Road-based goods transportation: A survey of real-world logistics applications from 2000 to 2015

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February 9, 2016

Abstract

The vehicle routing problem has been widely studied from a technical point of view for more than 50 years. Many of its variants are rooted in practical settings. This paper provides a survey of the main real-life applications of road-based goods transportation over the past 15 years. It reviews papers in the areas of oil, gas and fuel transportation, retail, waste collection and management, mail and package delivery and food distribution. Some perspectives on future research and applications are discussed.

Keywords: vehicle routing, applications, real-life cases, logistics

1 Introduction

Transportation is central to our modern society. It encompasses the distribution of products manufactured worldwide, the movement of people, and the provision of services such as waste collection. Transportation

and distribution problems are also central to scientific research in the areas of logistics and supply chain management. Two classical problems in transportation are the traveling salesman problem (TSP) and the vehicle routing problem (VRP), which are central to the fields of combinatorial optimization and integer programming. Hundreds of variants of these problems have been studied over the past 50 years. General references on the TSP and its variants are Lawler et al. [61], Gutin and Punnen [46] and Applegate et al. [8]. For the VRP and its variants, see Toth and Vigo [86, 87], Golden et al. [43], Schmid et al. [78] and Caceres-Cruz et al. [16].

Routing problems are rooted in a wide variety of real-world situations. Because of their complexity, they are mainly solved by means of heuristics, some of which are now very powerful [59]. The application of such algorithms has helped organizations improve their performance and offer better services, yielding reduced costs, lower energy consumption, and ultimately increased competitiveness. However, most papers in the area of vehicle routing focus on the methodological aspects as opposed to the actual solution of real problems.

The main aim of this paper is to offer an extensive survey of real VRP applications in five key areas: 1) oil, gas and fuel, 2) retail, 3) waste collection and management, 4) mail and small package delivery, and 5) food distribution. We limit our coverage to the past 15 years because the business contexts, communication capabilities, and algorithms have rapidly evolved in recent years, which means that older solution methodologies may no longer be relevant.

This paper contributes to the literature by identifying and classifying the main scientific contributions to practical problems arising in the road-based transportation of goods. We do not cover passenger transportation, rail, maritime and air transportation, which have their own distinguishing characteristics. For instance, Gorman et al. [44] surveyed the applications of operations research and management science in freight transportation. Their review spans oceanic, rail and intermodal freight transportation, truckload and less-than-truckload problems, and air freight. However, all truck related papers have focused on network design and management, on mobile asset allocation and management and terminal and hub management. Thus our work is complementary to theirs since we focus on the vehicle routing aspects.

We have analyzed hundreds of papers to ensure that we list here only those containing a practical application, not in the sense that the problem can appear in practice or is inspired from a real-world context, but that a real-world case has actually been modeled and solved. To be considered in this survey, the paper must clearly state that it uses real data relevant to the application. Simulated data based on real applications are not considered. The proposed methodology should be able to solve the real problem under consideration even if direct comparisons against the organization's results are not presented. We provide several summary tables of our findings, and when available, we establish a comparison between the prevailing solution and the solution yielded by the application of optimization techniques. More often than not, the difference is not negligible and one can therefore appreciate the value of applying

optimization techniques to practical problems.

The contribution of this paper is threefold. First, it provides scientific researchers interested in real-life applications a list of useful references and journals. Second, it can be used for teaching in courses that emphasize operations research applications. Third, it demonstrates to practitioners the benefits of applying operations research techniques to the solution of complex and often large-scale routing problems arising in real distribution management settings.

The remainder of this paper is organized as follows. Section 2 describes applications related to oil, gas and fuel transportation. Retail applications are reviewed in Section 3. Section 4 describes the applications to waste collection and management. Mail and parcels delivery applications are presented in Section 5. Contributions related to food distribution are dealt with in Section 6. Within each section, the contributions are listed in chronological order.

2 Oil, gas and fuel applications

The first category of problems surveyed covers applications related to the supply of oil, gas and fuel to houses, gas stations and companies. These problems present a number of specific features such as vehicles with capacitated compartments and sometimes the presence of flow meters to control the delivered quantity. The latter feature implies that sometimes the content of the same compartment can be used to satisfy the demands of several customers, whereas when there is no flow meter, the compartment must be completely emptied in a single customer tank. Cleaning operations may be needed between the loading of different products using the same compartment. These problems are generally solved over long-term planning horizons and incorporate mixed inventory and routing decisions [7, 28].

