Sustainable Transportation Systems: dynamic routing optimization for a last-mile distribution fleet

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Abstract:

Logistics costs control has always been considered a key issue for business development. In order to decrease transportation costs, companies are pushed to negotiate lower logistic service prices with Third-Party Logistics Service Providers (3PL) which, in turn, should be able to optimize their processes and reduce their costs in order to preserve the adequate profitability and allow their industrial customers to gain competitive advantage. In this paper a method to reduce industrial costs and negative externalities associated with fleet management on an Hub & Spoke transportation network is presented. We state that the *Time Dependent VRP with Pick-up and Deliveries and Time Windows* model may be the most suitable for goods distribution problem inside large cities. A dynamic version capable to consider road traffic along with variable congestion effects during the day has been created. Hence, we proposed a quick and flexible heuristic that has been validated with the real data of a subsidiary of a 3PL leader in the express transportation sector. The heuristic has demonstrated to be able to reduce travel time, travelled distance and, at the same time, significantly increase the service level, on top of the relative benefit for the community coming from a substantial reduction of air pollution, noise pollution, congestion and incidentally.

Keywords: Logistic Optimization, Sustainable Transportation Systems, Goods Distribution, Vehicle Routing Problem, 3PL

1. Introduction

Generally speaking, as a percent of sales, logistics costs vary significantly depending on industrial sector, from minimum values of 6% up to peak values over 20% for certain textile companies. As an average, transportation weights almost 50% on the total logistic costs. Compared to all other logistics costs components, transportation is the only one that has suffered a further increase (+11%), and its trend is positive since 2005 as it has been shown in the latest Council of Supply Chain Management Professionals Annual Conference held in October 2008 in the USA. The augmented specialization of industrial products, the globalization process and the developments in production and supply chain management systems have made the companies needs much more sophisticated: management of goods flows heavily depends on transportation systems, which are requested to be more and more reliable, timely and economic. Thus, the opportunity to invest in increasing transportation efficiency should be investigated in order to reduce firms' cost. It is also important to notice that the greatest part of industrial companies usually outsource their external logistic functions to the so called "3PLs" (Third-Party Logistics Service Provider, see Delfmann *et al.* 2003). A 3PL is a provider of logistics services that performs all or part of the customers' logistic functions, either external (e.g. management and execution of transport activities) or internal (e.g. material storage and handling). In order to decrease transportation costs, companies are pushed to negotiate lower logistic service prices with 3PL; hence, 3PLs should be able to develop the appropriate skills and competencies to ensure the achievement of scale and scope economies, in order to optimize their processes and reduce their costs, thus allowing their industrial customers to gain competitive advantage.

On top of this, it is important to remind that transportation issues have greatest consequences on social side, directly affecting community life; indeed, externalities from freight traffic (road transportation in particular) should not be underestimated: during the last two decades, the congestion of urban centers and of major highways has been growing throughout the old continent, threatening the competitiveness of European economy as the associated costs reached the 0.5 % of GDP. Moreover, road traffic is definitively the main responsible of air pollution, generating 84% of CO2 emissions of the whole transportation system - CO2 emissions from vehicles are estimated to reach 1'113 billion tonnes in 2010 (European Commission, 2001). Thus, road transportation optimization should be considered of maximum priority in any sustainable industrial development context; specifically, particular attention should be given to the short-range distribution and in particular to last-mile deliveries: approximately the 50% of freight traffic takes place inside the cities (90% considering light vehicles below 3.5 tonnes). In this context, optimization of vehicle routing management for distribution of goods plays a critical role. A further insight into transportation costs composition in industrial companies has shown the clear impact of fuel costs (25%) and drivers (43%) on the total (Davis, 2008), and these costs can be directly cut down through the reduction of travelled miles and time. Purpose of this paper is to present a method to reduce industrial costs and negative externalities associated with goods distribution in the cities, based on a fleet management optimization approach. This topic is included in the scope of a research project focused on the optimization of goods transportation strategies, developed together with a primary large-scale retailer Italian firm.

