A decision support system for a long-distance routing problem based on the ant colony optimization metaheuristic

Juan-Antonio Sicilia\textsuperscript{a}, Beatriz Royo\textsuperscript{a}, Emilio Larrodé\textsuperscript{a}, Alberto Fraile\textsuperscript{a,∗}

\textsuperscript{a}Department of Mechanical Engineering, University of Zaragoza, María de Luna 3, Zaragoza, 50018, Spain

Abstract

This paper presents a decision support system for the optimization of long distance freight transport by road in the Iberian Peninsula (Spain and Portugal) between several origins and destinations without warehouses at the origin and the final destination. In every order, there is at least one origin and one destination, and these two positions do not need to coincide with other origin/destination pairs for different orders. This can be considered to be a many-to-many type problem, where the freight is picked up at different customer locations and delivered in other client locations.

The aim of the system described consists of helping traffic managers of freight transport companies to reduce operational costs by optimizing the loading of freight in vehicles, optimizing routes and grouping orders following certain load/unload procedures in such a way that pick-up and delivery activities can be previously planned.

For the resolution of the problem, it is proposed an algorithm based on ant optimization techniques which has allowed the system to be modeled taking into account its most characteristic peculiarities: no depots at the beginning and end of the route, a maximum driving time per day, the capacity of vehicles, the compatibility of types of goods in the same vehicle, customers with time windows to pickup/deliver goods, and the manner of loading/unloading vehicles (Last Input First Output).

The effectiveness of the algorithm has been proved using data from real problems. The basis of our computational experiments is the historical data from a large transport company in the Iberian Peninsula.

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∗ Corresponding author. Tel.: +34-976-761-888; fax: +34-976-762-670.
E-mail address: jsicilia@unizar.es, broyoa@unizar.es, elarrode@unizar.es, afrailep@unizar.es
1. Introduction

In Spain, freight transport by road represents close to 90% of the total national freight transport, interregional transport being the more considerable in annual transported tons. In recent years, this type of transportation has become increasingly complex in operational terms. First, the number of operations has increased greatly while the average size of the transported goods has reduced. Second, the average value of the transported goods has increased slightly as have factors such as speed, safety and security, and transport reliability. Lastly, due to globalization and the opening up of markets, distances have increased in recent years. Profit margins have been reduced and the volume of freight has consequently increased in order to maintain a certain profit level (Ministry of Public Works, 2011). Given this context, freight transport companies need to reduce their operational costs. The two main aspects requiring improvement are sharing capacity and better route planning, taking into account, among others, the variable demand of transport, fuel costs and road congestion (Hoff, Andersson, Christiansen, Hasle, & Løkketangen, 2010). The resulting problem is rather complex and requires a considerable amount of information. Competitive advantage can therefore be achieved by the use of a Decision Support System (DSS) to manage transport operations.

The main objective of the system described in this paper consists of helping traffic managers of freight transport companies to reduce operational costs by optimizing the loading of freight in vehicles, optimizing routes and grouping orders following certain load/unload procedures in such a way that pick-up and delivery activities can be previously planned. Certain restrictions also need to be taken into account such as maximum driving time per day, the capacity of vehicles, the compatibility of types of goods in the same vehicle and the time windows imposed by the customer.

The requirements have made it necessary to define relevant criteria related to the objectives of the decision-maker. First, the results and information necessary for taking a decision must be presented in the system in an easy and comprehensible way so that they can be easily understood. Second, the system must be sufficiently intuitive for users who are very experienced in managing transport operations but not in using problem-solving methods and mathematical models. The system is a user-friendly application may be simply adapted to any case study defined by the user.

The remainder of this article is organized as follows. In Section 2, the problem is described. The state of the art and the different solutions used to solve the problem analyzed are stated in section 3 while section 4 presents the algorithm developed. In section 5, the functions of the system are detailed including the architecture and the interface. Section 6 presents the validation results of the system for a real case. Finally, some conclusions are presented in section 7.

