opening a supply station ρ_i, the cost of the machines p^m, and the cost of buying or renting vehicles β are expressed in [$/day] by dividing the cost by Num_j.

D. *Mixed Integer Programming model (MIP)*

The main objective of a LNG distribution company is to maximize its utilities by offering different fuel price to its customers depending on the number of days in contract, the amount of fuel consumed, and the company´s margin. The fuel price (S_j) to the customer $j \in J$ is calculated as the sum of all the company costs (CAPEX and OPEX) divided by the amount of fuel consumed plus the profit margin of the company:

$$S_j = \frac{CAPEX+OPEX}{fc_j} + margin_j \quad (1)$$

The CAPEX and OPEX are considered daily costs and then multiplied by the total number of days of the optimization period. The daily costs are expressed as a CAPEX and OPEX in equation (2).

$$S_j = \frac{Num_j*(CAPEX+OPEX)}{fc_j} + margin_j \quad (2)$$

The OPEX costs are *TRA*, *VEH*, *PEN*, and *RAW*, and the CAPEX costs are *INV* and *MCH*. The *TRA*, *VEH*, *PEN*, and *RAW* are daily costs throughout the contract period. The *INV* and *MCH* costs are paid at the beginning of the contract and must be divided by the planning time horizon. To optimize all the costs simultaneously, the model is set to optimize per day, therefore the *INV* and *MCH* costs are amortized along the contract period and considered as daily payment. By substituting the CAPEX and OPEX costs, equation (2) becomes:

$$S_j = \frac{Num_j*(TRA+VEH+PEN+RAW+INV+MCH)}{fc_j} + margin_j \tag{3}$$

Since Num_j, fc_j and $margin_j$ are not variables, but parameters, the maximization of the LNG distribution company utility is achieved by minimizing the company´s CAPEX and OPEX.

1) *Objective function*

In this paper, we propose to modify the MDMPVRPHF model objective function to consider CAPEX and OPEX. In this paper, we propose two modifications to the MDMPVRPHF to include management restrictions. The first modification considers *TRA*, *VEH*, *PEN*, *RAX*, *INV*, and *MCH* costs, we called this model the MDMPVRPHFMR model because it includes management restrictions considering production. The second modification only considers *TRA*, *VEH*, *PEN*, and *INV* costs, we called this model the MDMPVRPHFMRWP model because it includes management restrictions without considering production.

The MDMPVRPHFMR model aims to minimize the *TRA*, *VEH*, *PEN*, *RAX*, *INV*, and *MCH* costs, hence achieving a lower fuel price (S_j) for the customer and higher profit for the company. The objective function for the MDMPVRPHFMR model is shown in equation (4a).

$$\min f = \sum_{i\in N}\sum_{j\in N}\sum_{k\in K}\sum_{v\in V} r_{ij}\mu^v x^v_{ij_k} + \sum_{v\in V}\beta u^v + \sum_{i\in N}\sum_{k\in K}\sum_{v\in V}\gamma\, y^v_{i_k} + \sum_{i\in I}\rho_i P_i + \sum_{i\in I}\varrho_i CC_i + \sum_{i\in I}\sum_{m\in M} g^m_i\, p^m_i \tag{4}$$

The objective function first term is the daily *TRA*. The second term is the daily *VEH*. The third term is the penalty cost *PEN* in time spent visiting customers. The fourth term is the daily raw material costs *RAW*. The fifth term is the daily amortization of the opening costs *INV*. The last term is the daily amortization of the machine cost *MCH*.

The MDMPVRPHFMRWP model aims to minimize the *TRA*, *VEH*, *PEN*, and *INV* costs. The objective function for the MDMPVRPHFMRWP model is shown in equation (4b).

$$\min f = \sum_{i\in N}\sum_{j\in N}\sum_{k\in K}\sum_{v\in V} r_{ij}\mu^v x^v_{ij_k} + \sum_{v\in V}\beta u^v + \sum_{i\in N}\sum_{k\in K}\sum_{v\in V}\gamma\, y^v_{i_k} + \sum_{i\in I}\rho_i P_i \tag{4b}$$

Finally, the MDMPVRPHF model proposed by Mancini (2016) aims to minimizes only the *TRA* costs. The objective function for the MDMPVRPHF model is shown in equation (4c).

$$\min f = \sum_{i\in N}\sum_{j\in N}\sum_{k\in K}\sum_{v\in V} r_{ij}\mu^v x^v_{ij_k} \tag{4c}$$

2) *Mixed Integer Programming model (MIPM)*

The mathematical formulation is as follows:

s.t.

$$\sum_{i\in N|i\neq j} x^v_{ji_k} = y^v_{j_k} \quad \forall j\in J, \forall k\in K, \forall v\in V \tag{5}$$

$$\sum_{i\in N|i\neq j} x^v_{ij_k} = y^v_{j_k} \quad \forall j\in J, \forall k\in K, \forall v\in V \tag{6}$$

$$\sum_{j\in N|i\neq j} x^v_{ij_k} + \sum_{j\in N|i\neq j} x^v_{ji_k} \leq 2y^v_{i_k} \quad \forall i\in I, \forall k\in K, \forall v\in V \tag{7}$$

$$\sum_{j\in N|i\neq j} x^v_{ij_k} \leq L^v_{i_k} \quad \forall i\in I, \forall k\in K, \forall v\in V \tag{8}$$

$$x^v_{ij_k} \leq y^v_{i_k} \quad \forall i\in N, \forall j\in N, \forall k\in K, \forall v\in V \tag{9}$$

$$y^v_{j_k} \leq y^v_{i_k} \quad \forall i\in I, \forall j\in J, \forall k\in K, \forall v\in V \tag{10}$$

$$\sum_{j\in N, j\neq i} x^v_{ij_k} = Z^v_{i_k} \quad \forall i\in I, \forall k\in K, \forall v\in V \tag{11}$$

$$\sum_{i\in I}\sum_{j\in N|i\neq j} x^v_{ij_k} = \sum_{i\in I} Z^v_{i_k} \quad \forall k\in K, \forall v\in V \tag{12}$$

$$\sum_{j\in J} y^v_{j_k} \leq \eta * \sum_{i\in I} Z^v_{i_k} \quad \forall k\in K, \forall v\in \mathrm{V}, \text{is a very large constant} \tag{13}$$

$$T_{j\ k}^{v} \geq T_{i\ k}^{v} + \frac{1}{s} r_{ij} x_{ij_{k}}^{v} - \Theta\left(1 - x_{ij_{k}}^{v}\right)$$
$$\forall i \neq j, \forall i \in N, \forall j \in J, \forall k \in K, \forall v \in V \quad (14)$$

$$T_i = 0 \qquad \forall i \in I \quad (15)$$

$$W_k^v = \sum_{i \in N} \sum_{j \in N} \frac{1}{s} r_{ij} x_{ij_{k}}^{v} + \sum_{i \in N} \sum_{j \in N} \delta_i y_{ij_{k}}^{v}$$
$$\forall k \in K, \forall v \in V \quad (16)$$

$$W_k^v \leq \alpha \sum_{i \in I} Z_{i_k}^v \qquad \forall k \in K, \forall v \in V \quad (17)$$

$$\sum_{i \in I} \sum_{j \in J} q_{ij_k}^v \leq C^v \sum_{i \in I} Z_{i_k}^v \qquad \forall k \in K, \forall v \in V \quad (18)$$

$$\sum_{i \in I} q_{ij_k}^v \leq Q_j\, y_{j_k}^v \qquad \forall j \in J, \forall k \in K, \forall v \in V \quad (19)$$

$$\sum_{v \in V} \sum_{k \in K} \sum_{i \in I} q_{ij_k}^v = Q_i \qquad \forall j \in J \quad (20)$$

$$\sum_{i \in I} L_{i_k}^v \leq 1 \qquad \forall k \in K, \forall v \in V \quad (21)$$

$$L_{i_k}^v = \sum_{j \in N} x_{ji_w}^v$$
$$\forall i \in I, \forall v \in V, \forall\, w \in K \mid w = k - 1 \quad (22)$$

$$u^v \geq \sum_{i \in I} Z_{i_k}^v \qquad \forall v \in V, k = 1 \quad (23)$$

$$\sum_{k \in K} W_k^v \leq \Theta \qquad \forall v \in V \quad (24)$$

$$\sum_{v \in V} \sum_{k \in K} \sum_{j \in N | i \neq j} x_{ij_{k}}^{v} \leq \eta * P_i$$
$\forall i \in I, \eta$ is a very large constant (25)

$$CC_i = \sum_{v \in V} \sum_{k \in K} \sum_{j \in J} q_{ij_k}^v \qquad \forall i \in I \quad (26)$$

$$\sum_{m \in M} g_i^m\, c_i^m \geq CC_i \qquad \forall i \in I \quad (27)$$

$$T_{j\ k}^{v} \leq \alpha\, y_{j_k}^v \qquad \forall j \in J, \forall k \in K, \forall v \in V \quad (28)$$

$$q_{ij_k}^v \geq 0 \qquad \forall i \in I, \forall j \in J, \forall k \in K, \forall v \in V \quad (29)$$

$$L_{i_k}^v = \{0,1\} \qquad \forall i \in I, \forall k \in K, \forall v \in V \quad (30)$$

$$y_{i_k}^v = \{0,1\} \qquad \forall i \in N, \forall k \in K, \forall v \in V \quad (31)$$

$$Z_{i_k}^v = \{0,1\} \qquad \forall i \in I, \forall k \in K, \forall v \in V \quad (32)$$

$$x_{ij_k}^v = \{0,1\}$$
$$\forall i \in N, \forall j \in N, \forall k \in K, \forall v \in V \quad (33)$$

$$u^v = \{0,1\} \qquad \forall v \in V \quad (34)$$

$$CC_i \geq 0 \qquad \forall i \in I \quad (35)$$

$$g_i^m \geq \{0,1,2,\ldots,\infty\} \qquad \forall i \in I, \forall m \in M, \quad (36)$$

