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Survey

A literature review on the vehicle routing problem with multiple depots

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A B S T R A C T

In this paper, we present a state-of-the-art survey on the vehicle routing problem with multiple depots (MDVRP). Our review considered papers published between 1988 and 2014, in which several variants of the model are studied: time windows, split delivery, heterogeneous fleet, periodic deliveries, and pickup and delivery. The review also classifies the approaches according to the single or multiple objectives that are optimized. Some lines for further research are presented as well.

1. Introduction

Physical distribution is one of the key functions in logistics systems, involving the flow of products from manufacturing plants or distribution centers through the transportation network to consumers. It is a very costly function, especially for the distribution industries. The Operational Research literature has addressed this problem by calling it as the vehicle routing problem (VRP). The VRP is a generic name referring to a class of combinatorial optimization problems in which customers are to be served by a number of vehicles. The vehicles leave the depot, serve customers in the network and return to the depot after completion of their routes. Each customer is described by a certain demand. This problem was firstly proposed in the literature by Dantzig and Ramser (1959). After then, considerable number of variants has been considered: hard, soft and fuzzy service time windows, maximum route length, pickup and delivery, backhauls, etc. (Cordeau, Gendreau, Hertz, Laporte, & Sormany, 2005; Juan, Faulín, Adelanteado, Grasman, & Montoya Torres, 2009; López-Castro & Montoya-Torres, 2011; Montoya-Torres, Alfonso-Lizarazo, Gutiérrez-Franco, & Halabi, 2009; Ozfirat & Ozkarahan, 2010; Thangiah & Salhi, 2001). Solving the VRP is vital in the design of distribution systems in supply chain management.

1.1. VRP versus MDVRP

Formally, the classical vehicle routing problem (VRP) is represented by a directed graph $G(E,V)$, where $V = \{0,1,\ldots,n\}$ represents the set of nodes and E is the set of arcs. The depot is noted to be node $j = 0$, and clients are nodes $j = 1, 2, \ldots, n$, each one with demand $d_j > 0$. Each arc represents a route from node i to node j. The weight of each arc $C_{ij} > 0$ corresponds to the cost (time or even distance) of going from node i to node j. If $C_{ij} = C_{ji}$ then we are facing the symmetric VRP, otherwise the problem is asymmetric. From the complexity point of view, the classical VRP is known to NP-hard since it generalizes the Travelling Salesman Problem (TSP) and the Bin Packing Problem (BPP) which are both well-known NP-hard problems (Garey & Johnson, 1979). A review of mathematical formulations for the classical VRP can be found in the work of Laporte (1992).

In the literature, lots of surveys have been presented analyzing published works on either the classical version (Bodin, 1975; Bodin & Golden, 1981; Desrochers, Lenstra, & Savelsbergh, 1990; Eksioglu, Volkan, & Reisman, 2009; Laporte, 1992; Liong, Wan,

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Khairuddin, & Mourad, 2008; Maffioli, 2002) or its different variants: the capacitated VRP (Baldacci, Toth, & Vigo, 2010; Cordeau, Laporte, Savelsbergh, & Vigo, 2007; Gendreau, Laporte, & Potvin, 2002; Laporte & Nobert, 1987; Laporte & Semet, 2002; Toth & Vigo, 2002), the VRP with heterogeneous fleet of vehicles (Baldacci, Battarra, & Vigo, 2008; Baldacci, Toth, & Vigo, 2007; Baldacci et al., 2010), VRP with time windows (VRPTW), pickup and deliveries and periodic VRP (Solomon & Desrosiers, 1988), dynamic VRP (DVRP) (Psaraftis, 1995), Periodic VRP (PVRP) (Mourgaya & Vanderbeck, 2006), VRP with multiple trips (VPRMT) (Şen & Bülbül, 2008), Split Delivery vehicle routing problem (SDVRP) (Archetti & Speranza, 2008). All of these works consider only one depot. Fig. 1 presents a hierarchy of VRP variants. One of these variants considers a well-known (Crevier, Cordeau, & Laporte, 2007) more realistic situation in which the distributions of goods is done from several depots to final clients. This particular distribution network can be solved as multiple individual single depot VRP's, if and only if clients are evidently clustered around each depot; otherwise a multi-depot-based approach has to be used where clients are to be served from any of the depots using the available fleet of vehicles. In this paper, we consider the variant of the vehicle routing problem known as Multiple Depots Vehicle Routing Problem (MDVRP) in which more than one depot is considered (see Fig. 2). The reader must note that most exact algorithms for solving the classical VRP model are difficult to be adapted for solving the MDVRP.