2. Problem description

The problem analyzed consists of the optimization of long distance freight transport by road in the Iberian Peninsula (Spain and Portugal) between several origins and destinations without warehouses at the origin and the final destination. In every order, there is at least one origin and one destination, and these two positions do not need to coincide with other origin/destination pairs for different orders. The main objective in solving this problem is to minimize the necessary number of vehicles by optimizing the grouping of orders, taking into account the time window limitations for each client order. Given that daily routes are long distance, the vehicles will work for a maximum one route per day and, in some occasions, routes could take up two or three days due to legal restrictions on driving time and the drivers’ working and resting time.
In this scenario, one loading order is defined as an order sent by the customer to the transport company that can be picked up in one or several locations and can be delivered in one or several locations, respectively. The distance between the pick-up point and delivery point will be between 100 and 1500 km in what is known as long haul transportation.

Some time ago this type of transport was considered as full load, that is to say, one vehicle was used for only one order. In recent years, due to the decreasing demand of freight, it has been necessary to combine several orders in the same vehicle to achieve a return on the operation. In this scenario, it is necessary to reduce intermediate operations as much as possible, such as vehicles staying at the dock. Vehicles must be considered as LIFO type warehouses (Last Input First Output), therefore the first order picked up by the vehicle must be the last to be delivered.

During the order combination process, it is necessary to take into account the types of goods to be transported because of possible incompatibility among them. There is a general classification of types of goods that can be summarized in three types, Normal (N), Refrigerated (F) and Isotherm (I), which cannot share same vehicle due to the different temperatures needed for each type. This situation makes the fleet heterogeneous not in capacity but in technical properties.

Long distance freight is mainly transported over the peninsula by the major roads that cross it. There is not necessarily a single road between a pair of origin-destination nodes, so a road selection is necessary taking into account different criteria such as routing congestion, bank holidays, times and route costs or detours for intermediate orders. Note that this decision is made by the decision-maker, being completely transparent to the customer since the price that he pays does not depend on the selected route.

The daily work of this type of company varies greatly: the number of orders might vary each day, the geographical location of the customers is scattered, the quantity of goods varies constantly and sometimes the use of a specified vehicle is necessary. Note that if the number of orders per day is around 500, this implies at least 1000 nodes to be visited. This number can be considerably increased if the orders have more than one point of pickup or delivery. As additional information, the number of nodes that can be logged into the system exceeds 400,000. Considering this amount of data, storing a distance matrix and/or time matrix between the diverse nodes becomes unfeasible due to both memory size and access time to the database. On the other hand, it is unviable both economically and in terms of system performance times to access a Geographic Information System (GIS) via the web (i.e. Google Maps) due to the large number of requests necessary to determine all the matrix elements. Therefore, to establish the times between the nodes involved in the planning of a certain day, Euclidean distances from their GPS positions are considered.

Once the procedure to determine the distance between the customers is established, the next point to decide is the average speed of the vehicles, taking into account that the distances do not correspond with the real distances. In Barcos, Rodríguez, Álvarez, and Robusté (2010) the sensitivity of the solution in routing design for less-than-truckload motor carriers with regional consolidation centers and hubs (break-bulk terminals) is analyzed, changing the average speed between 80 and 75 km/h and with real distances between the nodes. This paper establishes an average speed value of 70 km/h, considering the Euclidean distances from the GPS positions.

The difficulty of the problem lies in the fact that if the number of orders is relatively large, the resulting combinatorial grows exponentially turning it into a NP-Hard problem for which the application of heuristic techniques are necessary to obtain a high-quality solution in reasonable computational times. This paper proposes a solution methodology based on an Ant Colony Optimization.
3. Related work

The VRP (Vehicle Routing Problem) is considered a one-to-many problem, unlike the type of problem considered here which is a many-to-many problem. The latter can therefore be considered as an extension of the former, inheriting characteristics from some of its variants. One of the most extensively studied variants is the VRP with capacity and time window constraints (CVRPTW), in which the routes start and finish at a warehouse, in which vehicles have a limited capacity and customers must be served in a specific time interval (Toth & Vigo, 2002). Other variant is Open VRP (OVRP) that studies the non-return of vehicles to the warehouse once the working day has finished (MirHassani & Abolghasemi, 2011).

A peculiarity of the problem is that the distance between the origin of the orders and the destination is very long; this is known as the “long haul transportation” problem. The references to this problem found in the literature are scarce. For Caramia and Guerriero (2009) the routes can be multimodal, the goal is to find the set of the shortest and cheapest routes, and the solution must satisfy constraints such as capacity, time windows and so on. In Çalişkan and Hall (2003) develop an efficient model which reduces distance, balances freight and tries to ensure that routes finish near the drivers' homes.