Subject to constraints related to vehicles and customer needs, the reduction of transportation costs in an industrial firm belongs to a wide range of operations research typical problems. The problem of minimizing the mileage or the total travel time is usually lead back to the class of "Vehicle Routing Problem" (VRP) and approached with integer linear programming. Despite the VRP can nowadays count on 50 years of literature (the first articles date back in 1959) and despite many problem variations have been investigated through many different algorithms (heuristics, tabu search, simulated annealing, genetic algorithms, etc.), it is still difficult to find validation instances that reflect the complexity of the dynamic aspects of the real logistics distribution problems. The new class of "Time Dependent Vehicle Routing Problem" (TDVRP) has been identified only recently (Malandraki and Daskin,1992) Most of the research in this area has focused on dynamic routing and scheduling, considering variations in customer demands. However, there has only been limited researches on routing and scheduling with congestion dependent travel times, despite the time-variability of traffic congestion represents the major element which affects transportation performance inside cities boundaries. Literature on TDVRP is relatively scarce and the proposed approaches seem not to be directly applicable to large cities distribution problems, due to strong assumptions oriented to simplify the model and reduce the high computational complexity of the algorithms. This trend is also reflected in the literature dedicated to 3PL: within the areas of research identified by Marasco (2008) in his exhaustive literature review, no article seems to validate the application of these models and algorithms with real problems of distribution fleet management.

In this paper, aiming at showing its potentialities in increasing the efficiency of a fleet of vehicles in reducing logistics costs of an industrial enterprise, a variation of the TDVRP has been implemented and validated with a flexible heuristic on a real case of a 3PL distribution fleet with delivery time windows, operating in a urban area with heavy traffic variability during the day. The algorithm has demonstrated to reach a good solution within a reasonable computational time, achieving a substantial reduction of the total travelled distance along with the associated internal and external costs. In conclusion, the optimization results are analyzed with the aim of evaluating the impact in terms of economic (reduction of internal costs) and environmental sustainability (reduction of externalities).

2. Last-mile distribution fleets importance

In the assessment of service level of a 3PL, time windows compliance (therefore, flexibility and speed of operations execution) and geographical coverage play a crucial role; meanwhile, the provider yearn for cost efficiency, traditionally aiming at decreasing the fleet size (in terms of number of carriers), maximizing load factors and minimizing the total travel time.

In 2007, Oxford Economics consultancy firm, in collaboration with the Italian Confindustria Study Center and AICAI (the Italian Association of International Air Carriers) published a research paper on logistics providers in which the importance of express transport (i.e. urgent door-to-door goods and documents service delivery, within certain time windows) is pointed out, as far as the production activity in our country is concerned. In particular, "next-day" services ("picked now and delivered tomorrow", possible thanks to night flights) are considered fundamental by many companies: in the cited survey, 37% of companies stated that their business would be dramatically damaged without next-day services due to the need of increasing inventories, to the expectation of losing part of orders, up to the evaluation of the opportunity of relocating the activities abroad.

Indeed, it is acknowledged that in the modern economic scenario, 3PL may grant significant competitive advantage to their customers (Tate, 1996) especially in case of SMEs - which typically do not own a capillary transportation system - and in case of companies located in remote regions - which can thus successfully and competitively participate in international trade. The ability of the logistics provider to simultaneously coordinate different customers, to adapt services to their specific needs, together with the ability to cooperate with the client and establish with him a long-term relationship, may result in many economic, organizational and financial benefits for the consigner, such as: reduced logistics costs, improved service levels, increased customer satisfaction, reduced circulating capital, saves in labor and equipment, increased flexibility and productivity, etc.

A modern trend to pursue these objectives, followed by major multinational 3PL, is to organize the logistic network in accordance to the "hub & spoke" model: freight flows convey to few points (hubs, typically located in the peripheral zones of large cities) from where originate the final delivery routes (spokes), that can thus be more easily optimized. This logic is slowly spreading to road transportation despite it has always been commonly adopted with air and maritime carrier management, where it meets the aim of maximizing the payloads. Transports between hub can be arranged in many different ways while the dispatching in "last-miles" is typically assigned to fleets of light vehicles, which delivery and pick up goods up to the customers.