According to Renaud, Laporte, and Boctor (1996), the MDVRP can be formally described as follows. Let $G = (V,E)$ be a graph, where V is the set of nodes and E is the set of arcs or edges connecting each pair of nodes. The set V is further partitioned into two subsets: $V_c = \{v_1, v_2, \dots, v_N\}$ which is the set of customers to be served; and $V_d = \{v_{N+1}, v_{N+2}, \dots, v_M\}$ which is the set of depots. Each customer $v_i \in V_c$ has a nonnegative demand d_i. Each arc belong to the set E has associated a cost, distance or travel time c_{ij}. There are a total of K vehicles, each one with capacity P_k. The problem consists on determining a set of vehicle routes in such a way that: (i) each vehicle route starts and ends at the same depot, (ii) each customer is serviced exactly once by a vehicle, (iii) the total demand of each route does not exceed the vehicle capacity, and (iv) the total cost of the distribution is minimized. According to Kulkarni and Bhave (1985), a mathematical model of the MDVRP requires the definition of binary decision variables x_{ijk} to be equal to 1 if the pair of nodes i and j are in the route of vehicle k, and 0 otherwise. Auxiliary variables y_i are required in order to avoid subtour elimination. According to this last reference, the model is as follows:

$$\text{Minimize} \sum_{i=1}^{N+M}\sum_{j=1}^{N+M}\sum_{k=1}^{K}(c_{ij}x_{ijk}) \tag{1}$$

Subject to :

$$\sum_{i=1}^{N+M}\sum_{k=1}^{K}x_{ijk} = 1 \quad j = 1,\dots,N \tag{2}$$

$$\sum_{j=1}^{N+M}\sum_{k=1}^{K}x_{ijk} = 1 \quad i = 1,\dots,N \tag{3}$$

$$\sum_{i=1}^{N+M}x_{ihk} - \sum_{j=1}^{N+M}x_{hjk} = 0 \quad \begin{matrix} k = 1,\dots,K \\ h = 1,\dots,N+M \end{matrix} \tag{4}$$

$$\sum_{i=1}^{N+M}Q_i\sum_{j=1}^{N+M}x_{ijk} \leqslant P_k \quad k = 1,\dots,K \tag{5}$$

$$\sum_{i=1}^{N+M}\sum_{j=1}^{N+M}c_{ij}x_{ijk} \leqslant T_k \quad k = 1,\dots,K \tag{6}$$

$$\sum_{i=N+1}^{N+M}\sum_{j=1}^{N}x_{ijk} \leqslant 1 \quad k = 1,\dots,K \tag{7}$$

$$\sum_{j=N+1}^{N+M}\sum_{i=1}^{N}x_{ijk} \leqslant 1 \quad k = 1,\dots,K \tag{8}$$

$$y_i - y_j + (M+N)x_{ijk} \leqslant N+M-1 \quad \text{For } 1 \leqslant i \neq j \leqslant N \text{ and } 1 \leqslant k \leqslant K \tag{9}$$

$$x_{ijk} \in \{0,1\} \quad \forall i,j,k \tag{10}$$

In this formulation, Constraints (2) and (3) ensure that each customer is served by one and only one vehicle. Route continuity is represented by Constraints (4). The sets of constraints (5) and (6) are the vehicle capacity and total route cost constraints. Vehicle availability is verified by Constraints (7) and (8) and subtour elimination is provided by Constraints (9). In this formulation, it is assumed that total demand at each node is either less than or at

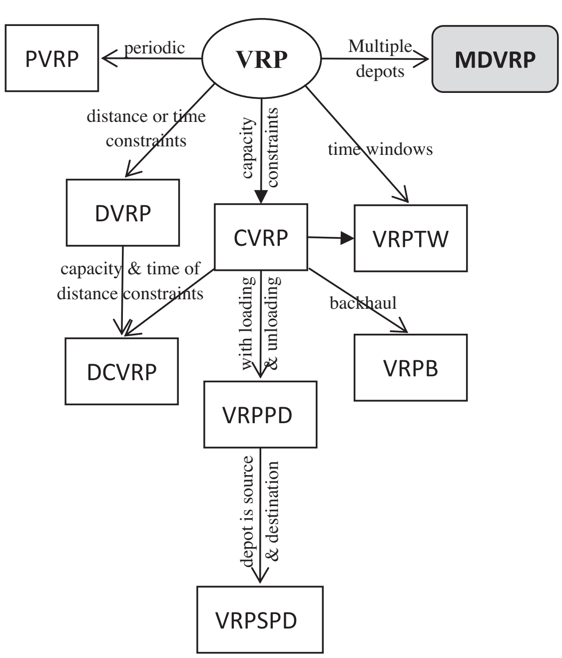

Fig. 1. Different variants of the VRP (adapted from Weise et al., 2010).