A further characteristic is the case in which the freight from different customers must be consolidated in the same vehicle, and the goods from each individual customer cannot therefore fill the vehicle. This is known as less-than-truckload. In Jian, Yaohua, and Jingbo (2007) try to reduce the cost while maintaining a good service level. This is very similar to the problem presented here, but without time windows. Also, between the last pickup and the first delivery there is a break-bull-terminal where the load is organized, and a genetic algorithm is applied.

Finally, the last aspect to be considered is that, in our case, the customers must be visited under a LIFO policy, meaning that the last order picked up will be the first delivered. Another way to organize customers is using a FIFO policy (First In First Out), which differs from the first in the sense that the first to be picked up is the first to be delivered. In the literature relating to FIFO, Cordeau, Dell'Amico, and Iori (2010) present a hub where the freight is organized enabling the first pickup to be the first delivered. In Li, Lim, Oon, Qin, and Tu (2011) the LIFO problems are resolved using a variable neighbourhood search heuristic.

There has been a growing interest in the creation, development and use of DSS due to the complications involved in resolving these types of problems and the complex requirements necessary to carry out feasible solutions to help large transport companies to make decisions effectively and manage their work efficiently. The DSS has emerged as a computer-based approach assisting decision-makers to address semi-structured problems by allowing them to use data and analytic models (Turban, 1993).

Significant contributions can be found in the literature regarding DSS. Santos, Coutinho-Rodrigues, and Antunes (2011) present a web spatial DSS aimed at generating optimized vehicle routes for multiple VRPs that involve serving the demand located along arcs of a transportation network. Faulin, Keefer, Bayo (2005) design a DSS to optimize routes for delivering the frozen products of a specific company according to two goals: to design a route builder geared specifically to the road network of the area and to integrate the DSS into the global management of the company. Caramia and Guerriero (2010) present a solution to a milk collection problem for an Italian dairy company that collects raw milk from farmers based on two mathematical formulations with the goal of minimizing the number of vehicles and the tour length.
4. ACO algorithm

This section describes the main aspects of the optimization algorithm designed for resolving the problem. The algorithm is based on the ACO approach, a technique for optimization which imitates the behaviour of ants in search of food (Dorigo & Stützle, 2010). In this search, the ants transmit information through a chemical substance called pheromone, whose quantity and quality depend on the way chosen for this purpose.

The algorithm starts with the allocation of each order to a vehicle, obtaining an initial feasible solution. However, this is only ideal if the load occupies almost all the space available in the vehicle. The present case assumes relatively small orders due to the fact that the perspective of the company is changing towards the so-called logistic operator which is responsible for managing the whole supply chain, so that the costs of inventory, maintenance and transportation are minimized as far as possible.

The proposed algorithm must take into account variations of the problem such as the allocation of alternative roads to communicate the same pair of nodes. The algorithm offers two possibilities for this. In the first case, it starts by allocating each order to a certain road from the set of feasible roads, subdividing the problem into as many problems as there are roads defined (18 in the case of the Iberian Peninsula), since only the orders in the same road can be grouped together. A first ant colony determines this allocation, applying the pseudo-random-proportional rule. In the second case, the road is not allocated a priori before designing the routes, but all orders can be combined mutually. The road will be allocated once the route has been designed. In both cases it is possible to introduce restrictions on the roads due to routing congestion or bank holidays, as well as the use of highways.

Second, since there are no depots at the beginning or end of the route, it is necessary to determine the first order loaded into the vehicle. For this purpose, a node is added operating as a fictitious warehouse which is connected with each order (first pickup) by arcs with zero unit cost. To that end, a second ant colony establishes, by the pseudo-random-proportional rule, which of the remaining orders not yet allocated to any route is the first for the next route.

Eventually, once the first order of the route is established, it only remains to add more orders in the route from those still unallocated, taking into the account the vehicle capacity constraints, time windows of customers and driving time limits, by means of a third ant colony.

As already mentioned, the main goal is to reduce the number of vehicles used. In the case of obtaining solutions with the same number of vehicles, that with the shorter distance is selected, as this is the second parameter that affects the distribution cost. The outline of the proposed algorithm is shown in Fig 1.