Campbell et al. [17] worked with Praxair, an industrial gases company with about 60 production facilities and more than 10,000 customers across North America. The problem, modeled as an inventory-routing problem, was solved by means of a two-phase heuristic that first assigns delivery days to customer, and then creates vehicle routes. It was applied to instances in which facilities can have between 50 and 87 customers. Chiang and Russell [23] integrated purchasing and routing decisions for a propane gas supply chain using set partitioning and tabu search techniques. They modeled the problem as a general multi-depot VRP with time windows in which a tanker starts from a depot, travels through a number of terminals (for pickups) and plants (for deliveries), and returns to the same depot. They reported results for the Illinois and Michigan dispatch areas. In the case of Michigan, they reduced the number of tankers used from 130 to 102 over a one-week planning period. Avella et al. [9] studied the case of a company supplying three types of fuel to a set of gas stations located in an urban area. They considered that each tank in the delivery vehicles must be either completely full or completely empty. They generated all

feasible routes having at most four clients and solved the resulting set partitioning problem by branch-and-price. They solved a one-week instance with 60 clients, and a fleet of six heterogeneous trucks was used to serve about 25 clients per day. Cornillier et al. [31] studied a problem similar to that of Avella et al. [9] but also considered the loading of tanker trucks divided into compartments, which is of primary importance since there are several small gas stations throughout Eastern Quebec, the area of application, and because trucks are not equipped with flow meters. Song and Savelsbergh [81] worked with Praxair on another variant of the inventory-routing problem. They developed bounds on the volume delivered per mile, which was used to determine customer-plant assignment. Ng et al. [66] designed a decision support system combining heuristic and optimal routing for a tanker assignment and routing problem for petroleum products in Hong Kong. They reported an increase in the volume delivered as well as better route designs. Cornillier et al. [32] studied a richer petrol station replenishment problem with time windows and obtained a distance reduction of about 22% over the solution obtained by the company dispatcher. On a 42-station instance, they reduced the number of routes from 26 to 23. Day et al. [33] studied the inventory replenishment of a company in Indiana, which distributes carbon dioxide to over 900 customer sites. They developed a heuristic capable of reducing driver labor cost by about 30%.

Table 1 provides a summary of the papers reviewed in this section. It lists the authors, year and journal of publication, as well as the solution method. When available, we present the product, the name of the company, and the geographical location. If a comparison against the solution used by the company is provided, we also present an estimate of the improvement yielded by the application of an analytical method.

We observe that recent applications often consider compartmentalized vehicles, such as in gas stations problems, in which an intrinsic assignment problem appears. Inventory considerations often plays a central role. We also note that a number of applications of fuel distribution arise in the maritime context, for which an extensive literature is also available [24, 25].

3 Retail applications

Retail involves the sales of goods and the provision of services to end-users. In this section we list applications dealing with a number of final products, and in various sectors such as supermarkets and consultancy services. These applications generally involve time windows and loading constraints.

Prins [73] studied the case of a French furniture manufacturer and modeled it as a heterogeneous VRP in which each vehicle can perform several trips. To solve it, he adapted several well-known VRP algorithms and developed a tabu search algorithm. On a one-week data set containing 775 stores, his results showed a reduction of 11.7% in distribution costs. Poot et al. [71] described a savings-based heuristic implemented

Table 1: Summary of contributions about oil, gas and fuel distribution

Author	Year	Journal	Algorithm	Product/Company/Location	Estimated improvement
Campbell et al.	2002	VRP2002	Two-phase heuristic	Gases/Praxair/North America	
Chiang and Russell	2004	EJOR	Set partitioning and tabu search	Propane/One of the largest USA distributor/Illinois and Michigan	9.4% reduction in total cost and 21.5% in number of vehicles
Avella et al.	2004	EJOR	Set partitioning and branch-and-price	Fuel//	22-25% reduction in total cost
Song and Savelsbergh	2007	TS	Lower bounds	Gases/Praxair/	
Cornillier et al.	2008	JORS	Matching and column generation	Fuel//Eastern Quebec, Canada	17.2% reduction in distance and 1.16% increase in quantity delivered
Ng et al.	2008	JORS	Heuristic and integer programming with multiple objectives		Better route design and increased volume delivered
Cornillier et al.	2009	COR	Heuristics based on arc and route preselection	Fuel//Eastern Quebec, Canada	22% reduction in distance
Day et al.	2009	OME	Three-phase heuristic	Carnon dioxide//Indiana	30% reduction in driver labor cost

COR: *Computers & Operations Research*; EJOR: *European Journal of Operational Research*; JORS: *Journal of the Operational Research Society*; OME: *Omega*; TS: *Transportation Science*; VRP2002: *The Vehicle Routing Problem*, 2002.