"Last mile" goods distribution problem – often led back to the "city logistics" problem general framework – can be optimized using a complex linear programming model known as *Time-Dependent Vehicle Routing Problem with Pick-up and Delivery and Time Windows*, which belongs to the largest class of the Vehicle Routing Problem (VRP). VRP generally works on a topological network defined as a graph G = (V, E) where V = (0, ..., n) is the set of nodes corresponding to depots and customers locations while E = (1, ..., m) is the set of edge corresponding to the roads between nodes. Each edge, which can be oriented or not in accordance to the characteristics of the road, has a travelling cost that is usually related to its metric length; as it has been said in the introduction, travel time may heavily depend on the hour of the day at which the road is driven through; this is the reason why it makes sense to model vehicle routing problems in a "time-dependent" dynamic way.

3. The Time-Dependent Vehicle Routing Problem

The main reason for adopting time-dependent models is that the vehicles in routing problems operate in a traffic network, which may naturally be congested depending upon the time of the day: while it seems reasonable to assume that the service time at each vertex of the graph (i.e. operations lead time at the customer's premise) may be known in advance, this is definitely not the case for travel times, which result by a stochastic process associated to variables such as the number of vehicles travelling on the same arc and on their speed. Acknowledging that road travelling time varies with traffic behavior, this should lead to a dynamic missions scheduling policy in managing fleet operations, in particular in large cities.

In the Time Dependent VRP, travel times may vary either on the time of the day (Malandraki and Daskin,1992) or according to the service sequence (Picard and Queyranne, 1978; Lucena, 1990). In the former case, a first approach was proposed by Malandraki and Dial in 1996 to solve the simplier *Time-Dependent Travelling Salesman Problem*. Few application of traffic simulation for travel time prediction have been tested (Psafaris, 1980, Fox et al., 1980) and however it seems to lack a connection between simulation and a solver of the modeled problem. The first attempts to approach the *Time Dependent Vehicle Routing Problems with Time Windows* were performed by Ahn and Shin in 1991. One year after, Malandraki and Daskin introduced a rough discrete travel time function and developed an heuristic algorithm based on a nearest-neighbor method and a mathematical programming approach with cutting plans; the authors randomly generated 10÷25 nodes problems with variable travel time in dependence to the daytime slot (morning, midday and afternoon): nearest-neighbor heuristic produced a quick solution while the cutting plans algorithm resulted to be computationally more expensive even for small instances. Hill and Benton (1992), Horn (2000) and Fleischmann et al. (2004) approached the time dependent routing problem with a piecewise speed function, without considering time windows. Chen et al. (2002) developed an algorithm for the time-dependent vehicle routing problem with time-windows but did not validate it using real problems. Chang et al. (2003) tackled the real-time VRPTW with simultaneous delivery/pickup demand, proposing a heuristic comprising route construction, route improvement and tabu search. Ichoua et al. (2003) used a model based on discrete travel time by adding correction factors to reproduce the congestion effect on each edge of the graph. In order to reduce run times and complexity, the authors tested the model using, again, three time slot. Anyway, no details are provided on how to relate the correction factors to the characteristics of real-life problems.

Recently, research on this topic has been intensified. Haghania and Jungb (2005) proposed a mathematic approach to find a lower bound solution implementing a genetic algorithm which resulted to be effective only on small instances due to computational issues. Donati et al. (2008) proposed an interesting algorithm based on the "ant colony"approach: this allowed to find good solutions but seems to be not directly applicable to real 3PL needs. Soler et al. (2009) managed to solve TDVRP, transforming the problem into an Asymmetric Capacitated VRP; howevere the algorithm is still characterized by an high computational time and this reduces its application to very small instances. In another approach Tabu Search algorithm was used to solve a real instance, but the problem setting seemes to be too much simplified as typical pick-up and delivery constraints were not considered.

The inclusion of Pick-up and Delivery constraints in the TDVRP problem requires the association of vertex i to two non-negative quantities d_i and p_i representing the amount of goods to be respectively delivered and withdrawn (it may be even assigned a single parameter for each customer, equal to the net difference $d_i = d_i - p_i$) and two parameters O_i and D_i representing respectively the origin of the goods to be delivered in i and the destination of the goods be withdrawn from i (Toth and Vigo, 2002). In the case of a Hub & Spoke distribution network, for each vertex i both O_i and D_i coincide with the hub which plays the role of the central depot.