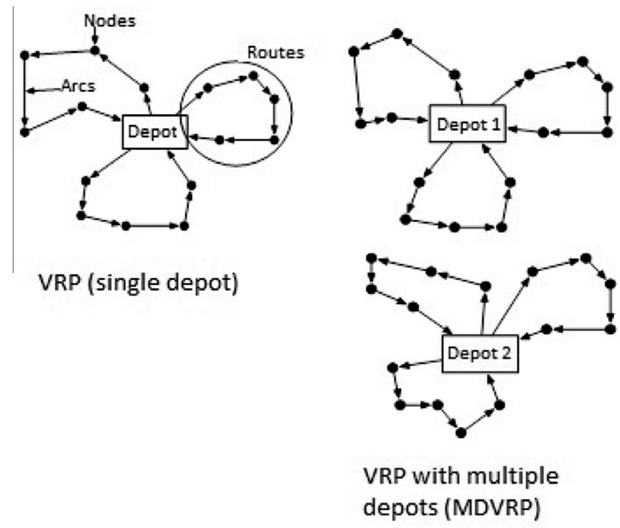

Fig. 2. Comparison between VRP versus MDVRP.

the most equal to the capacity of each vehicle. Similar to single depot VRP, the subtour elimination constraint (9) can be rewritten in a more compact form as:

$$y_i - y_j + (M+N)\sum_{k=1}^{V} x_{ijk} \leqslant M+N-1 \quad \text{for } i \leqslant i \neq j \leqslant M+N-1 \tag{11}$$

1.2. Motivation for a review of research papers on MDVRP

The MDVRP is more challenging and sophisticated than the single-depot VRP. The variant with multiple depots appears first in the literature on the works of Kulkarni and Bhave (1985), and Laporte, Nobert, and Taillefer (1988) and Carpaneto, Dell'amico, Fischetti, and Toth (1989). Since then, considerable amount of research has been published (see Table 1) in the form of journal paper, conference paper, research/technical report, thesis or book. To the best of our knowledge, despite the great amount of research papers published, there is no rigorous literature survey exclusively devoted to the vehicle routing problem with multiple depots. A short overview of academic works was proposed by Liu, Jiang, Liu, and Liu (2011), but only presenting the most representative research papers. From the 58 cited references in their paper, only 23 of them explicitly refer to the MDVRP. Besides, these authors focus on the problem definition, solution methods (dividing them into exact algorithms, heuristics and meta-heuristics) and mention some problem variants. In fact, no actual systematic review was presented in that paper. Our intention now is to present a rigorous review of scientific literature, by presenting a taxonomic classification of those works. Most of the published works focus on the single objective problem, while a few consider the multi-objective case. In this paper, we intend to provide an analysis of both single and multiple objective problems.

1.3. Review methodology

This paper presents a review of relevant literature on the vehicle routing problem with multiple depots, with both single and multiple objective functions. An ambitious search was conducted using the library databases covering most of the major journals. Some conference papers are also included in this review. In addition, the websites of leading research groups and the principal authors of major publications were also searched for further information about their research projects (Ph.D. projects and sponsored projects) and publications. We intentionally excluded working papers, theses and research reports not available online on the Internet because they are very difficult to obtain.

The initial collection of references was screened first for their relevance and their significance for the purpose of this review. In order to control the length of this paper, only some representative publications were selected to be explained in detail within the text of this manuscript, which are authored by leading researchers or groups. These selected authors and research groups have, in fact, published a long list of research papers and reports in the field. A collection of a total of 147 representative publications are short-listed in this review (see Tables A1 and A2 in Appendix). The short-listed publications are then examined in more detail. The analysis of methodological issues and problem variants are presented in detail in Section 4 of the paper.

Table 1
Number and types of publications on MDVRP.

Type of publication	Total
Journal	125
Conference	28
Thesis	7
Technical report	4
Book/book chapter	9
Total	173

1.4. Paper organization

The rest of this paper is organized as follows. Section 2 presents the review of papers studying the single-objective problem, while those focused on multiple objectives are reviewed in Section 3. In both sections, papers are briefly commented and most important facts are highlighted. The literature is quantified and measured in Section 4. The paper ends in Section 5 by presenting some concluding remarks and discussing some research opportunities.