5. A decision support system for the decision-maker

Given the diversity and complexity of the problem and the large amount of information involved, the system design must be effective, efficient and user-friendly. To achieve this, information relating to parameters and results should be shown intuitively. In this context, a DSS becomes an essential application for studying this set of problems because it combines efficiency and simplicity in the processing of information. One of the main concerns in designing and developing the DSS has been to give users a flexible and easy-to-use web-based application. The system architecture, the main graphical aspects and the representation of the results are explained in the following sections.
5.1. Architecture

This application is divided into three parts: DataBase (DB), where the data are stored; Graphical User Interface (GUI), through which the user interacts and the graphical information is displayed; and the algorithm or calculation tool which generates the solution. The interaction between the GUI and the calculation tool is achieved by means of the DB. The tool reads the data stored in the DB and also writes the results there. The schematic representation of the architecture and the modus operandi of the implemented system are presented in Fig 2.

Fig. 1. ACO algorithm

begin
  Generate an initial feasible solution of the problem
  Initialize ACO parameters
  while the stopping condition is not verified (iterations) do
    while the number of ants \( m < M \) do
      Use the \( m \)th ant to construct a feasible solution
      ACO I - Order-to-via-allocation ()
      ACO II - First-order-in-route-insertion ()
      ACO III - Rest-of-orders-in-route-insertion ()
      Update pheromone trail of selected arcs (local updating)
      Solve the lower level problem associated with routes of \( m \)th ant
    end while
    Update pheromone trail (global updating)
  end while
end
The system has been developed as a web-based application hosted on a terminal server accessed through every remote computer in the network. The Data Base Management System used is MySQL, and the GUI has been developed with PHP, a general-purpose server-side scripting language which requires installing a web server on the terminal server. To provide these services, a free Apache distribution has been installed on the terminal server called Xampp that includes MySQL, PHP and Perl. Other languages and technologies such as Javascript, Ajax and CSS have been included to give the GUI greater attractiveness and speed. The integrated development environment (IDE) Microsoft Visual Studio 2008 has been used for the calculation tool. The IDE allows programs to be written in C++, one of the most efficient and rapid languages for generating a large amount of computer calculations.

5.2. Graphical user interface

The main objective of the GUI is to facilitate the use of the DSS on the part of the decision-maker so that he can manage the information and results of the system simply. Fundamental principles of usability have been considered to develop it: consistency, robustness, intuitiveness, scalability and interactivity (Dix, Finlay, Abowd, & Beale, 2004).

The interface is made up of a set of different windows where the information is displayed and the user interacts in different ways depending on the functionality provided. This windows show orders for grouping and generating routes, parameters where the value of constraints and calculation variables are modified, rates of cost between each pair of provinces, and results obtained by the calculation tool showed in Fig 3.
On the upper side there is an information management menu that allows the user to execute different edition operations. Below the management menu there is a summary of the solution including the number of vehicles required, the total cost, and so on. The routes created by the calculation tool appear in the centre of the window with their most important characteristics in order for the user to be able to identify mistakes and peculiarities.

To validate each route, the decision-maker must be able to visualize the route characteristics as well as the vehicle load state in each segment. The most important route characteristics are: origin and destination, type of goods, vehicle load state, and estimated dates and times for each intermediate vehicle stop. The itinerary of each route is shown using Google Maps. This allows each route to be viewed on real maps in order to get a better vision of the problem.

6. Computational experiments

6.1. Experimental data

The basis of our computational experiments is the historical data from a large transport company in Spain relating to a number of days during a six months period. To create an instance, all the daily attended orders were extracted from the historical data, including for each of them the geographical location of the pickup and delivery points, the quantity and type of goods, the time required to complete the operation, and the time windows to reach the customers. The number of daily orders during the six months of the study varies from 95 orders per day to nearly 1000. It should be noted that at least double the number of customers will be visited. The restrictions imposed in all the instances are the same: maximum vehicle capacity (24000 kilograms, 13.5 linear meters, 33 non-stackable pallets and 92.95 cubic meters), average speed (70 km/h), maximum driving time for the drivers (9 hours) and pickup and delivery times for each customer (1.5 hours).

Next, the size of the orders was revised (quantity of goods picked up or delivered in each order), because this is a basic parameter for group orders in a given vehicle. Three types of orders were established according to the quantity of goods: small (0 - 4999 kg), medium (5000 - 14999 kg) and large (15000 - 24000 kg) representing 68-80%, 15-25% and 4-10% respectively. For most days the number of orders belonging to each group remains within this specific range.