Constraints (5) and (6) ensure that a customer is only visited on a route if it is assigned to that route. Constraint (7) allows the vehicle to return to the supply station from which it departed. Constraint (8) implies that the arcs leaving a supply station may be used only if the vehicle $v \in V$ is located in that supply station in the previous route $(k-1)$. Constraints (9) and (10) are logical inequalities. Constraints (11) and (12) indicate that if vehicle $v \in V$ travels in route $k \in K$, it must depart from and arrive at a supply station $i \in I$. Constraint (13) states that a customer $j \in J$ can be assigned to route $k \in K$ only if the route is used. Constraints (14) and (15) guarantee sub tour elimination. Constrains (16) and (17) limit vehicle $v \in V$ travelling time. Constraints (18) restricts vehicle $v \in V$ capacity. Constraint (19) ensures no product quantity is delivered if customer $j \in J$ is not assigned to route $k \in K$. Constraint (20) guarantees that during period Θ, the total quantity required is delivered. Constraints (21) and (22) determine the starting supply station $i \in I$ for each route $k \in K$, depending on the final location of vehicle $v \in V$ on the previous route $k \in K$. Constraint (23) determines if the vehicle $v \in V$ is used. Constraint (24) defines the planning time horizon. Constraint (25) determines if supply station $i \in I$ is used. Constraint (26) states the production capacity required in supply station $i \in I$. Constraint (27) guarantees the machines $m \in M$ selected can produce the capacity required for each supply station $i \in I$. Constraint (30) specifies that if a location is not visited, no time can be assigned to it. Finally, constraints (29) to (36) specify the variable domain.

3. STUDY CASE

In this Section, a real-life study case is presented to evaluate the performance of the proposed MDMPVRPHFMR model against the performance of the MDMPVRPHFMRWP model and the MDMPVRPHF model. For the real-life study case, the names of the locations are confidential and therefore not shown.

In this study case, the currency is USD and the input data is as follows: a contract period of 5 years, the maximum route travelling time α is equal to 10 [h], the vehicles average speed s is equal to 50 [km/h], the planning time horizon Θ is equal to 24 [h], the transport capacity per vehicle C^v is equal to 23,128 m3 of LNG, the cost of usage per vehicle μ^v is equal to 0.526 [$/km], the time to discharge/charge the hazardous material from the vehicle to each customer δ_j is equal to 0.5 [h], the penalty cost in time γ is 20 [$], the cost of renting/buying the vehicle β^v is equal to 6.36 [$/h] and the machines production capacity of LNG c_i^m is equal to 863.33 [m3/h].

The cost of opening the supply stations are shown in Table 1. This costs correspond to the legal paperwork and a physical installations needed to connect the station to a natural gas supply, which is the raw material. In the case of Supply Station 2 (SS_2), there is no cost because the client already has a connection to the natural gas pipe line. The supply station opening cost ρ_i for Supply Station 1 (SS_1) and Supply Station 3 (SS_3) for a 5-year contract period is $\rho_1 = \rho_3 =$ 500,000 / (5*365) = 273.97 [$/day].

Table 1. Supply Station Opening Costs in USD

Supply Station node	Opening Costs [$]
SS_1	500,000.00
SS_2	0.00
SS-3	500,000.00

Table 2 shows the distance between nodes or between supply stations and customers in km. Where Customer 1 (C_1), Customer 2 (C_2) and Customer 3 (C_3) are three demand nodes for the same customer and SS_1, SS_2 and SS_3 are the three possible supplier stations.

The total amount of fuel consumed by the three demand nodes (C_1, C_2 and C_3) for a 5-year contract period is 412,836,900[m3].

Table 2. Distance between nodes for case study in km.

	C_1	C_2	C_3	SS_1	SS_2	SS_3
C_1	0	210	122	126	30	245
C_2	210	0	98	86	180	54
C_3	122	98	0	32	92	118
SS_1	126	86	32	0	94	96
SS_2	30	180	92	94	0	202
SS_3	245	54	118	96	202	0

The customer demand nodes are shown in Table 3.

Table 3. Daily demand per location.

Customer node	Daily demand [m3/day]
C_1	32,424.00
C_2	130,788.00
C_3	63,000.00

Fig. 1 shows the results for the application of the MDMPVRFHF model. In Fig. 1, Fig. 2 and Fig. 3, the dark circles indicate supply stations that are not part of the solution, the big dark dots indicate the supply stations that are part of the solution, the little light dots indicate the customer locations and the medium size dots indicate the customer locations where LNG is delivered. Each row corresponds to a vehicle $v \in V$ whereas the columns correspond to the route $k \in K$. Each route has a title, e.g. “V1-R2 T=5.5h” with the following notation: “V” corresponds to the vehicle, “R” corresponds to the route, “T” corresponds to the time of the route. Vehicle routes are consecutive, it means “R1” happens before “R2”, and so on. The quantity delivered of LNG is indicated by the number with an arrow pointing to its location in [m3]. The subscript of the quantity delivered corresponds to the supply station number where that quantity is produced.

The production needed in SS_1, SS_2 and SS_3 to satisfy the customer demands at C_1, C_2 and C_3 are shown in Table 4.

Table 4. Supply Stations productions using the MDMPVRFHF model.

Supply Station	Production [m3/day]	No. of Machines	Machine Utilization
SS_1	86,128.00	5	83.10%
SS_2	32,424.00	2	78.20%
SS_3	107,660.00	6	86.60%

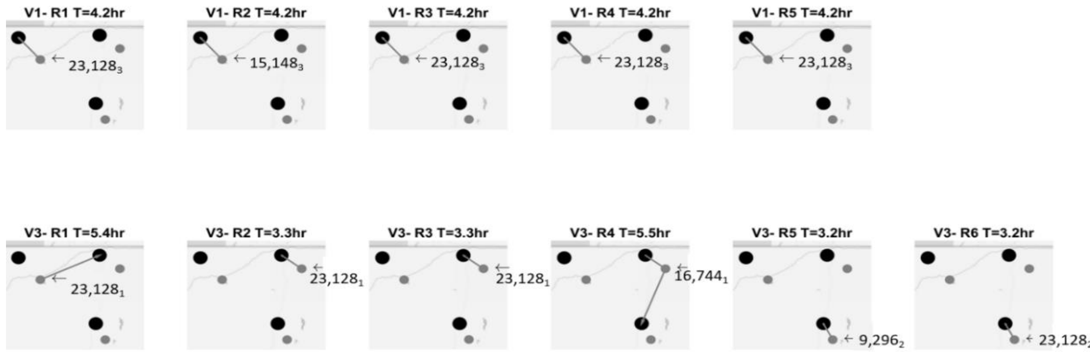

Fig. 1. Transport routes of the solution obtained with the MDMPVRFHF model.

The transport routes using the MDMPVRFHF model are shown in Fig. 1. Vehicle 1 (V1) operates five routes per day and vehicle 2 (V2) operates six routes per day.

Although, in the MDMPVRFHF model only *TRA* and *VEH* are minimized, all CAPEX and OPEX costs are considered for the calculation of the customers fuel priceas shown in Table 5.

Table 5. Case study costs using objective function the MDMPVRFHF model.

Cost	Total Cost [$]	Unitary Cost [$/m3]
TRA	1,041,200.00	0.00250
VEH	557,110.00	0.00143
RAW	51,605,000.00	0.12500
INV	1,000,000.00	0.00250
MCH	48,085,000.00	0.11643
	Total:	0.24786

The transport routes using the MDMPVRFHFMRWP model are shown in Fig. 2. Vehicle 1 (V1) operates five routes per day, vehicle 2 (V2) operates one route per day, and vehicle 3 (V3) operates five routes per day. The production needed in SS_2 and SS_3 to satisfy the customer demands at C_1, C_2 and C_3 are shown in Table 6. The results indicate that SS_1 is not required to operate, therefore there are no opening costs for this station.

Table 6. Supply Stations productions using the MDMPVRFHFMRWP model.

Supply Station	Production [m3/day]	No. of Machines	Machine Utilization
SS_1	0.00	0	-
SS_2	95,424.00	5	92.10%
SS_3	130,788.00	7	90.20%

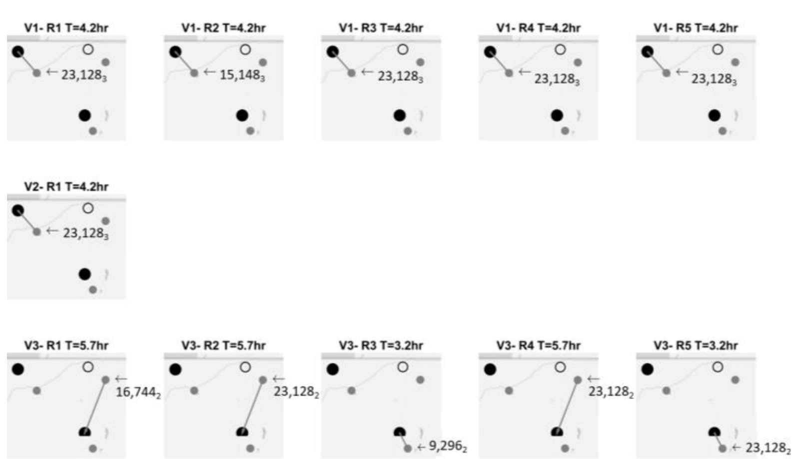

Fig. 2. Transport routes of the solution obtained with the MDMPVRFHFMRWP model.

Table 7 shows all the costs considered for the customer's fare when using the MDMPVRFHFMRWP model. By comparing the total cost per m3 of LNG from Table 5 and Table 7, it is possible to conclude that the total cost is reduced from \$0.24786 to \$0.23893 USD. The results demonstrate that the MDMPVRFHFMRWP model achieves lower costs than the MDMPVRFHF model.

Table 7. Case study costs using objective function the MDMPVRFHFMRWP model.