within Shortrec Distriplanner®, a commercial virtual reality system sold by ORTEC Consultants, a Dutch software provider. The authors dealt with several types of constraints such as consistently assigning the same customers to drivers, grouping customers that should be visited first (or last) in a route, and forbidding some product combinations. Results were reported for four anonymous companies. Gaur and Fisher [39] solved a periodic inventory-routing problem for Albert Heijn, a supermarket chain in the Netherlands. They reported transportation savings of about 4% in the first year of implementation. Gendreau et al. [40] studied the case of an Italian company manufacturing bedroom furniture. The problem was modeled as a capacitated VRP with three-dimensional loading constraints and was solved by tabu search. Solutions were obtained on five instances involving up to 64 customers, 181 products and four vehicles. Kant et al. [54] reported the implementation of the ORTEC vehicle routing software (see Poot et al. [71]) for Coca-Cola. The authors considered a problem involving about 10,000 trucks daily, and reported an annual cost savings of about $45 million, as well as major improvements in customer service. Belfiore and Yoshizaki [15] worked with a Brazilian retail group composed of 519 stores present in 11 Brazilian states. They modeled the problem as a heterogeneous VRP with time windows and split deliveries, and proposed a scatter search heuristic to solve it. Using one week of data, they reported a cost reduction of about 7.5% which could translate into a yearly saving of one million dollars. Chang et al. [21] described a stochastic dynamic TSP with time windows which was applied to FamilyMart, the second-largest convenience store in Taiwan, with more than 1,500 sales points. They proposed an algorithm combining a shortest n-path algorithm with a convolution-propagation heuristic. They performed their experiments on a 12-customer instance which was said to be representative of a typical route. Wen et al. [90] solved a VRP with cross-docking for the Danish consultancy Transvision. In this application identical vehicles are used to transport orders from suppliers to customers through a cross-dock. The authors developed a tabu search heuristic embedded within an adaptive memory search to solve an instance containing up to 200 pairs of nodes. They obtained within a few minutes, solutions that were less than 5% away from optimality. As in the previous section, a summary of the papers mentioned in this section is provided in Table 2.

We note that many retail companies must face the challenges of last-mile distribution and that the modeling and algorithmic know-how provided by operations research can significantly improve their operations. However, while algorithmic design is a rich terrain for academics, many companies rely on commercial blackboxes to determine their routing. When they collaborate with academics, often data are not allowed to be publicly used, which may explain in part the low number of real applications described in the scientific literature.

Table 2: Summary of contributions about retail applications

Author	Year	Journal	Algorithm	Product/Company/Location	Estimated improvement
Prins	2002	JMMA	Construction, improvement and tabu search algorithm	Furniture//Nantes, France	Reduction in distribution time of 11.7%
Poot et al.	2002	JORS	ORTEC software based on savings and local search		
Gaur and Fisher	2004	OR	Mathematical programming and matching	Supermarket/Albert Heijn/ the Netherlands	4% cost reduction
Gendreau et al.	2006	TS	Tabu search	Bedroom furniture//Italy	
Kant et al.	2008	INTER	ORTEC software based on savings and local search	Soft drinks/Coca-Cola/USA	Annual cost saving of $45 million
Belfiore and Yoshizaki	2009	EJOR	Scatter search	Supermarkets//Brazil	7.5% cost reduction
Chang et al.	2009	EJOR	Heuristic based on n-path algorithm and convultion-propagation	Convenience stores/FamilyMart/ Taiwan	
Wen et al.	2009	JORS	Tabu search within an adaptive memory procedure	/Transvision/Denmark	

EJOR: *European Journal of Operational Research*; INTER: *Interfaces*; JMMA: *Journal of Mathematical Modelling and Algorithms*; JORS: *Journal of the Operational Research Society*; OR: *Operations Research*; TS: *Transportation Science*.

4 Waste collection and management

Waste collection is essential to the proper functioning of any collectivity. Ghiani et al. [41] presented a survey of the strategic and tactical issues related to the application of operations research in solid waste management. A variant of the problem deals with hazardous waste management in which collection, transportation, treatment and disposal of hazardous materials are involved. These problems are characterized by loading and unloading constraints, time windows, and inter-arrival time constraints at customer points.