2. Single objective MDVRP

This section presents a literature review of papers considering the single objective case of the MDVRP. For the total of papers considered in this review, 88.44% considers only one optimization objective. The list of reviewed papers is presented in Table A1 in the Appendix. This section is divided into three main parts, each one corresponding to the type of solution procedure employed: exact method, heuristic or meta-heuristic. After the first works were published in the decade of 1980, more than one hundred of papers have studied the classical version of the MDVRP and its variants, some of them inspired from real-life applications.

2.1. Exact methods

In the decade of the 1970's, some works already mentioned some problems related to distribution of goods with multiple depots. However, to the best of our knowledge, the first paper presenting formal models or procedures to find optimal solution for the multi-depot vehicle routing problem are those of Laporte, Nobert, and Arpin (1894) who formulated the symmetric MDVRP as integer linear programs with three constraints. These authors then proposed a branch-and-bound algorithm using a LP relaxation. The works of Kulkarni and Bhave (1985), Laporte et al. (1988) and Carpaneto, Dell'amico, Fischetti, and Toth (1989) can also be considered as part of the pioneer works on exact methods for the MDVRP. The mathematical formulation proposed by Kulkarni and Bhave (1985) was later revised by Laporte (1989). More recently, Baldacci and Mingozzi (2009) proposed mathematical formulations for solving several classes of vehicle routing problems including the MDVRP, while Nieto Isaza, López Franco, and Herazo Padilla (2012) presented an integer linear program for solving the heterogeneous fleet MDVRP with time windows. Dondo, Mendez, and Cerdá (2003) proposed a mixed-integer linear programming (MILP) model to minimize routing cost in the HFMDVRP, in which heterogeneous fleet of vehicles are available. The variant with pickup and deliveries and heterogeneous fleet was modeled by Dondo, Méndez, and Cerdá (2008) using MILP model: this model is able to solve only small sized instances, and hence a local search improvement algorithm was then proposed by the authors for medium to large sized instances. This approach was later employed by Dondo and Cerdá (2009) to solve the HFMDVRPTW. The work of Kek, Cheu, and Meng (2008) proposes a mixed-integer linear programming model and a branch-and-bound procedure for the MDVRP with fixed fleet and pickup and delivery. The objective function is the minimization of the total cost of routes. Cornillier, Boctor, and Renaud (2012) presented a MILP model for the problem in which heterogeneous fleet of vehicles is available and with maximization of total net revenue as objective function, while maximum and minimum demands constraints are given. Seth, Klabjan, and Ferreira (2013) studied an application case from the printed circuit board production process modeled as a MDVRP with mobile depots. They presented an exact algorithm based on network-flow formulation and proposed a iterated tour partitioning heuristic. Branch-and-cut algorithms were proposed by Benavent and Martínez (2013) and Braekers, Caris, and Jenssens (2014). Former authors focused also on studying the polyhedral structure of the problem which allowed the extension of their procedure to the location-routing problem (LRP), while latter authors considered a dial-a-ride problem with multiple depots. The LRP with multiple depots was also studied by Contardo, Cordeau, and Gendron (2014) who proposed a cut-and-column generation procedure for the capacitated case. Other configurations of the MDVRP have been studied through exact algorithms. For instance, Contardo and Martinelli (2014) studied the capacitated MDVRP with route length constraints; Ray, Soeanu, Berger, and Debbabi (in press) modeled the version with split deliveries; Li, Li, and Pardalos (in press) proposed an integer programming model for the MDVRP with shared depots and time windows; and Adelzadeh, Asi, and Koosha (in press) proposed a mathematical model and a fuzzy-based heuristic for the particular case of the MDVRP with fuzzy time windows and heterogeneous fleet of vehicles.

2.2. Heuristics

Because the NP-hardness of the MDVRP, several heuristic algorithms have been proposed in the literature. This section summarizes some of the most relevant works concerning different variants of the problem. The first works were published in the 1990's, in order to solve the capacitated version. Min, Current, and Schilling (1992) studied the version of the MDVRP with backhauling and proposed a heuristic procedure based on problem decomposition. Hadjiconstantinou and Baldacci (1998) considered a real-life problem taken from a company supplying maintenance services. Their problem consists on determining the boundaries of the geographic areas served by each depot, the list of customers visited each day and the routes followed by the gangs. The objective is to provide improved customer service at minimum operating cost subject to constraints on frequency of visits, service time requirements, customer preferences for visiting on particular days and other routing constraints. This situation was solved using the periodic variant: MDPVRP for which a five-level heuristic was proposed: first and second levels solve the problem of determining the service areas and service days (the periodic VRP); third level solves the VRP for each day; fourth level solves a TSP for each route, and fifth level seeks the optimization of routes.