Cost	Total Cost [\$]	Unitary Cost [\$/m3]
TRA	1,267,900.00	0.00321
VEH	835,660.00	0.00214
RAW	51,605,000.00	0.12500
INV	500,000.00	0.00107
MCH	44,387,000.00	0.10750
	Total:	0.23893

Finally, the transport routes using the MDMPVRFHFMR model are shown in Fig. 3. Vehicle 1 (V1) operates four routes per day, vehicle 2 (V2) operates two routes per day, and vehicle 3 (V3) operates five routes per day. The production needed in SS_1 and SS_2 to satisfy the customer demands at C_1, C_2 and C_3 are shown in Table 8. The results indicate that SS_3 is not required to operate, therefore there are no opening costs for this station.

Table 8. Supply Stations productions using the MDMPVRFHFMR model.

Supply Station	Production [m3/day]	No. of Machines	Machine Utilization
SS1	206,976.00	10	99.90%
SS1	19,236.00	1	92.80%
SS1	-	0	-

Table 9 shows all the costs considered for the customer's fare when using the MDMPVRFHFMR model. By comparing the total cost per m3 of LNG from Table 5 (\$0.24786), Table 7 (\$0.23893), and Table 9 (\$0.23), it is possible to conclude that the minimum total cost, and hence the minimum fuel price (S_j), is reached when using the MDMPVRFHFMR model. Therefore, the results obtained with the proposed MDMPVRFHFMR model indicates that *TRA*, *VEH*, *PEN*, *RAX*, *INV*, and *MCH* costs must be considered. It also demonstrates that the model proposed by Mancini (2016) (the MDMPVRFHFMR model) does not achieve the lowest possible cost.

Table 9. Case study costs using objective function the MDMPVRFHFMR model.

Cost	Total Cost[\$]	Unitary Cost[\$/m3]
TRA	1,383,100.00	0.00321
VEH	835,660.00	0.00214
RAW	51,605,000.00	0.12500
INV	500,000.00	0.00107
MCH	40,688,000.00	0.09857
	Total:	0.23000

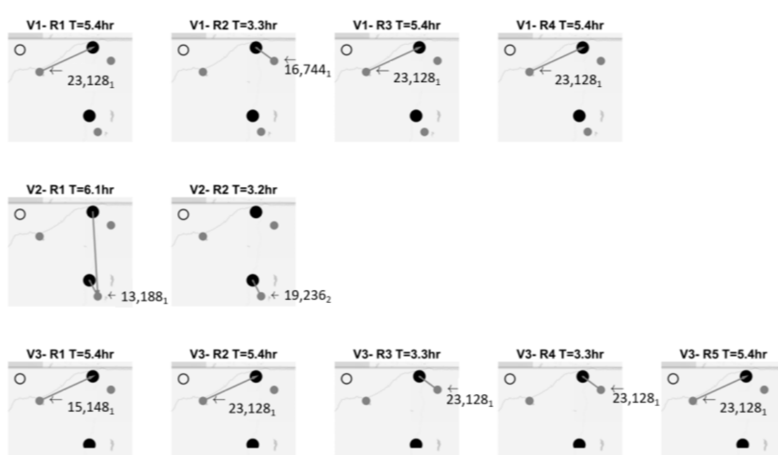

Fig. 3. Transport routes of the solution obtained with the MDMPVRFHFMR model.

The best fuel price for the customer (S_j) is obtained when using the proposed MDMPVRFHFMR model. It is important to notice that the machine utilization increases when we consider the *MCH*. The unitary costs *TRA*, *VEH* and *INV* for the three models are compared in Fig. 4. The unitary costs *RAW*, *MCH* and the sum of all costs are compared in Fig. 5 for the three models under study.

Although OPEX increases when all costs are minimized, the *MCH* costs decreases and therefore the total cost is minimized and the best fuel price for the customer (S_j) is obtained.

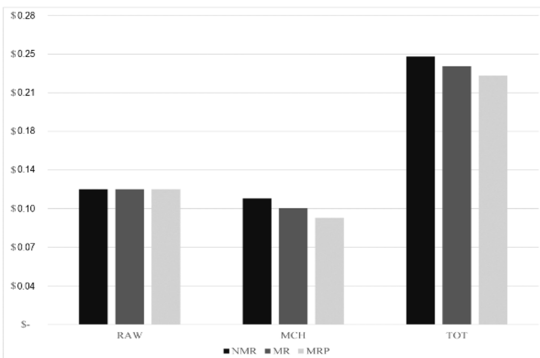

Fig. 4. The *RAW*, *MCH* and the total costs for the MDMPVRPHF model.

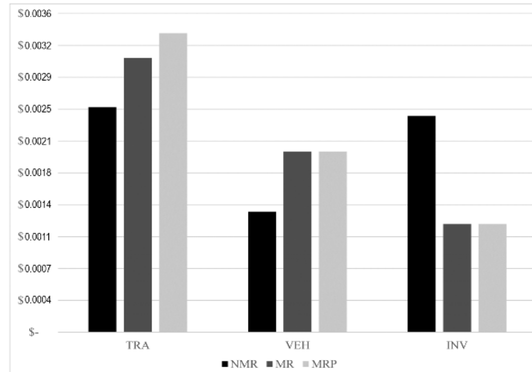

Fig. 5. The *TRA*, *VEH* and *VEH* costs for the MDMPVRPHF model.

4. COMPUTATIONAL RESULTS

In this section, we test the performance of the MDMPVRPHF model, the MDMPVRPHFMRWP model, and the MDMPVRPHFMR model. These tests study how suitable the models are to solve small and medium instances. A description of the instances used in the computational study is given in Appendix A. Table 10 shows the computation results for each instance tested.

Table 10. Computation results for each instance.

	MDMPVRPHF					MDMPVRPHFMRWP					MDMPVRPHFMR				
Instance	UB	LB	Gap (%)	CPU (s)	$/m3	UB	LB	Gap (%)	CPU (s)	$/m3	UB	LB	Gap (%)	CPU (s)	$/m3
3_10_2_3	748	748	0.00	145	0.2432	1005	1004	0.00	374	0.2293	17836	17835	0.00	52	0.2229
3_15_2_3	1012	918	0.09	3604	0.2411	1229	1098	0.11	3603	0.2236	25601	25545	0.00	3604	0.2236
3_20_3_3	1460	1202	0.18	3647	0.2368	1288	1012	0.21	3629	0.2279	30632	30287	0.01	3675	0.2214
3_25_4_4	1357	1011	0.25	3683	0.2454	1879	1236	0.34	3600	0.2346	-	-	-	>3600	-
4_10_2_3	626	626	0.00	23	0.2650	968	968	0.00	158	0.2471	15679	15678	0.00	214	0.2379
4_15_2_3	894	865	0.03	3603	0.2300	1168	1065	0.09	3618	0.2325	24793	24649	0.01	3609	0.2218
4_20_3_3	1154	1019	0.12	3615	0.2325	1621	1209	0.25	3932	0.2282	30340	30033	0.01	3601	0.2168
4_25_4_4	1524	1016	0.33	3605	0.2389	-	-	-	>3600	-	-	-	-	>3600	-
5_10_2_3	754	754	0.00	136	0.2539	983	983	0.00	54	0.2521	15624	15622	0.00	58	0.2400
5_15_2_3	909	855	0.06	3605	0.2393	1206	1051	0.13	3607	0.2286	22473	22408	0.00	3604	0.2146
5_20_3_3	1264	1091	0.14	3628	0.2464	1644	1294	0.21	3653	0.2289	31040	30842	0.01	3645	0.2146
5_25_4_4	-	-	-	>3600	-	-	-	-	>3600	-	-	-	-	>3600	-

Fig. 6 shows the relative gap between the upper and lower bounds. Here, it is possible to conclude that the MDMPVRPHFMR model achieves the lowest relative gap in the same amount of computing time. For solving the MDMPVRPHFMRWP, the relative gap increases probably because the MDMPVRPHF does not narrow the possible best solutions. In the case of the MDMPVRPHFMR model, OPEX and CAPEX narrows the feasible solutions region.

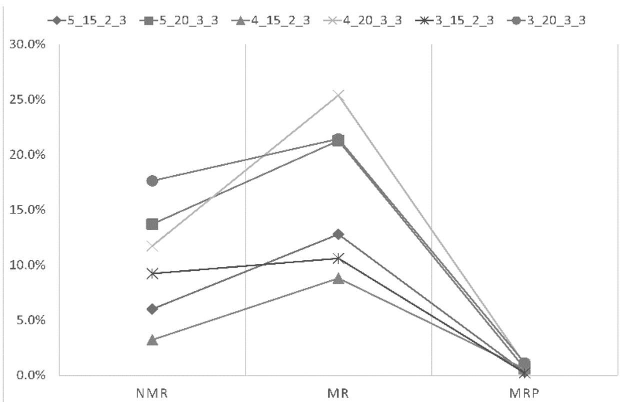

Fig. 6. Relative gap for instances with 15 and 20 demand points.

Fig. 7 shows the LNG fuel prices achieved with the MDMPVRPHF model, the MDMPVRPHFMRWP model and the MDMPVRPHFMR model. The LNG fuel price are minimized for all instances when using the MDMPVRPHFMR model. Therefore, we can conclude that companies must consider CAPEX and OPEX for designing their supply chain networks when the contract period is fixed between the supplier and the customer.

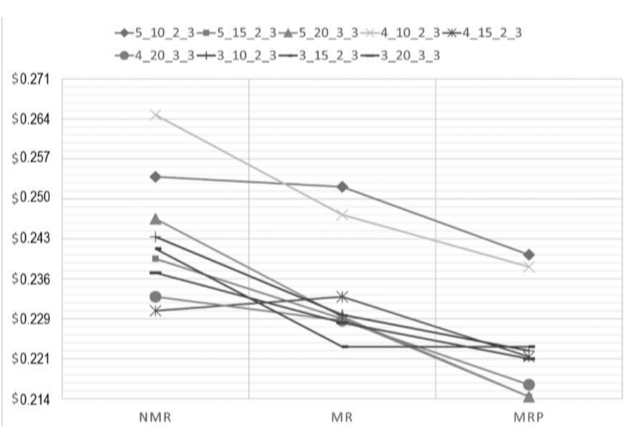

Fig. 7. Fuel cost for instances with 10, 15 and 20 demand points.