Tung and Pinnoi [88] studied the waste collection of households and streets garbage cans in five districts of Hanoi. The service is provided by Urenco, a private company paid by the municipal government based on the volume collected. The authors reported a reduction of 4.6% in operating cost and showed that they could reduce their fleet size by 20% or, conversely, increase the volume of waste collected with the current fleet by 20%. Shih and Chang [79] modeled the routing and scheduling of medical waste from a set of hospitals and clinics as a periodic VRP. The system, tested in central Taiwan, uses dynamic programming to partition customers into routes and a simple 2-opt heuristic to improve each route individually. The authors solved an instance with 346 clinics over six days, with two or three routes scheduled per day with up to 47 visited clinics. Baptista et al. [10] extended the algorithm of Christofides and Beasley [26] for the periodic VRP to the collection of recycling paper containers in Almada, Portugal. In this application, a single vehicle must perform a route in the morning and another in the afternoon to collect 59 containers. The problem was solved over a one-month horizon. Still in Portugal, Teixeira et al. [85] studied an urban recyclable waste problem where three types of products (glass, paper and plastic/metal) must be collected separately. They modeled the problem as a periodic VRP which was solved through a three-phase heuristic. Their algorithm yielded a distance reduction of about 29% over historic distances travelled. A similar problem with different types of waste was studied by Nuortio et al. [67] in Eastern Finland. These authors developed a scheduler and an optimizer system based on a guided variable neighborhood thresholding metaheuristic and reported an average distance improvement of 12%, and a reduction of 44% on a specific instance. Sahoo et al. [77] worked with Waste Management Inc., a provider of waste-management services based in Houston, which services nearly 20 million residential customers and two million commercial customers throughout the Unites States and Canada. They developed a complete route-management system, deployed over 36 markets areas, and yielding 984 fewer routes and \$18 million in savings after one year. In the long run, the number of routes was expected to be reduced by 10%.

Li et al. [62] developed a prototype decision support system (DSS) for the solid waste collection services in Porto Alegre, Brazil. They analyzed the impact of disruptions in trips and the strategy to use when unexpected events occur. In the context of hazardous waste disposal, Alumur and Kara [6] proposed a model that determines where to open treatment centers, which technologies to employ, how to assign

different types of hazardous waste to compatible treatment technologies, and how to route waste residues to disposal centers. The system was applied in the Central Anatolian region of Turkey. Repoussis et al. [75] developed a complete DSS to manage waste lube oils collection and recycling operations for a multinational Greek company. They modeled this problem as an open VRP with time windows and solved it by means of a list-based threshold accepting metaheuristic. Unit cost reductions of up to 30% were achieved. Coene et al. [29] studied the problem of a Belgian company collecting waste at slaughterhouses, butcher stores, and supermarkets. Waste products were divided into two categories – high-risk and low-risk – and different vehicles were used for each type. This led to two distinct periodic VRPs, one with 48 low-risk customers and three trucks over a planning period of one week, and one with 262 high-risk customers and three trucks over a two-week planning horizon. Since planning occurs over a time period of several days, the problem was solved as a periodic VRP using a two-phase heuristic in which customers are first assigned to days, and VRPs are solved for each day in the second phase. Hauge et al. [47] dealt with the transportation of bulky waste containers. This roll-on/roll-off routing problem arises in the collection of industrial waste. It was formulated as a generalized set partitioning problem and solved by means of a hybrid column generation and a tabu search procedure. Hemmelmayr et al. [48] studied the problem of designing a collection system for general waste in Italy. They considered the bin configuration and sizing problem at each collection site, as well as the service frequency over a given horizon. They analyzed the resulting trade-offs between the bin investment cost and the routing cost. They proposed a hierarchical solution procedure in which the bin location problem was first solved and was followed by the solution of the VRP. They tested both a sequential and an integrated approach. Battarra et al. [12] solved an urban garbage collection in Italy as a clustered VRP in which 456 large street bins are located at 385 collection points. Aksen et al. [4] studied the case of a biodiesel production facility in Istanbul, which collects used vegetable oil from restaurants, catering companies and hotels. The resulting selective and periodic inventory-routing problem was solved by means of an adaptive large neighborhood search algorithm. Huang and Lin [51] studied the problem of efficiently routing and scheduling collectors for municipal waste collection in Taiwan where it is required that residents personally bring their waste to collection vehicles. They proposed a bilevel optimization model that first selects collection points by solving a set covering problem and then solves a VRP with pickup delivery by means of an ant colony optimization heuristic. They used two instances from a subnetwork of Kaohsiung City in Taiwan, involving 262 and 611 nodes. Table 3 presents a summary of the papers mentioned in this section.

In contrast to other applications, waste collection is in great part the responsibility of municipal governments, which usually do not have the expertise or possibility to invest in expensive and intricate specialized software. Also, since privacy or security issues are less critical than in the public sector, they are more prone to collaborate with researchers. Finally we observe that if the waste collection of containers and bins is managed as a vehicle routing problem, most of the home waste management collection problems are modeled as arc routing problems [42].