Both in the specific literature on the subject and in pilot experiments carried out in this field, it is noted that one of the most important restrictions on group orders are the time windows imposed by customers. In the present case, some of the customers do not impose a time window but they do set the time scheduled for the vehicle to arrive at the dock. This produces long waiting times. Thus, a measure to reduce costs is based on extending the time windows. The influence of this restriction is therefore studied here, extending the time windows by 2 and 4 hours. It has already been mentioned in previous sections that it is possible to find different roads to communicate two customers, obliging the order to be allocated to a certain road in the first step of the allocation algorithm. The last parameters characterizing the problems to be solved consist of activating this possibility or not. If a specific road is not assigned to each order in the first step of the algorithm, the number of possible combinations is a lot bigger.

6.2. Results analysis

The experiments were performed on a PC Pentium Dual at 1.8GHz with 2GB of RAM under Windows XP. For each configuration, 10 runs of the instance were done; hence the problem was solved 300 times. The computing time did not exceed 2 minutes in any case. To measure the efficiency of the overall solution, three
performance metrics were reported. The first is the objective function of the algorithm: the total number of vehicles involved \((f_1)\). The other two are the percentage of the grouped orders with respect to the total number of orders \((f_2)\) and the percentage of vehicles with more than one order with respect to total number of vehicles used \((f_3)\). The results of the experiments are listed in Table 1. The first four columns define the settings of the experiment (the test problem, the number of orders, the allocation of roads before or after designing the route \((0=\text{before}, 1=\text{after})\) and the extending of the time windows of all the customers (in hours)). The rest refer to the three performance metrics, showing the best solution, the worst solution and the average of the 10 runs of each instance.

As expected, the results showed that in all cases when the time window of the customers increased, the number of routes decreased. When the time window was extended by 2 hours, if the road was assigned after creating the route the number of routes decreased by around 40%. The decrease in routes was less appreciable when the time window was extended from 2 to 4 hours. Thus, carriers should concentrate their efforts on negotiating a 2 hour extension of the time window. Furthermore, both the total number of routes and the metric \(f_3\) decrease when the time window extends from 2 to 4 hours. This means that the number of routes with more than one order decreases, but not those that only carry one order as they carry orders that cannot be grouped with others.

### Table 1. Algorithm results of the test problems

<table>
<thead>
<tr>
<th>Problem</th>
<th>Orders</th>
<th>Roads</th>
<th>ΔTW</th>
<th>N° vehicles</th>
<th>% grouped orders</th>
<th>% vehicles with grouped orders</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(f_1) (f_2) (f_3) (f_1)</td>
<td>(f_1) (f_2) (f_3)</td>
<td>(f_1) (f_2) (f_3)</td>
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Another influential factor is how the algorithm allocates the road to the routes. In all cases, it appears that the best results are obtained when the road is allocated after creating the route. One aspect that may be involved is that orders are not uniformly distributed in the Iberian Peninsula, because their origin or destination is located in specific regions. This feature therefore influences the optimization.

7. Conclusions

This paper presents a DSS for route planning by companies that daily transport goods long distance by road in the Iberian Peninsula, with a large and variable number of orders and without stores at the beginning and the end of the route. One of the premises has been that the designed tool should be easy to use by the decision-maker both in the data entry and in the reading of results, bearing in mind that this agent does not need to have knowledge about the optimization tool. The resolution of the problem has made use of an approximation based on an ant colony, which has allowed the system to be modeled taking into account its most characteristic peculiarities: no depots at the beginning and end of the route, the possibility of communicating two nodes by more than one road, customers with time windows to pickup/deliver goods; load incompatibility; and manner of loading/unloading vehicles (LIFO). Furthermore, five instances have been solved from the historical data of a carrier with a number of orders between 99 and 990, in which the influence of the manner of road allocation has been studied, as well as the size of the time windows in terms of the objective function (number of used vehicles), the percentage of grouped orders with respect to the total and the percentage of vehicles that carry more than one order with respect to the total number of vehicles. Finally, it should be emphasized that the system has been designed as a support system for the decision-maker who ultimately decides what routes are to be used and in what manner, given a solution.

References