5. CONCLUSIONS AND FUTURE WORK

The Multi Depot Multi Period Vehicle Routing Problem with heterogeneous fleet and management restrictions (MDMPVRPHFMR) has been introduced and formulated in this paper. This is a modification of Mancini (2016) Multi Depot Multi Period Vehicle Routing Problem with heterogeneous fleet (MDMPVRPHF) to consider capital expenditures and operating expenses (MDMPVRPHFMR). In the MDMPVRPHFMR, the goal is to carry out delivery operations at the minimum costs by considering transport costs, vehicle rent costs, time services, raw material, investments, and machine costs. In this paper, we test the proposed MDMPVRPHFMR model and the MDMPVRPHF model in a real case scenario and by solving different instances with random parameters to test the effectiveness and efficacy of these models. The results allows to compare the performance of the proposed MDMPVRPHFMR model with the results obtained using the model proposed by Mancini (2016) or MDMPVRPHF model. By comparing results, it is possible to conclude that the minimum total cost, and hence the minimum fuel price (S_j), is reached when using the MDMPVRFHFMR model. The results indicates that CAPEX and OPEX must be considered. It also demonstrates that the model proposed by Mancini (2016) (the MDMPVRFHFMR model) does not achieve the lowest possible cost in a real company scenario.

The major contribution of this paper is the proposition of a model capable of minimizing CAPEX and OPEX at the same time with the aim of designing a LNG supply chain network considering must of the variables presented in a real company scenario. By considering more variables and having more real restrictions the feasible solutions region is narrowed and therefore the relative gap between the upper and lower bound is reduced. Finally, it is possible to conclude that companies must consider CAPEX and OPEX for designing real supply chain networks when the contract period is fixed between the supplier and the customer.

As future work, a Periodic Multi Period Vehicle Routing Problem with heterogeneous fleet and management restrictions can be developed for companies that require periodic deliveries. Such a model can be an extension of the periodic vehicle routing problem

APPENDIX A.

All instances have the parameters shown in Table A.1.

Table A.1. Fixed parameters for all instances.

Description	Variable	Value	Unit
Contract period	-	7	[year]
Maximum route duration	α	24	[h]
Vehicles average speed	s	50	[km/h]
Planning time horizon	Θ	24	[h]
Transport capacity per vehicle	C^v	23,128	[m3]
Cost of usage per vehicle	μ^v	$ 0.50	[$/km]
Machine cost	p^m	$ 1,447.70	[$/day]
Production capacity of machine	c^m	20,720	[m3/day]
Time to discharge/charge material	δ_i	60	[h]
Penalty cost in visit times	γ	20	[$]
Cost of renting/buying the vehicle	β	150	[$/day]

Instance 3_10_2_3:

Table A.2. General information of instance

Description	Variable	Value	Unit
No. of possible supply stations	I	3	[-]
No. of demand locations	D	10	[-]
No. of vehicles	V	2	[-]
No. of routes	K	3	[-]
No. of machines	M	1	[-]

Table A.3. Daily demand, opening costs and raw material cost of instance.

Location	Demand [m3/day]	Supply Station	Opening cost [$/day]	Raw material cost [$/m3]
C_1	11,760	SS_1	195.69	0.1464
C_2	3,500	SS_2	195.69	0.1429
C_3	6,776	SS_3	195.69	0.1393
C_4	10,332			
C_5	11,480			
C_6	1,624			
C_7	13,468			
C_8	10,024			
C_9	3,892			
C_10	6,076			

Table A.4. Distance matrix for instance.

[km]	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_10	SS_1	SS_2	SS_3
C_1	0	150	43	173	152	191	25	124	151	121	32	75	105
C_2	150	0	137	136	170	157	100	19	180	100	9	9	136
C_3	43	137	0	50	11	60	124	48	146	56	181	138	28
C_4	173	136	50	0	94	31	117	49	82	131	27	147	172
C_5	152	170	11	94	0	46	7	147	191	40	28	80	33
C_6	191	157	60	31	46	0	170	66	186	80	35	66	153
C_7	25	100	124	117	7	170	0	24	60	63	122	179	12
C_8	124	19	48	49	147	66	24	0	119	139	43	50	118
C_9	151	180	146	82	191	186	60	119	0	19	104	63	35
C_10	121	100	56	131	40	80	63	139	19	0	198	82	146
SS_1	32	9	181	27	28	35	122	43	104	198	0	142	107
SS_2	75	9	138	147	80	66	179	50	63	82	142	0	184
SS_3	105	136	28	172	33	153	12	118	35	146	107	184	0

Instance 3_15_2_3:

Table A.5. General information of instance.

Description	Variable	Value	Unit
No. of possible supply stations	I	3	[-]
No. of demand locations	*D*	15	[-]
No. of vehicles	*V*	2	[-]
No. of routes	K	3	[-]
No. of machines	*M*	1	[-]

Table A.6. Daily demand, opening costs and raw material cost of instance.

Location	Demand [m3/day]	Supply Station	Opening cost [$/day]	Raw material cost [$/m3]
C_1	11,760	SS_1	195.69	0.1464
C_2	2,688	SS_2	195.69	0.1429
C_3	3,388	SS_3	195.69	0.1393
C_4	6,776			
C_5	10,332			
C_6	3,108			
C_7	13,020			
C_8	7,532			
C_9	11,480			
C_10	1,624			
C_11	7,448			
C_12	13,468			
C_13	10,024			
C_14	3,892			
C_15	6,076			

Table A.7. Distance matrix for instance.

[km]	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_10	C_11	C_12	C_13	C_14	C_15	SS_1	SS_2	SS_3
C_1	0	124	154	43	173	56	141	124	152	191	181	25	124	151	121	32	75	**105**
C_2	124	0	149	67	199	118	195	193	157	42	150	28	14	86	104	57	36	**149**
C_3	154	149	0	46	41	193	195	150	23	156	53	67	28	54	168	111	26	**15**
C_4	43	67	46	0	50	105	81	52	11	60	25	124	48	146	56	181	138	**28**
C_5	173	199	41	50	0	19	127	193	94	31	39	117	49	82	131	27	147	**172**
C_6	56	118	193	105	19	0	198	109	66	170	30	140	21	188	184	167	88	**40**
C_7	141	195	195	81	127	198	0	7	127	157	118	6	172	52	102	161	76	**122**
C_8	124	193	150	52	193	109	7	0	47	55	15	106	140	107	195	184	196	**109**
C_9	152	157	23	11	94	66	127	47	0	46	165	7	147	191	40	28	80	**33**
C_10	191	42	156	60	31	170	157	55	46	0	99	170	66	186	80	35	66	**153**
C_11	181	150	53	25	39	30	118	15	165	99	0	50	133	14	85	116	63	**85**
C_12	25	28	67	124	117	140	6	106	7	170	50	0	24	60	63	122	179	**12**
C_13	124	14	28	48	49	21	172	140	147	66	133	24	0	119	139	43	50	**118**
C_14	151	86	54	146	82	188	52	107	191	186	14	60	119	0	19	104	63	**35**
C_15	121	104	168	56	131	184	102	195	40	80	85	63	139	19	0	198	82	**146**
SS_1	32	57	111	181	27	167	161	184	28	35	116	122	43	104	198	0	142	**107**
SS_2	75	36	26	138	147	88	76	196	80	66	63	179	50	63	82	142	0	**184**
SS_3	105	149	15	28	172	40	122	109	33	153	85	12	118	35	146	107	184	**0**

Instance 3_20_3_3:

Table A.8. General information of instance.

Description	Variable	Value	Unit
No. of possible supply stations	I	3	[-]
No. of demand locations	*D*	20	[-]
No. of vehicles	*V*	3	[-]
No. of routes	K	3	[-]
No. of machines	*M*	1	[-]

Table A.9. Daily demand, opening costs and raw material cost of instance.

Location	Demand [m3/day]	Supply Station	Opening cost [$/day]	Raw material cost [$/m3]
C_1	11,760	SS_1	195.69	0.1464
C_2	9,184	SS_2	195.69	0.1429
C_3	2,688	SS_3	195.69	0.1393
C_4	3,388			
C_5	1,624			
C_6	3,500			
C_7	6,776			
C_8	10,332			
C_9	3,108			
C_10	13,020			
C_11	7,532			
C_12	11,480			
C_13	2,492			
C_14	6,468			
C_15	1,624			
C_16	7,448			
C_17	13,468			
C_18	10,024			
C_19	3,892			
C_20	6,076			

Table A.10. Distance matrix for instance.