Table 3: Summary of contributions about waste collection and management

Author	Year	Journal	Algorithm	Product/Company/Location	Estimated improvement
Tung and Pinnoi	2000	EJOR	Heuristic route construction and improvement	Household and street solid waste/ /Urenco/Hanoi, Vietnam	4.6% operating cost reduction
Shih and Chang	2001	EMA	Heuristic route construction and improvement	Medical waste// Tainan City, Taiwan	
Baptista et al.	2002	EJOR	Heuristic route construction and improvement	Recycling paper containers// Almada, Portugal	
Teixeira et al.	2004	EJOR	Three-phase heuristic	Glass, paper, plastic, metal// Portugal	29% reduction in distance
Sahoo et al.	2005	INTER	Iterative two-phase algorithm	Waste/Waste Management Inc./USA	984 fewer routes, saving $18 million
Nuortio et al.	2006	ESA	Guided variable neighborhood thresholding metaheuristic	Municipal waste/Jätekukko Ltd/ Finland	12% distance reduction on average
Alumur and Kara	2007	COR	Mathematical model solved by CPLEX	Hazardous waste// Central Anatolia, Turkey	
Li et al.	2007	COR	DSS with optimization	Municipal waste/DMLU/ Porto Alegre, Brazil	
Repoussis et al.	2009	EJOR	DSS with hybrid metaheuristics	Lube oil//Greece	25% to 30% reduction in per unit cost
Coene et al.	2010	JORS	Two-phase mathematical based algorithm	Animal waste//Belgium	
Hauge et al.	2014	CIE	Hybrid column generation and tabu search	Industrial waste//Italy	
Hemmelmayr et al.	2013	TS	VNS and ILP	General waste//Italy	
Battarra et al.	2014	OR	BC&P	Garbage//Italy	
Aksen et al.	2014	EJOR	ALNS	Used oil//Istanbul, Turkey	
Huang and Lin	2015	OME	Set covering and ant colony	Municipal waste //Kaohsiung, Taiwan	

CIE: *Computers & Industrial Engineering*; COR: *Computers & Operations Research*; EJOR: *European Journal of Operational Research*; EMA: *Environmental Modeling and Assessment*; ESA: *Expert Systems with Applications*; JORS: *Journal of the Operational Research Society*; INTER: *Interfaces*; OME: *Omega*; OR: *Operations Research*; TS: *Transportation Science*; WM: *Waste Management*.

5 Mail and small package delivery

This section reviews applications ranging from mail delivery to the delivery of Internet orders, touching many variants of the classical VRP such as those involving time windows and pickups and deliveries.

Larsen et al. [60] modeled and solved the routing problem of an overnight mail service provider as an a priori dynamic TSP with time windows. The objective was to minimize the lateness of deliveries. They worked with United Parcel Service (UPS), using 10 days of data for each of four selected areas. Hollis et al. [49] used a vehicle routing and crew scheduling algorithm based on set covering with column generation to solve the Melbourne metropolitan mail distribution at Australia Post. They worked with instances containing up to 339 locations and five depots and reported a potential cost saving of about 10%. Cohn et al. [30] studied the load-matching and routing problem with equipment balancing for small package carriers. In this problem, all packages of a given commodity move through the same sequence of intermediate sorting facilities, and the commodities are grouped by common destination to fill trailers more efficiently. The authors used data from a regional subnetwork from UPS, with 263 nodes and more than 2,000 requests, and reported cost reductions of about 5%. Groër et al. [45] solved a consistent VRP in a context where the objective is to plan the routes in order to have customers consistently visited by the same driver over time, so as to develop good working relationships. They solved an instance with 3,715 customers locations based on five weeks of real customer data provided by a company in the small package shipping industry. Sungur et al. [82] studied a VRP with time windows in which customers appear probabilistically and have uncertain service times. They worked on two data sets provided by UPS having up to 5,178 potential customers and more than 25,000 service requests. They reported improvements of up to 20% over a weighted objective function value. Pignac-Robitaille et al. [70] solved a pickup and delivery company specialized in transportation of biomedical samples in Quebec City. They worked on a data set containing 946 requests in which up to 30% of them were known one day in advance. By using the company's strategy which neglects this information, they reduced the number of routes from 54 to 50. Using information about known requests allowed cutting off one additional route and reducing the total distance by an additional 1.3%. Table 4 summarizes the articles of this section.

Mail and package delivery is a very important industry. While traditional mail delivery activities are in decline, parcel delivery is growing as a result of Internet trade. This industry operates in a highly competitive environment which forces companies to use state-of-the-art systems and software.

6 Food distribution

Food distribution has its own characteristics, constraints and challenges such as product quality, health and safety [3]. The products often have a limited shelf-life, so that distribution operations must take into

Table 4: Summary of contributions about mail and small package delivery

Author	Year	Journal	Algorithm	Product/Company/Location	Estimated improvement
Larsen et al.	2004	TS	Dynamic construction and improvement heuristics	Courier/UPS/	
Hollis et al.	2006	EJOR	Set covering with column generation	Mail/Australia Post/ Australia	Potential cost savings of 10%
Cohn et al.	2007	TS	Column generation and enumeration based heuristics	Courier/UPS/USA	Cost reduction of about 5%
Groër et al.	2009	MSOM	Record-to-record travel heuristic	Small packages//	
Sungur et al.	2010	TS	Insertion based and tabu search	Courier/UPS/USA	Up to 20% over a weighted objective function
Pignac-Robitaille et al.	2014	INFOR	Improvement heuristics	Medical samples// Quebec City, Canada	