Either for the central depot or for the customers' premises, specific time windows in which delivery and withdrawn can be completed are defined: the time windows starts at moment e_i and ends at time l_i. The solution of the problem corresponds to the determination of distribution tours, assigned to the available vehicles, with the aim of minimizing the global transportation cost, considering the variation of travel time during the day in each route subject to the following constraints:

- each tour starts and ends within the time window of the depot;
- each customer is visited in exactly one tour;
- each customer is supplied within its time window: an early arrive causes additional waiting time and a late service entails a penalty cost;
- the total quantity carried in each tour does not exceed the capacity of the assigned vehicle;
- clearly, the assigned vehicle must have enough capacity for picking-up the commodities at each visited customer.

The TDVRP with Pickup and Deliveries in Time Windows belongs to the class of NP-Hard problem, considering that it is a special case of the VRP, which is proven to be NP-Hard itself (Savelsbergh, 1985); indeed, in literature the solution approaches are often founded on the elimination of one or more of the above mentioned constraints. In this paper a quick heuristic approach which takes into account all of the previously defined constraints is proposed.

4. Solving the Time Dependent VRP with Pickup and Deliveries and Time Windows

4.1 Building the graph

The approach to a real-life distribution problem obviously requires to deal with a road network, which is typically very complex. Hence, at first, a simplified graph needs to be built, in which only customers' premises and the depot are reported, and each arc between couples of nodes represents the shortest path between them. To each arc from node i to node j, a temporary label which reports the arc travelling time t_{ij} is assigned. Note that the t_{ij} value changes as time passes to take into considerations the traffic variations. To this extent - similarly to the approach chosen by the previously cited authors - a certain number of significant time slot must be identified. In this case four time slot were selected, according to a recent urban traffic analysis performed on the North of Italy territory (Zamboni, 2008), but a higher number of time slot may be eventually identified with a bearable increase in the computational complexity, because a new travelling time graph is indeed generated for each time slot. It may be possible to define different travelling speed in each time slot per each arc; this obviously results in an increase of the computational complexity of the pre-processing phase as well. In the validated case however, carrier speed is considered constant on each route, varying only among each different time slots and each different road types (urban, extra-urban, motorways), as it is shown in Figure 1 below.

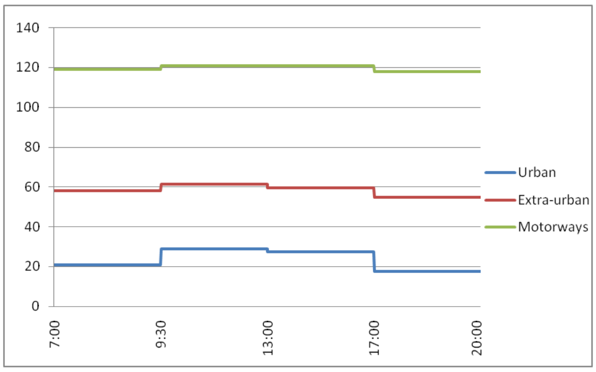

Figure 1. Average speed in each time slot and per each road type

4.2 Nodes clustering

Clearly, in order to perform timely operations, the departure time τ_i^k of the carrier k starting from node i and travelling to node j should satisfy the following constraint:

$$\tau_i^k \leq l_j - t_{ij}(x) - s_j \tag{1}$$

where $t_{ij}(x)$ is the travel time from node i to node j in the time slot x; l_j and s_j are respectively the latest time to deliver to customer j and its service time (load/unload operations lead time). Note that this constraint is not binding because it may be possible that some nodes are served with a delay with respect to their time windows. For the customer to be served in the first time slot, the following constrain should be accomplished:

$$\tau_0^k + t_{0j}(x) \leq b_1 \tag{2}$$

where node 0 represents the central depot and b_1 is the end of the first time slot. Thus, among the set of the graph vertices, some *critical nodes* are identified as those customers j whose delivery require the vehicles to depart from the depot as soon as possible. From (1) and (2), for these critical nodes it stands:

$$l_j - s_j \leq b_1 \tag{3}$$

In particular, the difference $l_i - s_i$ can be used as a node criticality measurement: the more the node is critical, the less time is available to serve it.