[km]	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_10	C_11	C_12	C_13	C_14	C_15	C_16	C_17	C_18	C_19	C_20	SS_1	SS_2	SS_3
C_1	0	139	124	154	152	150	43	173	56	141	124	152	11	59	191	181	25	124	151	121	32	75	105
C_2	139	0	187	47	121	26	80	123	125	76	114	121	44	36	15	182	184	15	112	23	1	166	87
C_3	124	187	0	149	172	165	67	199	118	195	193	157	92	186	42	150	28	14	86	104	57	36	149
C_4	154	47	149	0	198	6	46	41	193	195	150	23	192	14	156	53	67	28	54	168	111	26	15
C_5	152	121	172	198	0	83	188	166	18	129	133	196	159	117	183	138	180	158	151	185	175	176	170
C_6	150	26	165	6	83	0	137	136	101	173	105	170	91	128	157	27	100	19	180	100	9	9	136
C_7	43	80	67	46	188	137	0	50	105	81	52	11	67	131	60	25	124	48	146	56	181	138	28
C_8	173	123	199	41	166	136	50	0	19	127	193	94	12	173	31	39	117	49	82	131	27	147	172
C_9	56	125	118	193	18	101	105	19	0	198	109	66	149	12	170	30	140	21	188	184	167	88	40
C_10	141	76	195	195	129	173	81	127	198	0	7	127	102	164	157	118	6	172	52	102	161	76	122
C_11	124	114	193	150	133	105	52	193	109	7	0	47	40	106	55	15	106	140	107	195	184	196	109
C_12	152	121	157	23	196	170	11	94	66	127	47	0	86	139	46	165	7	147	191	40	28	80	33
C_13	11	44	92	192	159	91	67	12	149	102	40	86	0	43	65	145	166	131	54	23	101	89	2
C_14	59	36	186	14	117	128	131	173	12	164	106	139	43	0	166	186	68	104	51	60	81	32	155
C_15	191	15	42	156	183	157	60	31	170	157	55	46	65	166	0	99	170	66	186	80	35	66	153
C_16	181	182	150	53	138	27	25	39	30	118	15	165	145	186	99	0	50	133	14	85	116	63	85
C_17	25	184	28	67	180	100	124	117	140	6	106	7	166	68	170	50	0	24	60	63	122	179	12
C_18	124	15	14	28	158	19	48	49	21	172	140	147	131	104	66	133	24	0	119	139	43	50	118
C_19	151	112	86	54	151	180	146	82	188	52	107	191	54	51	186	14	60	119	0	19	104	63	35
C_20	121	23	104	168	185	100	56	131	184	102	195	40	23	60	80	85	63	139	19	0	198	82	146
SS_1	32	1	57	111	175	9	181	27	167	161	184	28	101	81	35	116	122	43	104	198	0	142	107
SS_2	75	166	36	26	176	9	138	147	88	76	196	80	89	32	66	63	179	50	63	82	142	0	184
SS_3	105	87	149	15	170	136	28	172	40	122	109	33	2	155	153	85	12	118	35	146	107	184	0

Instance 3_25_4_4:

Table A.11. General information of instance.

Description	Variable	Value	Unit
No. of possible supply stations	I	3	[-]
No. of demand locations	*D*	25	[-]
No. of vehicles	*V*	4	[-]
No. of routes	K	4	[-]
No. of machines	*M*	1	[-]

Table A.12. Daily demand, opening costs and raw material cost of instance.

Location	Demand [m3/day]	Supply Station	Opening cost [$/day]	Raw material cost [$/m3]
C_1	2,352	SS_1	195.69	0.1464
C_2	5,880	SS_2	195.69	0.1429
C_3	1,484	SS_3	195.69	0.1393
C_4	4,424			
C_5	10,220			
C_6	3,500			
C_7	1,876			
C_8	6,244			
C_9	1,624			
C_10	7,448			
C_11	4,424			
C_12	9,492			
C_13	1,624			
C_14	7,448			
C_15	5,264			
C_16	952			
C_17	7,588			
C_18	3,948			
C_19	6,748			
C_20	9,604			
C_21	2,940			
C_22	8,540			
C_23	4,592			
C_24	7,168			
C_25	1,876			

Table A.13. Distance matrix for instance.

[km]	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_10	C_11	C_12	C_13	C_14	C_15	C_16	C_17	C_18	C_19	C_20	C_21	C_22	C_23	C_24	C_25	SS_1	SS_2	SS_3
C_1	0	28	188	119	60	56	43	22	12	58	135	176	167	49	30	24	136	20	41	91	7	61	23	145	79	107	157	133
C_2	28	0	28	118	52	68	77	88	92	14	131	200	146	167	182	77	11	147	104	129	67	194	183	134	148	115	114	71
C_3	188	28	0	134	178	58	6	57	145	17	107	173	106	163	129	163	161	128	11	27	150	180	97	36	196	83	163	70
C_4	119	118	134	0	90	35	95	198	68	14	144	8	166	126	33	49	136	15	173	91	129	39	171	111	105	3	116	51
C_5	60	52	178	90	0	80	67	122	81	82	101	109	103	1	114	177	190	25	89	131	34	1	162	192	86	141	189	191
C_6	56	68	58	35	80	0	196	51	106	25	98	200	111	76	187	143	19	197	110	166	191	143	38	120	42	102	175	60
C_7	43	77	6	95	67	196	0	27	179	89	100	103	43	181	157	76	182	100	114	62	109	174	50	162	65	77	102	32
C_8	22	88	57	198	122	51	27	0	156	180	188	175	118	137	138	50	102	5	137	81	51	24	11	197	23	13	158	73
C_9	12	92	145	68	81	106	179	156	0	71	78	15	29	76	94	51	123	11	75	177	116	8	122	178	76	72	95	149
C_10	58	14	17	14	82	25	89	180	71	0	24	198	11	127	53	154	64	29	16	141	184	120	156	43	66	47	166	142
C_11	135	131	107	144	101	98	100	188	78	24	0	185	137	49	114	10	16	179	92	49	180	121	103	7	69	41	65	141
C_12	176	200	173	8	109	200	103	175	15	198	185	0	122	115	50	138	171	94	10	152	97	104	6	91	164	163	196	2
C_13	167	146	106	166	103	111	43	118	29	11	137	122	0	197	64	125	29	113	148	59	89	2	199	3	107	79	56	75
C_14	49	167	163	126	1	76	181	137	76	127	49	115	197	0	183	150	75	99	8	56	63	138	101	95	105	11	15	181
C_15	30	182	129	33	114	187	157	138	94	53	114	50	64	183	0	196	125	14	191	2	12	190	67	191	155	76	151	64
C_16	24	77	163	49	177	143	76	50	51	154	10	138	125	150	196	0	200	180	149	75	151	175	35	50	25	155	167	120
C_17	136	11	161	136	190	19	182	102	123	64	16	171	29	75	125	200	0	58	188	88	27	23	126	78	126	34	185	60
C_18	20	147	128	15	25	197	100	5	11	29	179	94	113	99	14	180	58	0	103	61	72	71	116	87	70	183	66	26
C_19	41	104	11	173	89	110	114	137	75	16	92	10	148	8	191	149	188	103	0	59	80	49	151	167	67	64	161	78
C_20	91	129	27	91	131	166	62	81	177	141	49	152	59	56	2	75	88	61	59	0	178	113	31	165	115	66	108	164
C_21	7	67	150	129	34	191	109	51	116	184	180	97	89	63	12	151	27	72	80	178	0	123	72	91	173	41	93	197
C_22	61	194	180	39	1	143	174	24	8	120	121	104	2	138	190	175	23	71	49	113	123	0	29	77	40	154	165	173
C_23	23	183	97	171	162	38	50	11	122	156	103	6	199	101	67	35	126	116	151	31	72	29	0	186	135	14	191	17
C_24	145	134	36	111	192	120	162	197	178	43	7	91	3	95	191	50	78	87	167	165	91	77	186	0	181	191	16	68
C_25	79	148	196	105	86	42	65	23	76	66	69	164	107	105	155	25	126	70	67	115	173	40	135	181	0	32	142	48
SS_1	107	115	83	3	141	102	77	13	72	47	41	163	79	11	76	155	34	183	64	66	41	154	14	191	32	0	47	64
SS_2	157	114	163	116	189	175	102	158	95	166	65	196	56	15	151	167	185	66	161	108	93	165	191	16	142	47	0	110
SS_3	133	71	70	51	191	60	32	73	149	142	141	2	75	181	64	120	60	26	78	164	197	173	17	68	48	64	110	0

Instance 4_10_2_3:

Table A.14. General information of instance.

Description	Variable	Value	Unit
No. of possible supply stations	I	4	[-]
No. of demand locations	*D*	10	[-]
No. of vehicles	*V*	2	[-]
No. of routes	K	3	[-]
No. of machines	*M*	1	[-]

Table A.15. Daily demand, opening costs and raw material cost of instance.

Location	Demand [m3/day]	Supply Station	Opening cost [$/day]	Raw material cost [$/m3]
C_1	3,388	SS_1	195.69	0.1357
C_2	13,020	SS_2	195.69	0.1393
C_3	2,492	SS_3	195.69	0.1429
C_4	6,468	SS_4	195.69	0.1464
C_5	1,624			
C_6	4,424			
C_7	13,468			
C_8	10,024			
C_9	3,892			
C_10	6,076			

Table A.16. Distance matrix for instance.

[km]	**C_1**	**C_2**	**C_3**	**C_4**	**C_5**	**C_6**	**C_7**	**C_8**	**C_9**	**C_10**	**SS_1**	**SS_2**	**SS_3**	**SS_4**
C_1	0	195	192	14	156	53	67	28	54	168	111	26	43	**15**
C_2	195	0	102	164	157	118	6	172	52	102	161	76	84	**122**
C_3	192	102	0	43	65	145	166	131	54	23	101	89	52	**2**
C_4	14	164	43	0	166	186	68	104	51	60	81	32	186	**155**
C_5	156	157	65	166	0	99	170	66	186	80	35	66	94	**153**
C_6	53	118	145	186	99	0	50	133	14	85	116	63	51	**85**
C_7	67	6	166	68	170	50	0	24	60	63	122	179	87	**12**
C_8	28	172	131	104	66	133	24	0	119	139	43	50	141	**118**
C_9	54	52	54	51	186	14	60	119	0	19	104	63	81	**35**
C_10	168	102	23	60	80	85	63	139	19	0	198	82	37	**146**
SS_1	111	161	101	81	35	116	122	43	104	198	0	142	172	**107**
SS_2	26	76	89	32	66	63	179	50	63	82	142	0	75	**184**
SS_3	43	84	52	186	94	51	87	141	81	37	172	75	0	**152**
SS_4	15	122	2	155	153	85	12	118	35	146	107	184	152	**0**

Instance 4_15_2_3:

Table A.17. General information of instance.

Description	Variable	Value	Unit
No. of possible supply stations	I	4	[-]
No. of demand locations	*D*	15	[-]
No. of vehicles	*V*	2	[-]
No. of routes	K	3	[-]
No. of machines	*M*	1	[-]

Table A.18. Daily demand, opening costs and raw material cost of instance.