EJOR: *European Journal of Operational Research*; INFOR: *INFOR*; MSOM: *Manufacturing & Service Operations Management*; OME: *Omega*; TS: *Transportation Science*.

account temperature, humidity and time-in-transit considerations, as well as many other product-related constraints. The review of Akkerman et al. [3] focuses on the challenges of food safety, quality and sustainability. These authors outline practical contributions related to strategic network design, tactical network planning and operational transportation planning. Ahumada and Villalobos [2] studied the particular agri-food supply chain and reviewed the main contribution in the specific field of production and distribution planning for agri-foods based on agricultural crops.

Tarantilis and Kiranoudis [83] dealt with the distribution of fresh milk for one of the largest dairy companies in Greece. The problem was formulated as a heterogeneous fixed fleet VRP and solved through a backtracking adaptive threshold accepting algorithm. The authors solved an instance containing 299 supermarkets located in Athens, with a heterogeneous fleet of 29 vehicles, reducing the total distance by 28% in comparison with the solution used by the company. Cheong et al. [22] studied a soft drink distribution problem arising in several districts of Singapore. They reduced both the average and maximum number of vehicles needed over a 23-day period. Tarantilis and Kiranoudis [84] modeled the distribution of fresh meat from depots to 174 butcher shops in Athens as an open multi-depot VRP and solved it by means of a threshold accepting-based metaheuristic. They reported reducing the total traveled distance by 17%. Prindezis et al. [72] developed a solution system that was applied to the Greater Athens area for the benefit of Athens Central Food Market enterprises. The system, based on a tabu search metaheuristic, is used by nearly 150 Central Market enterprises for planning their daily routes. Faulín [35, 36] solved a logistics problem for Alimentos Congelados, S.A., a canning company located in Navarra, Spain. Heuristics were used for the initial solution which was improved by linear programming. Results obtained over 11 days showed a 4.6% average distance reduction. Pamuk et al. [69] improved distribution operations for a major beer producer having about 4,000 customers in Ankara. They used a workload balancing and partitioning model to assign customers to workdays, followed by a simple nearest-neighbor routing heuristic.

Ruiz et al. [76] worked with Nanta S.A., a leading Iberian feed compounder in Spain, offering pig, poultry, ruminants, rabbits and other livestock feeding, and developed a complete DSS. The authors partitioned the customers into regions and created routes with few clients, generally less than six. They reported distance reductions ranging from 7% to 12% and cost reductions of 9% to 11%. Faulín et al. [37] worked with the Frilac company in Pamplona, northern Spain, which delivers frozen goods such as ice cream, vegetables, precooked dishes, seafood and meat. They developed a complete DSS with database and visualization capabilities based on a savings algorithm. They reported reductions of 13.5% in distance and 10.8% in cost seven months after the implementation. Belenguer et al. [14] presented a computer program developed to design delivery routes for a medium-sized meat company in Valencia. They used seven days of data to plan the routes of a fleet of seven vehicles serving between 94 and 148 orders per day. They considerably reduced the total lateness and the routes lengths by 8.96%. Ioannou [52] studied the supply chain of the Hellenic sugar industry in Greece. They handled the transportation part by means of the