In the proposed approach, critical nodes are served at first (nodes are ordered from the more critical to the less one) and then vehicles routing is completed according to the nearest neighbor rule (Solomon, 1987) aiming at finding the right trade-off between service level increase (in terms of respect of time windows) and cost reduction (in terms of reduction of travel distances and time)

4.4 The proposed heuristic

Solomon's nearest neighbor heuristic resulted to be suitable to real case resolution because it does not require huge computing time and can be easily adapted to include new constraints. With respect to Solomon's contribution, indeed, in this paper the pick-up / delivery constraints and the *critical nodes* scheduling criteria concept are added. This, on top of considering time–dependent travel times as it is necessary in the TDVRP problem.

The proposed heuristic steps are the following:

step 1: identify critical nodes and sort them from the more to the less critical one. Set the number of vehicles equal to the total number of available vehicles;

step 2: assign a critical node – following the criticality order – to each vehicle. All the vehicles are assumed to start the tour from the central depot, i.e. the hub. The vehicles capacity constraint is the only one considered in this assignment, because – as it has been said before - it may happen that, for some remote nodes, the (1) and (2) constraints are not satisfied. In these cases, these delivery delays are recorded and this contribute in determining the value of the service level indicator for the solution. The selected nodes represent the first stop of each vehicle routing;

step 3: if all the critical nodes are assigned to a vehicle, then go to step 4; else, each unassigned critical node must be assigned to the vehicle which serves the nearest assigned one. These nodes indeed represent the second stop of some vehicles routing;

step 4: complete vehicles routing with Solomon's nearest neighbor heuristic, basically assigning each unassigned customer to the nearest vehicle;

step 5: assign the depot as the final stop for each vehicle. If the demand is completely satisfied then reduce the number of vehicles by one and go back to step 2; else if this is the first iteration of the algorithm, this means that the fleet cannot satisfy the demand, i.e. the number of available vehicles is not sufficient.

Note that the algorithm runs on a dynamic scenario because the travelling time graphs changes every time slot. This has forced the utilization of simulation in order to validate the performance results.

5. Validation on a real case

5.1 Background

The analyzed firm is one of the leader 3PL company in the European express transportation sector, where it actually manages one of the biggest distribution network structured with a Hub & Spoke logic. Its large and differentiated services set for *door-to-door* distribution (with deliveries completed before 10:00-12:00 AM in the day following the order receipt, as it happens with medical goods transportation) needs optimized fleet management, because this becomes crucial in order to guarantee the required rapidity, punctuality and flexibility for reaching the maximum service level at a minimum transportation cost. The data used to validate the algorithm are relative to the transportation services provided by one of most important subsidiary in the north of Italy. This subsidiary serve a big conurbation - it can be assimilated to a medium size city, <2.000 km^2 – with an hub located 180 km far from the area center. The objective of this case study is understanding how the previously described optimization heuristic can improve 3PL performance in terms of costs and service level. The performance of the route configurations obtained with the proposed heuristic and with the aid of simulation is compared with that reached in the real case and computed from the available historical data (actually the fleet management criteria used by the subsidiary is simply based on assigning one carrier to each predetermined service zones; scheduling and routing issues are completely let to the drivers experience and feeling).

5.2 Case data

The subsidiary is equipped with 9 vehicles of 2 tonnes / 15 m^3 maximum capacity. Due to an internal policy, the firm imposes a 65% maximum load factor per each vehicle. Daily travel time is constrained too, on the basis of the 561/2006 EC Regulation (European Parliament and Council, 2006), with an upper bound of 9 hours and a minimum of 45-minutes stop after the first 4,5 hours of travelling. In the specific case, customers may accept deliveries and pickups in one of the following two alternative time windows: from 08:00 AM to 10:00 AM or from 08:00 AM to 06:00 PM; service time is composed by a fixed amount (equal to 5 minutes for each order or 2 hours for preparing a full load at the depot) and a variable share which depends on the volume of the order (we assume a loading rate of 8,3 m^3/h and an unloading rate of 17,0 m^3/h), on the specific kind of service (delivery and/or pick-up) and on the type of parcel..

The relative stability of the number and assortment of incoming orders allowed, without loss of generality, to focus the analysis and optimization of the 3PL fleet on a single day. Table 1 shows the number and typology of units moved to/from each customer in the 9 zones originally individuated by the subsidiary, along with their total weight.