Location	Demand [m3/day]	Supply Station	Opening cost [$/day]	Raw material cost [$/m3]
C_1	11,844	SS_1	195.69	0.1357
C_2	3,388	SS_2	195.69	0.1393
C_3	7,168	SS_3	195.69	0.1429
C_4	6,776	SS_4	195.69	0.1464
C_5	13,020			
C_6	7,532			
C_7	11,480			
C_8	2,492			
C_9	6,468			
C_10	1,624			
C_11	4,424			
C_12	13,468			
C_13	10,024			
C_14	3,892			
C_15	6,076			

Table A.19. Distance matrix for instance.

[km]	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_10	C_11	C_12	C_13	C_14	C_15	SS_1	SS_2	SS_3	SS_4
C_1	0	47	26	80	76	114	121	44	36	15	182	184	15	112	23	1	166	151	**87**
C_2	47	0	6	46	195	150	23	192	14	156	53	67	28	54	168	111	26	43	**15**
C_3	26	6	0	137	173	105	170	91	128	157	27	100	19	180	100	9	9	112	**136**
C_4	80	46	137	0	81	52	11	67	131	60	25	124	48	146	56	181	138	171	**28**
C_5	76	195	173	81	0	7	127	102	164	157	118	6	172	52	102	161	76	84	**122**
C_6	114	150	105	52	7	0	47	40	106	55	15	106	140	107	195	184	196	72	**109**
C_7	121	23	170	11	127	47	0	86	139	46	165	7	147	191	40	28	80	98	**33**
C_8	44	192	91	67	102	40	86	0	43	65	145	166	131	54	23	101	89	52	**2**
C_9	36	14	128	131	164	106	139	43	0	166	186	68	104	51	60	81	32	186	**155**
C_10	15	156	157	60	157	55	46	65	166	0	99	170	66	186	80	35	66	94	**153**
C_11	182	53	27	25	118	15	165	145	186	99	0	50	133	14	85	116	63	51	**85**
C_12	184	67	100	124	6	106	7	166	68	170	50	0	24	60	63	122	179	87	**12**
C_13	15	28	19	48	172	140	147	131	104	66	133	24	0	119	139	43	50	141	**118**
C_14	112	54	180	146	52	107	191	54	51	186	14	60	119	0	19	104	63	81	**35**
C_15	23	168	100	56	102	195	40	23	60	80	85	63	139	19	0	198	82	37	**146**
SS_1	1	111	9	181	161	184	28	101	81	35	116	122	43	104	198	0	142	172	**107**
SS_2	166	26	9	138	76	196	80	89	32	66	63	179	50	63	82	142	0	75	**184**
SS_3	151	43	112	171	84	72	98	52	186	94	51	87	141	81	37	172	75	0	**152**
SS_4	87	15	136	28	122	109	33	2	155	153	85	12	118	35	146	107	184	152	**0**

Instance 4_20_3_3:

Table A.20. General information of instance.

Description	Variable	Value	Unit
No. of possible supply stations	I	4	[-]
No. of demand locations	*D*	20	[-]
No. of vehicles	*V*	3	[-]
No. of routes	K	3	[-]
No. of machines	*M*	1	[-]

Table A.21. Daily demand, opening costs and raw material cost of instance.

Location	Demand[m3/day]	Supply Station	Opening cost [$/day]	Raw material cost [$/m3]
C_1	9,856	SS_1	195.69	0.1357
C_2	11,844	SS_2	195.69	0.1393
C_3	2,688	SS_3	195.69	0.1429
C_4	3,388	SS_4	195.69	0.1464
C_5	1,624			
C_6	7,168			
C_7	6,776			
C_8	10,332			
C_9	3,108			
C_10	13,020			
C_11	7,532			
C_12	11,480			
C_13	2,492			
C_14	6,468			
C_15	1,624			
C_16	4,424			
C_17	13,468			
C_18	10,024			
C_19	3,892			
C_20	6,076			

Table A.22. Distance matrix for instance.

[km]	C_	C_	C_	C_	C_	C_	C_	C_	C_	C_	C_	C_	C_	C_	C_	C_	C_	C_	C_	C_	SS	SS	SS	SS
C_1	0	139	124	154	152	150	43	173	56	141	124	152	11	59	191	181	25	124	151	121	32	75	7	**105**
C_2	139	0	187	47	121	26	80	123	125	76	114	121	44	36	15	182	184	15	112	23	1	166	151	**87**
C_3	124	187	0	149	172	165	67	199	118	195	193	157	92	186	42	150	28	14	86	104	57	36	141	**149**
C_4	154	47	149	0	198	6	46	41	193	195	150	23	192	14	156	53	67	28	54	168	111	26	43	**15**
C_5	152	121	172	198	0	83	188	166	18	129	133	196	159	117	183	138	180	158	151	185	175	176	136	**170**
C_6	150	26	165	6	83	0	137	136	101	173	105	170	91	128	157	27	100	19	180	100	9	9	112	**136**
C_7	43	80	67	46	188	137	0	50	105	81	52	11	67	131	60	25	124	48	146	56	181	138	171	**28**
C_8	173	123	199	41	166	136	50	0	19	127	193	94	12	173	31	39	117	49	82	131	27	147	112	**172**
C_9	56	125	118	193	18	101	105	19	0	198	109	66	149	12	170	30	140	21	188	184	167	88	181	**40**
C_10	141	76	195	195	129	173	81	127	198	0	7	127	102	164	157	118	6	172	52	102	161	76	84	**122**
C_11	124	114	193	150	133	105	52	193	109	7	0	47	40	106	55	15	106	140	107	195	184	196	72	**109**
C_12	152	121	157	23	196	170	11	94	66	127	47	0	86	139	46	165	7	147	191	40	28	80	98	**33**
C_13	11	44	92	192	159	91	67	12	149	102	40	86	0	43	65	145	166	131	54	23	101	89	52	**2**
C_14	59	36	186	14	117	128	131	173	12	164	106	139	43	0	166	186	68	104	51	60	81	32	186	**155**
C_15	191	15	42	156	183	157	60	31	170	157	55	46	65	166	0	99	170	66	186	80	35	66	94	**153**
C_16	181	182	150	53	138	27	25	39	30	118	15	165	145	186	99	0	50	133	14	85	116	63	51	**85**
C_17	25	184	28	67	180	100	124	117	140	6	106	7	166	68	170	50	0	24	60	63	122	179	87	**12**
C_18	124	15	14	28	158	19	48	49	21	172	140	147	131	104	66	133	24	0	119	139	43	50	141	**118**
C_19	151	112	86	54	151	180	146	82	188	52	107	191	54	51	186	14	60	119	0	19	104	63	81	**35**
C_20	121	23	104	168	185	100	56	131	184	102	195	40	23	60	80	85	63	139	19	0	198	82	37	**146**
SS_1	32	1	57	111	175	9	181	27	167	161	184	28	101	81	35	116	122	43	104	198	0	142	172	**107**
SS_2	75	166	36	26	176	9	138	147	88	76	196	80	89	32	66	63	179	50	63	82	142	0	75	**184**
SS_3	7	151	141	43	136	112	171	112	181	84	72	98	52	186	94	51	87	141	81	37	172	75	0	**152**
SS_4	105	87	149	15	170	136	28	172	40	122	109	33	2	155	153	85	12	118	35	146	107	184	152	**0**

Instance 4_25_4_4:

Table A.23. General information of instance.

Description	Variable	Value	Unit
No. of possible supply stations	I	4	[-]
No. of demand locations	*D*	25	[-]
No. of vehicles	*V*	4	[-]
No. of routes	K	4	[-]
No. of machines	*M*	1	[-]

Table A.24. Daily demand, opening costs and raw material cost of instance.

Location	Demand [m3/day]	Supply Station	Opening cost [$/day]	Raw material cost [$/m3]
C_1	2,352	SS_1	195.69	0.1357
C_2	5,880	SS_2	195.69	0.1393
C_3	1,484	SS_3	195.69	0.1429
C_4	4,424	SS_4	195.69	0.1464
C_5	10,220			
C_6	3,500			
C_7	1,876			
C_8	6,244			
C_9	1,624			
C_10	7,448			
C_11	4,424			
C_12	9,492			
C_13	1,624			
C_14	7,448			
C_15	5,264			
C_16	952			
C_17	7,588			
C_18	3,948			
C_19	6,748			
C_20	9,604			
C_21	2,940			
C_22	8,540			
C_23	4,592			
C_24	7,168			
C_25	1,876			

Table A.25. Distance matrix for instance.