Map-Route system created by Ioannou et al. [53]. This system was developed for a wholesaler and logistics service provider supplying packaged goods and beverages to supermarkets and retail outlets in the Central Athens area. Their objective was to minimize long-term average inventory and routing costs. Privé et al. [74] studied the distribution of soft drinks and collection of recyclable containers for Distribution Jacques Dubois, a Quebec-based distributor in Canada. They considered vehicle routing costs and the revenue generated by the collection of recyclable containers for 164 customers ordering 125 different products over a one-week planning period. They reported a distance reduction of about 23% with respect the the manually designed routes of the company. Cetinkaya et al. [20] improved the operations of Frito-Lay North America by modeling them as a large-scale, integrated multiproduct inventory lot-sizing and VRP. They solved the model using CPLEX by decomposing it into two subproblems involving complementary inventory and routing components. They also used some classical TSP heuristics such as savings and cheapest insertions to improve the routes. Their results yield higher vehicle utilization and indicate that financial benefits could be achieved in inventory and delivery management. Hu et al. [50] studied a food distribution problem for the Northern Grocery company in Beijing. Routes were constructed over a circular transportation network, leading to special characteristics, which helped the generation process. Battarra et al. [11] studied the distribution of three different types of foods to supermarkets (vegetables, fresh food and non-perishable), which were incompatible in the sense that they could not be delivered simultaneous in the same vehicle. The problem was modelled as a multi-trip VRP with time windows. Six days of data were used with an average of 422 customers per day. Incompatibility constraints were also considered by Caramia and Guerriero [18] for a milk collection problem where some small farms are inaccessible by large trucks. Since farmers produce different milk types, they used multi-compartments trucks. They worked with ASSO. LA. C. which collects milk from 158 farmers in four towns in Calabria, in southern Italy. They were able to obtain a reduction of about 14.4% in the total distance traveled and they also increased the filling ratio of the tank trucks from 85% to 95%. Zachariadis et al. [91] worked with a frozen food distribution company operating in Athens. This company uses 27 types of boxes and a homogeneous fleet of eight-pallet trucks. Thus, the problem was modelled as a pallet-picking VRP with three-dimensional rectangular boxes. The authors developed a tabu search algorithm in which pallet-packing is solved with a packing heuristic. Martínez and Amaya [64] worked with a home delivery service company that produces and delivers Spanish paella. The food is cooked in paella pans which are then delivered to the customers. This problem was solved as a multi-trip VRP with time windows and a loading component for these circulars items. On a set of 19 real instances they reported that their tabu search heuristic could reduce the total trip time by 25.5% on average. Cattaruzza et al. [19] developed an iterated local search heuristic for the milk collection problem of Battarra et al. [11]. Lahrichi et al. [56] worked with the Fédération des producteurs de lait du Québec which is responsible for negotiating the transportation cost on behalf of the dairy producers' of the province of Quebec. They studied two examples having up to 226 farms, four depots and eight vehicles. When optimizing only

the collection sequence, they reported small improvements of about 0.5% demonstrating that the current plan was very good. When they allowed the reassignment of farms and plants to vehicles, they obtained up to 4% in distance reduction, which corresponds to savings of a few hundred thousands dollars yearly.

Demir et al. [34] worked with Nabuurs B.V., a Netherlands-based logistics service provider specialized in refrigerated, frozen and ambient food products including beverages. They analyzed the shift from a single-depot planning to a centralized multi-depot planning process. They used a SHORTREC-based simulation model which includes many routing construction and improvement algorithms. They discussed the managerial implications as well as the implementation of the SHORTREC as a tactical planning tool.

Lahyani et al. [57] studied the olive oil collection process in Tunisia. Since olive oil comes in three different grades, it must be transported in multi-compartment vehicles. Cleaning operations may be needed if a compartment must be reused for a different oil grade. On a set of instances having up to seven producers and 39 requests they reported an average reduction of about 11.7% in the total distance traveled. The contributions of this section are summarized in Table 5.

Table 5: Summary of contributions about food distribution

Author	Year	Journal	Algorithm	Product/Company/Location	Estimated improvement
Tarantilis and Kiranoudis	2001	JFE	Backtracking adaptive threshold accepting	Milk//Athens	28% distance reduction
Cheong et al.	2002	APJ	Tree search, column generation over a set covering formulation	Soft drink//Singapore	Consistent reduction in the maximum number of vehicles required
Tarantilis and Kiranoudis	2002	JFE	List-based threshold accepting	Meat//Athens	17% distance reduction
Ioannou et al.	2002	JORS	DSS with GIS, look-ahead heuristic	Packaged goods and beverages// Athens	Lower number of routes and vehicles
Prindezis et al.	2003	JFE	Tabu search	Vegetables, fruits and meat/Central Food Market/Athens	
Faulín	2003	IJL	Heuristics and linear programming	Canning/Alimentos Congelados S.A./Navarra, Spain	Average of 4.6% distance reduction
Faulín	2003	OME	Heuristics and linear programming	Canning/Alimentos Congelados S.A./Navarra, Spain	Average of 4.6% distance reduction
Ruiz et al.	2004	EJOR	B&B with Lingo	Animal food/Nanta S.A./Spain	Reduction of up to 11% in cost and 12% in distance
Pamuk et al.	2004	JORS	Workload balancing, partitioning and routing	Beer//Ankara	
Faulín et al.	2005	INTER	DSS based on savings and sweep algorithm	Frozen goods/Frilac/ Pamplona, Spain	13.5% distance and 10.8% cost reduction
Belenguer et al.	2005	JFE	Constructive heuristic with tabu search improvement	Meat//Valencia, Spain	8.96% distance reduction
Ioannou	2005	JFE	DSS with GIS, look ahead heuristic	Sugar//Greece	About 25% in total transportation cost
Privé et al.	2006	JORS	Constructive and improvement	Soft drink/Distribution J. Dubois/Quebec, Canada	23% in distance reduction
Hu et al.	2009	COR	Route generation and selection	Packet meat/Northern Grocery Co./Beijing	