Zone	*Parcels*	*Envelopes*	*Packages*	*Weight (kg)*
1	60	23	9	1’389
2	89	27	9	3’898
3	53	20	5	1’134
4	68	4	5	1’457
5	85	17	13	2’873
6	130	19	15	3’324
7	25	4	3	726
8	45	11	8	1’094
9	23	1	0	309
Tot.	*579*	*125*	*68*	*16’204*

Table 1. Shipping units on a single day

These data are provided only to the extent of exemplifying the order of magnitude of the analyzed instance because evidently the simulation locates the graph nodes basing on the specific addresses of the 409 customers’ premises thanks to the use of MS MapPoint.

5.3 Simulation and Results

The algorithm ran on a 4GB RAM 3 GHz Intel Core 2 Duo CPU machine and reached the following solution in about 33 minutes (two iteration were executed). Table 2 shows the total number of orders assigned to each vehicle along with the travel time and travelled distance.

Vehicle	*Travel time (h:min)*	*Travelled distance (km)*	*Assigned orders*
1	8:39	225	47
2	8:37	89	72
3	8:36	150	61
4	8:33	833	64
5	8:58	1381	62
6	8:29	80	75
7	8:48	131	67
8	8:15	159	59
9	8:31	325	33
Tot.	*77:29*	*3372*	*540*

Table 2. Results for each vehicle

The evaluation of an algorithm performance requires to switch to operative research and computer science point of view. However these theoretical investigation have been set aside, considering the only interest of the authors in the industrial consequences of the adoption of a simple vehicle routing heuristic as far as the 3PL and the involved stakeholder’s business is concerned.

Table 3 shows the comparison between the performance of the heuristic solution and that of the original subsidiary fleet management approach, in terms of total travel time, travelled distance and, most important, of service level measured as the ratio between satisfied orders and total received orders.

	Travel time (h:min)	*Travelled distance (km)*	*Service level (%)*
Subsidiary approach	78:33	3664	72
Proposed heuristic	77:29	3372	100
Gap	1:04 (-2%)	-292 (-8%)	+28 (+39%)

Table 3. proposed heuristic effectiveness

On top of the significant increase in service level – which represents a remarkable and valuable improvement in the interest of the 3PL customers – the heuristic showed a potential reduction of 292 km per day. This may be translated in a reduction of more than 90’000 km/year for this 9-vehicles fleet operating on the chosen area, if the analyzed day can be considered a significant sample in the year.

Despite the company did not provide the internal costs data, assuming 1,09 euro/km as the subsidiary operative cost on the basis of the estimation of the Italian Department for Economic Development, we proved that the application of the proposed heuristic may lead to a nearly 100’000 euro/year cost reduction; as an alternative, admitting an hypothesis of linearity, during the saved 300+ hours the subsidiary may increase the number of accomplished orders by almost 48’000. We should not forget that saving in terms of travelled distance also correspond to reduction of externalities and benefits for the community: estimating a total external cost of 0,32 euro per travelled kilometer (Maibach et al., 2007), thus including air pollution (9%), noise pollution (12%), congestion (41%) and incidentality (38%), the total external cost reduction amounts to 29’000 euro/year.

Note that, in this case, the proposed heuristic found the best solution in just two iterations, showing that the available vehicles in the fleet were the minimum required in order to satisfy the demand. In the case of an oversized fleet, the low computational time of the algorithm would anyway allow to find the optimimal solution - in terms of minimizing the number of needed vehicles too – simply with an iterative approach, thus decresing the number of vehicles each cycle.

6. Conclusions

Operations Research methodologies should be better unstitched from scientific books and applied in real industrial contexts. For 50 years, vehicle routing literature has concentrated on refining complex algorithms in order to reach good solutions on famous NP-hard problems, while European enterprises completely ignore that from the adoption of a simple heuristic a 9-vehicle express courier fleet may reach a 100'000 euro of saving per year.

The heuristic has demonstrated to be able to reduce travel time, travelled distance and, at the same time, significantly increase the service level, on top of the relative benefit for the community coming from a substantial reduction of air pollution, noise pollution, congestion and incidentally. The cost for the development of a simple decision support system that can be used daily by a 3PL to optimize its fleet management criteria is negligible if compared with the entity of the pursuable benefits. Once more it has been clearly pointed out the inefficiencies originating from the lack of information sharing and technology transfer from the universities to the industrial world.

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