[km]	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_10	C_11	C_12	C_13	C_14	C_15	C_16	C_17	C_18	C_19	C_20	C_21	C_22	C_23	C_24	C_25	SS_1	SS_2	SS_3	SS_4
C_1	0	28	188	119	60	56	43	22	12	58	135	176	167	49	30	24	136	20	41	91	7	61	23	145	79	107	186	130	133
C_2	28	0	28	118	52	68	77	88	92	14	131	200	146	167	182	77	11	147	104	129	67	194	183	134	148	115	147	141	71
C_3	188	28	0	134	178	58	6	57	145	17	107	173	106	163	129	163	161	128	11	27	150	180	97	36	196	83	150	187	70
C_4	119	118	134	0	90	35	95	198	68	14	144	8	166	126	33	49	136	15	173	91	129	39	171	111	105	3	82	138	51
C_5	60	52	178	90	0	80	67	122	81	82	101	109	103	1	114	177	190	25	89	131	34	1	162	192	86	141	48	114	191
C_6	56	68	58	35	80	0	196	51	106	25	98	200	111	76	187	143	19	197	110	166	191	143	38	120	42	102	105	77	60
C_7	43	77	6	95	67	196	0	27	179	89	100	103	43	181	157	76	182	100	114	62	109	174	50	162	65	77	44	127	32
C_8	22	88	57	198	122	51	27	0	156	180	188	175	118	137	138	50	102	5	137	81	51	24	11	197	23	13	169	73	73
C_9	12	92	145	68	81	106	179	156	0	71	78	15	29	76	94	51	123	11	75	177	116	8	122	178	76	72	133	82	149
C_10	58	14	17	14	82	25	89	180	71	0	24	198	11	127	53	154	64	29	16	141	184	120	156	43	66	47	164	74	142
C_11	135	131	107	144	101	98	100	188	78	24	0	185	137	49	114	10	16	179	92	49	180	121	103	7	69	41	159	94	141
C_12	176	200	173	8	109	200	103	175	15	198	185	0	122	115	50	138	171	94	10	152	97	104	6	91	164	163	94	101	2
C_13	167	146	106	166	103	111	43	118	29	11	137	122	0	197	64	125	29	113	148	59	89	2	199	3	107	79	62	183	75
C_14	49	167	163	126	1	76	181	137	76	127	49	115	197	0	183	150	75	99	8	56	63	138	101	95	105	11	138	42	181
C_15	30	182	129	33	114	187	157	138	94	53	114	50	64	183	0	196	125	14	191	2	12	190	67	191	155	76	198	68	64
C_16	24	77	163	49	177	143	76	50	51	154	10	138	125	150	196	0	200	180	149	75	151	175	35	50	25	155	154	115	120
C_17	136	11	161	136	190	19	182	102	123	64	16	171	29	75	125	200	0	58	188	88	27	23	126	78	126	34	166	98	60
C_18	20	147	128	15	25	197	100	5	11	29	179	94	113	99	14	180	58	0	103	61	72	71	116	87	70	183	142	53	26
C_19	41	104	11	173	89	110	114	137	75	16	92	10	148	8	191	149	188	103	0	59	80	49	151	167	67	64	120	116	78
C_20	91	129	27	91	131	166	62	81	177	141	49	152	59	56	2	75	88	61	59	0	178	113	31	165	115	66	151	176	164
C_21	7	67	150	129	34	191	109	51	116	184	180	97	89	63	12	151	27	72	80	178	0	123	72	91	173	41	100	13	197
C_22	61	194	180	39	1	143	174	24	8	120	121	104	2	138	190	175	23	71	49	113	123	0	29	77	40	154	174	89	173
C_23	23	183	97	171	162	38	50	11	122	156	103	6	199	101	67	35	126	116	151	31	72	29	0	186	135	14	14	17	17
C_24	145	134	36	111	192	120	162	197	178	43	7	91	3	95	191	50	78	87	167	165	91	77	186	0	181	191	194	113	68
C_25	79	148	196	105	86	42	65	23	76	66	69	164	107	105	155	25	126	70	67	115	173	40	135	181	0	32	20	108	48
SS_1	107	115	83	3	141	102	77	13	72	47	41	163	79	11	76	155	34	183	64	66	41	154	14	191	32	0	110	154	64
SS_2	186	147	150	82	48	105	44	169	133	164	159	94	62	138	198	154	166	142	120	151	100	174	14	194	20	110	0	47	197
SS_3	130	141	187	138	114	77	127	73	82	74	94	101	183	42	68	115	98	53	116	176	13	89	17	113	108	154	47	0	150
SS_4	133	71	70	51	191	60	32	73	149	142	141	2	75	181	64	120	60	26	78	164	197	173	17	68	48	64	197	150	0

Instance 5_10_2_3:

Table. General information of instance A.26.

Description	Variable	Value	Unit
No. of possible supply stations	I	5	[-]
No. of demand locations	*D*	10	[-]
No. of vehicles	*V*	2	[-]
No. of routes	K	3	[-]
No. of machines	*M*	1	[-]

Table A.27. Daily demand, opening costs and raw material cost of instance.

Location	Demand [m3/day]	Supply Station	Opening cost [$/day]	Raw material cost [$/m3]
C_1	700	SS_1	195.69	0.1500
C_2	1,288	SS_2	195.69	0.1464
C_3	8,344	SS_3	195.69	0.1429
C_4	3,388	SS_4	195.69	0.1393
C_5	11,788	SS_5	195.69	0.1357
C_6	12,012			
C_7	13,496			
C_8	6,860			
C_9	3,108			
C_10	3,192			

Table A.28. Distance matrix for instance.

[km]	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_10	SS_1	SS_2	SS_3	SS_4	SS_5
C_1	0	139	124	154	152	150	43	173	56	141	32	161	75	7	**105**
C_2	139	0	187	47	121	26	80	123	125	76	1	70	166	151	**87**
C_3	124	187	0	149	172	165	67	199	118	195	57	17	36	141	**149**
C_4	154	47	149	0	198	6	46	41	193	195	111	103	26	43	**15**
C_5	152	121	172	198	0	83	188	166	18	129	175	74	176	136	**170**
C_6	150	26	165	6	83	0	137	136	101	173	9	148	9	112	**136**
C_7	43	80	67	46	188	137	0	50	105	81	181	105	138	171	**28**
C_8	173	123	199	41	166	136	50	0	19	127	27	161	147	112	**172**
C_9	56	125	118	193	18	101	105	19	0	198	167	164	88	181	**40**
C_10	141	76	195	195	129	173	81	127	198	0	161	38	76	84	**122**
SS_1	32	1	57	111	175	9	181	27	167	161	0	77	142	172	**107**
SS_2	161	70	17	103	74	148	105	161	164	38	77	0	29	117	**51**
SS_3	75	166	36	26	176	9	138	147	88	76	142	29	0	75	**184**
SS_4	7	151	141	43	136	112	171	112	181	84	172	117	75	0	**152**
SS_5	105	87	149	15	170	136	28	172	40	122	107	51	184	152	**0**

Instance 5_15_2_3:

Table A.29. General information of instance.

Description	Variable	Value	Unit
No. of possible supply stations	I	5	[-]
No. of demand locations	*D*	15	[-]
No. of vehicles	*V*	2	[-]
No. of routes	K	3	[-]
No. of machines	*M*	1	[-]

Table A.30. Daily demand, opening costs and raw material cost of instance.

Location	Demand [m3/day]	Supply Station	Opening cost [$/day]	Raw material cost [$/m3]
C_1	700	SS_1	195.69	0.1500
C_2	1,288	SS_2	195.69	0.1464
C_3	8,344	SS_3	195.69	0.1429
C_4	3,388	SS_4	195.69	0.1393
C_5	11,788	SS_5	195.69	0.1357
C_6	12,012			
C_7	13,496			
C_8	6,860			
C_9	3,108			
C_10	3,192			
C_11	7,532			
C_12	10,696			
C_13	4,872			
C_14	6,468			
C_15	8,960			

Table A.31. Distance matrix for instance.

[km]	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_10	C_11	C_12	C_13	C_14	C_15	SS_1	SS_2	SS_3	SS_4	SS_5
C_1	0	139	124	154	152	150	43	173	56	141	124	152	11	59	191	32	161	75	7	**105**
C_2	139	0	187	47	121	26	80	123	125	76	114	121	44	36	15	1	70	166	151	**87**
C_3	124	187	0	149	172	165	67	199	118	195	193	157	92	186	42	57	17	36	141	**149**
C_4	154	47	149	0	198	6	46	41	193	195	150	23	192	14	156	111	103	26	43	**15**
C_5	152	121	172	198	0	83	188	166	18	129	133	196	159	117	183	175	74	176	136	**170**
C_6	150	26	165	6	83	0	137	136	101	173	105	170	91	128	157	9	148	9	112	**136**
C_7	43	80	67	46	188	137	0	50	105	81	52	11	67	131	60	181	105	138	171	**28**
C_8	173	123	199	41	166	136	50	0	19	127	193	94	12	173	31	27	161	147	112	**172**
C_9	56	125	118	193	18	101	105	19	0	198	109	66	149	12	170	167	164	88	181	**40**
C_10	141	76	195	195	129	173	81	127	198	0	7	127	102	164	157	161	38	76	84	**122**
C_11	124	114	193	150	133	105	52	193	109	7	0	47	40	106	55	184	25	196	72	**109**
C_12	152	121	157	23	196	170	11	94	66	127	47	0	86	139	46	28	165	80	98	**33**
C_13	11	44	92	192	159	91	67	12	149	102	40	86	0	43	65	101	128	89	52	**2**
C_14	59	36	186	14	117	128	131	173	12	164	106	139	43	0	166	81	4	32	186	**155**
C_15	191	15	42	156	183	157	60	31	170	157	55	46	65	166	0	35	180	66	94	**153**
SS_1	32	1	57	111	175	9	181	27	167	161	184	28	101	81	35	0	77	142	172	**107**
SS_2	161	70	17	103	74	148	105	161	164	38	25	165	128	4	180	77	0	29	117	**51**
SS_3	75	166	36	26	176	9	138	147	88	76	196	80	89	32	66	142	29	0	75	**184**
SS_4	7	151	141	43	136	112	171	112	181	84	72	98	52	186	94	172	117	75	0	**152**
SS_5	105	87	149	15	170	136	28	172	40	122	109	33	2	155	153	107	51	184	152	**0**

Instance 5_20_3_3:

Table A.32. General information of instance.

Description	Variable	Value	Unit
No. of possible supply stations	I	5	[-]
No. of demand locations	*D*	20	[-]
No. of vehicles	*V*	3	[-]
No. of routes	K	3	[-]
No. of machines	*M*	1	[-]

Table A.33. Daily demand, opening costs and raw material cost of instance.

Location	Demand [m3/day]	Supply Station	Opening cost[$/day]	Raw material cost [$/m3]
C_1	700	SS_1	195.69	0.1500
C_2	1,288	SS_2	195.69	0.1464
C_3	8,344	SS_3	195.69	0.1429
C_4	3,388	SS_4	195.69	0.1393
C_5	11,788	SS_5	195.69	0.1357
C_6	12,012			
C_7	13,496			
C_8	6,860			
C_9	3,108			
C_10	3,192			
C_11	7,532			
C_12	10,696			
C_13	4,872			
C_14	6,468			
C_15	8,960			
C_16	12,852			
C_17	2,268			
C_18	10,024			
C_19	8,092			
C_20	6,076			

Table A.34. Distance matrix for instance.