Continued on next page

Table 5 – *Continued from previous page*

Author	Year	Journal	Method	Product/Company/Location	Estimated improvement
Cetinkaya et al.	2009	INTER	Mathematical decomposition and heuristics	Snacks/Frito-Lay/ North America	
Battarra et al.	2009	COR	Heuristics with adaptive guidance mechanism	//	
Caramia and Guerriero	2010	INTER	Mathematical programming and local search multi-start	Milk/ASSO. LA. C./Italy	14.4% distance reduction
Zachariadis et al.	2012	TS	Tabu search and packing heuristic	Frozen food//Athens	
Martínez and Amaya	2012	JORS	Insertion, tabu search and bin packing heuristics	Spanish paella//	25.5% in total trip time over a set of 19 instances
Cattaruzza et al.	2014	COR	Iterated local search	//	
Lahrichi et al.	2014	JORS	Generalized unified tabu search	Milk/Fédération des producteurs de lait du Québec/Quebec, Canada	
Demir et al.	2014	INTER	Construction and improvement	Refrigerated, frozen and ambient food products and beverages/ Nabuurs B.V./the Netherlands	
Lahyani et al.	2015	OME	Branch-and-cut	Olive oil//Tunisia	11.7% distance reduction

APJ: *Asia-Pacific Journal of Operational Research*; COR: *Computers & Operations Research*; EJOR: *European Journal of Operational Research*; INTER: *Interfaces*; JFE: *Journal of Food Engineering*; JMMA: *Journal of Mathematical Modelling and Algorithms*; JORS: *Journal of the Operational Research Society*; IJL: *International Journal of Logistics Research and Applications*; OME: *Omega*; TS: *Transportation Science*.

Food distribution in an industry characterized by both many specific constraints and low return margins, which make this industry less suited for generic optimization software. This specific environment has led to several fruitful research collaborations between academia and industry.

7 Conclusions

We have presented an extensive review of practical contributions of the VRP arising in a real-world context. We have classified almost a hundred papers and provided several tables summarizing the main contributions and key information from these papers. We have observed that many industries have engaged in close relations with scientific researchers, whereas this is less the case in the public sector.

This survey paper has clearly demonstrated that the application of operations research techniques to the field of vehicle routing is highly successful and can generate substantial savings, often in excess of 10%. Since vehicle routing decisions must be implemented frequently, quite often on a daily basis, this can translate into large sums of money on a yearly basis. Because real-life vehicle routing problems include a wide variety of constraints, they can rarely be solved through the execution of off-the-shelf software. In all the applications surveyed, the researchers had to devise ad hoc algorithms. These range from the implementation of simple mechanisms such basic constructive and improvement steps to more sophisticated local search heuristics like tabu search, record-to-record travel, iterated local search and variable neighborhood search. Heuristics are sometimes hybridized with exact algorithms such at column generation. In many cases, heuristics are coupled with DSS or GIS software.

Regarding future research, we see three main research trends in connection with the topic of this survey. The first is related to green transportation [13, 55], in which one aims to minimize not only traditional distance or cost objectives, but also environmental externalities, such as pollution, greenhouse gas emissions, congestion and noise. The second trend relates to routing with time-dependent or congestion-related travel time, where real-time traffic information is available and vehicle routes can be planned accordingly [38]. This area of research can benefit from advances in technology-related fields, such as the design of GPS and telecommunication capabilities, and on the capacity of efficiently processing huge amounts of data in real time [65, 89]. The third trend is related to the integration of quality of service (as opposed to cost) as an objective or a constraint. This yields models and algorithms that can handle quality of service, such those of Coelho et al. [27] and Smilowitz et al. [80].

As for future applications and algorithmic developments for real-world applications, it is clear that exact algorithms have reached a limit with respect to the size of instances they can consistently solve within reasonable computing times. Thus, powerful metaheuristics will continue to be the methodology of choice for the solution of rich versions of real problems with the features we have just outlined. Recent

and successful implementation combine metaheuristics and mathematical programming, yielding what is known as matheuristics [63]. These are usually reliable and significantly faster than exact methods, even if some accuracy is lost in the process [59]. However, they do allow for real-time data acquisition, processing and integration.

Finally, we expect new applications to emerge from the integration of routing problems with other components of the supply chain such as production scheduling, lot-sizing and inventory management [1, 28]. Another promising area of research is the integration of vehicle routing with other transportation modes such as ships and trains. One such example arises in the management of large container ports which are essentially multi-modal hubs [5, 68].

Acknowledgments

This research was partly supported by grants OGP 0172633, OGP 2014-05764 and OGP 016189 from the Canadian Natural Sciences and Engineering Research Council. This support is gratefully acknowledged. Thanks are due to a referee and to the two editors for their valuable comments.

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