[km]	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_10	C_11	C_12	C_13	C_14	C_15	C_16	C_17	C_18	C_19	C_20	SS_1	SS_2	SS_3	SS_4	SS_5
C_1	0	139	124	154	152	150	43	173	56	141	124	152	11	59	191	181	25	124	151	121	32	161	75	7	**105**
C_2	139	0	187	47	121	26	80	123	125	76	114	121	44	36	15	182	184	15	112	23	1	70	166	151	**87**
C_3	124	187	0	149	172	165	67	199	118	195	193	157	92	186	42	150	28	14	86	104	57	17	36	141	**149**
C_4	154	47	149	0	198	6	46	41	193	195	150	23	192	14	156	53	67	28	54	168	111	103	26	43	**15**
C_5	152	121	172	198	0	83	188	166	18	129	133	196	159	117	183	138	180	158	151	185	175	74	176	136	**170**
C_6	150	26	165	6	83	0	137	136	101	173	105	170	91	128	157	27	100	19	180	100	9	148	9	112	**136**
C_7	43	80	67	46	188	137	0	50	105	81	52	11	67	131	60	25	124	48	146	56	181	105	138	171	**28**
C_8	173	123	199	41	166	136	50	0	19	127	193	94	12	173	31	39	117	49	82	131	27	161	147	112	**172**
C_9	56	125	118	193	18	101	105	19	0	198	109	66	149	12	170	30	140	21	188	184	167	164	88	181	**40**
C_10	141	76	195	195	129	173	81	127	198	0	7	127	102	164	157	118	6	172	52	102	161	38	76	84	**122**
C_11	124	114	193	150	133	105	52	193	109	7	0	47	40	106	55	15	106	140	107	195	184	25	196	72	**109**
C_12	152	121	157	23	196	170	11	94	66	127	47	0	86	139	46	165	7	147	191	40	28	165	80	98	**33**
C_13	11	44	92	192	159	91	67	12	149	102	40	86	0	43	65	145	166	131	54	23	101	128	89	52	**2**
C_14	59	36	186	14	117	128	131	173	12	164	106	139	43	0	166	186	68	104	51	60	81	4	32	186	**155**
C_15	191	15	42	156	183	157	60	31	170	157	55	46	65	166	0	99	170	66	186	80	35	180	66	94	**153**
C_16	181	182	150	53	138	27	25	39	30	118	15	165	145	186	99	0	50	133	14	85	116	104	63	51	**85**
C_17	25	184	28	67	180	100	124	117	140	6	106	7	166	68	170	50	0	24	60	63	122	109	179	87	**12**
C_18	124	15	14	28	158	19	48	49	21	172	140	147	131	104	66	133	24	0	119	139	43	122	50	141	**118**
C_19	151	112	86	54	151	180	146	82	188	52	107	191	54	51	186	14	60	119	0	19	104	153	63	81	**35**
C_20	121	23	104	168	185	100	56	131	184	102	195	40	23	60	80	85	63	139	19	0	198	172	82	37	**146**
SS_1	32	1	57	111	175	9	181	27	167	161	184	28	101	81	35	116	122	43	104	198	0	77	142	172	**107**
SS_2	161	70	17	103	74	148	105	161	164	38	25	165	128	4	180	104	109	122	153	172	77	0	29	117	**51**
SS_3	75	166	36	26	176	9	138	147	88	76	196	80	89	32	66	63	179	50	63	82	142	29	0	75	**184**
SS_4	7	151	141	43	136	112	171	112	181	84	72	98	52	186	94	51	87	141	81	37	172	117	75	0	**152**
SS_5	105	87	149	15	170	136	28	172	40	122	109	33	2	155	153	85	12	118	35	146	107	51	184	152	**0**

Instance 5_25_4_4:

Table A.35. General information of instance.

Description	Variable	Value	Unit
No. of possible supply stations	I	5	[-]
No. of demand locations	D	25	[-]
No. of vehicles	V	4	[-]
No. of routes	K	4	[-]
No. of machines	M	1	[-]

Table A.36. Daily demand, opening costs and raw material cost of instance.

Location	Demand [m3/day]	Supply Station	Opening cost [$/day]	Raw material cost [$/m3]
C_1	2,352	SS_1	195.69	0.1500
C_2	5,880	SS_2	195.69	0.1464
C_3	1,484	SS_3	195.69	0.1429
C_4	4,424	SS_4	195.69	0.1393
C_5	10,220	SS_5	195.69	0.1357
C_6	3,500			
C_7	1,876			
C_8	6,244			
C_9	1,624			
C_10	7,448			
C_11	4,424			
C_12	9,492			
C_13	1,624			
C_14	7,448			
C_15	5,264			
C_16	952			
C_17	7,588			
C_18	3,948			
C_19	6,748			
C_20	9,604			
C_21	2,940			
C_22	8,540			
C_23	4,592			
C_24	7,168			
C_25	1,876			

Table A.37. Distance matrix for instance

[km]	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_10	C_11	C_12	C_13	C_14	C_15	C_16	C_17	C_18	C_19	C_20	C_21	C_22	C_23	C_24	C_25	SS_1	SS_2	SS_3	SS_4	SS_5
C_1	0	28	188	119	60	56	43	22	12	58	135	176	167	49	30	24	136	20	41	91	7	61	23	145	79	107	186	157	130	133
C_2	28	0	28	118	52	68	77	88	92	14	131	200	146	167	182	77	11	147	104	129	67	194	183	134	148	115	147	114	141	71
C_3	188	28	0	134	178	58	6	57	145	17	107	173	106	163	129	163	161	128	11	27	150	180	97	36	196	83	150	163	187	70
C_4	119	118	134	0	90	35	95	198	68	14	144	8	166	126	33	49	136	15	173	91	129	39	171	111	105	3	82	116	138	51
C_5	60	52	178	90	0	80	67	122	81	82	101	109	103	1	114	177	190	25	89	131	34	1	162	192	86	141	48	189	114	191
C_6	56	68	58	35	80	0	196	51	106	25	98	200	111	76	187	143	19	197	110	166	191	143	38	120	42	102	105	175	77	60
C_7	43	77	6	95	67	196	0	27	179	89	100	103	43	181	157	76	182	100	114	62	109	174	50	162	65	77	44	102	127	32
C_8	22	88	57	198	122	51	27	0	156	180	188	175	118	137	138	50	102	5	137	81	51	24	11	197	23	13	169	158	73	73
C_9	12	92	145	68	81	106	179	156	0	71	78	15	29	76	94	51	123	11	75	177	116	8	122	178	76	72	133	95	82	149
C_10	58	14	17	14	82	25	89	180	71	0	24	198	11	127	53	154	64	29	16	141	184	120	156	43	66	47	164	166	74	142
C_11	135	131	107	144	101	98	100	188	78	24	0	185	137	49	114	10	16	179	92	49	180	121	103	7	69	41	159	65	94	141
C_12	176	200	173	8	109	200	103	175	15	198	185	0	122	115	50	138	171	94	10	152	97	104	6	91	164	163	94	196	101	2
C_13	167	146	106	166	103	111	43	118	29	11	137	122	0	197	64	125	29	113	148	59	89	2	199	3	107	79	62	56	183	75
C_14	49	167	163	126	1	76	181	137	76	127	49	115	197	0	183	150	75	99	8	56	63	138	101	95	105	11	138	15	42	181
C_15	30	182	129	33	114	187	157	138	94	53	114	50	64	183	0	196	125	14	191	2	12	190	67	191	155	76	198	151	68	64
C_16	24	77	163	49	177	143	76	50	51	154	10	138	125	150	196	0	200	180	149	75	151	175	35	50	25	155	154	167	115	120
C_17	136	11	161	136	190	19	182	102	123	64	16	171	29	75	125	200	0	58	188	88	27	23	126	78	126	34	166	185	98	60
C_18	20	147	128	15	25	197	100	5	11	29	179	94	113	99	14	180	58	0	103	61	72	71	116	87	70	183	142	66	53	26
C_19	41	104	11	173	89	110	114	137	75	16	92	10	148	8	191	149	188	103	0	59	80	49	151	167	67	64	120	161	116	78
C_20	91	129	27	91	131	166	62	81	177	141	49	152	59	56	2	75	88	61	59	0	178	113	31	165	115	66	151	108	176	164
C_21	7	67	150	129	34	191	109	51	116	184	180	97	89	63	12	151	27	72	80	178	0	123	72	91	173	41	100	93	13	197
C_22	61	194	180	39	1	143	174	24	8	120	121	104	2	138	190	175	23	71	49	113	123	0	29	77	40	154	174	165	89	173
C_23	23	183	97	171	162	38	50	11	122	156	103	6	199	101	67	35	126	116	151	31	72	29	0	186	135	14	14	191	17	17
C_24	145	134	36	111	192	120	162	197	178	43	7	91	3	95	191	50	78	87	167	165	91	77	186	0	181	191	194	16	113	68
C_25	79	148	196	105	86	42	65	23	76	66	69	164	107	105	155	25	126	70	67	115	173	40	135	181	0	32	20	142	108	48
SS_1	107	115	83	3	141	102	77	13	72	47	41	163	79	11	76	155	34	183	64	66	41	154	14	191	32	0	110	47	154	64
SS_2	186	147	150	82	48	105	44	169	133	164	159	94	62	138	198	154	166	142	120	151	100	174	14	194	20	110	0	80	47	197
SS_3	157	114	163	116	189	175	102	158	95	166	65	196	56	15	151	167	185	66	161	108	93	165	191	16	142	47	80	0	118	110
SS_4	130	141	187	138	114	77	127	73	82	74	94	101	183	42	68	115	98	53	116	176	13	89	17	113	108	154	47	118	0	150
SS_5	133	71	70	51	191	60	32	73	149	142	141	2	75	181	64	120	60	26	78	164	197	173	17	68	48	64	197	110	150	0

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