Salhi and Sari (1997) proposed the so-called "multi-level composite heuristic". This heuristic found as good solutions as those known at that time in the literature but using only 5 to 10% of their computing time. The heuristic was also tested on the problem with heterogeneous fleet. Salhi and Nagy (1999) proposed an insertion-based heuristic in order to minimize routing cost. Later, these authors (Nagy & Salhi, 2005) also studied the problem with pickup and deliveries (MDVRPPD). Their approach avoids the concept of insertion and proposes a method that treats pickups and deliveries in an integrated manner. The procedure first finds a solution to the VRP, then it modifies this solution to make it feasible for the VRPPD and it finally ensures that it is also feasible for the multi-depot case. Jin, Guo, Wang, and Lim (2004) modeled the MDVRP as a binary programming problem. Two solving methodologies were presented. The first one is a two-stage approach that decomposes and solves the problem into two independent subproblems: assignment and routing. The second proposed approach treats both assignment and routing problems in an integrated manner. Their experimental results showed that the one-stage algorithm outperforms the other one.

The HFMDVRP, in which heterogeneous fleet of vehicles is available have captured the attention of researchers since the work presented by Salhi and Sari (1997). Irnich (2000) proposed a set covering heuristic coupled with column generation and branch-and-price algorithm for cost minimization for the heterogeneous fleet and pickup and delivery MDVRP. Dondo and Cerdá (2007) proposed a MILP model as well as a three-stage heuristic. Before, a preprocessing stage for node clustering is performed and a more compact cluster-based MILP problem formulation is developed. Many other papers have been appeared in literature on or before 2007 and solution approaches have primarily been focused on meta-heuristic algorithms. Hence, this will be discussed more in detail in the next subsection.

Concerning the periodic MDVRP, few works appear in literature with heuristic algorithm as solution approach. We have identified only the works of Hadjiconstantinou and Baldacci (1998), Vianna, Ochi, and Drummond (1999), Yang and Chu (2000), Maischberger and Cordeau (2011), and Maya, Sörensen, and Goos (2012). The problem with time windows was studied by Chiu, Lee, and Chang (2006) who presented a two-phase heuristic method. In contrast with other works in literature, these authors considered the waiting time as objective function. Results indicate that the waiting time has a significant impact on the total distribution time and the number of vehicles used when solving test problems with narrow time windows. The authors also considered a real-life case study of a logistics company in Taiwan.

Tsirimpas, Tatarakis, Minis, and Kyriakidis (2007) considered the case of a single vehicle with limited capacity, multiple-products and multiple depot returns. Another characteristic of their problem is that the sequence of visits to customer is predefined. They developed a suitable dynamic programming algorithm for the determination of the optimal routing policy. For the MDSDVRP which consists on the combination of the MDVRP and the Split Delivery VRP (SDVRP). The work of Gulczynski, Golden, and Wasil (2011) developed an integer programming-based heuristic. The objective of this study was to determine the reduction in traveled distance that can be achieved by allowing split deliveries among vehicles based at the same depot and vehicles based at different depots. The multi-depot capacitated vehicle routing problem with split delivery (MDCVRPSD) is studied by Liu, Jiang, Fung, Chen, and Liu (2010). A mathematical model is proposed based on a graph model. The objective function is the minimization of movements of empty vehicle. A greedy algorithm is proposed as well, in order to solve large-scale instances. More recent works on the application of dedicated heuristics include the work of Vahed, Crainic, Gendreau, and Rei (in press) for the case of a MDVRP with the objective of determining the optimal vehicle fleet size, and the work of Afshar-Nadjafi and Afshar-Nadjafi (in press) for the study of the time-dependent MDVRP with heterogeneous vehicles and time windows.

2.3. Meta-heuristics

As for other NP-hard combinatorial optimization problems, meta-heuristic procedures have been employed by several researchers for efficiently solving the single-objective MDVRP. The first meta-heuristic was proposed in the work of Renaud, Laporte et al. (1996) who study the MDVRP with the constraints of vehicle capacities and maximum duration of routes (e.g. the time of a route cannot exceed the maximum working time of the vehicle). The objective to be optimized is the total operational cost. These authors proposed a Tabu Search algorithm for which the initial solution is built using the Improved Petal heuristic of Renaud, Boctor, and Laporte (1996b). Experiments were carried out using classical instances of Christofides and Eilon (1969) and Gillett and Johnson (1976). Later, Cordeau, Gendreau, and Laporte (1997) proposed a Tabu Search algorithm with the initial solution being generated randomly for the MDVRP that can also be used to solve the periodic VRP (PVRP), while Tüzün and Burke (1999) proposed a Tabu Search procedure for minimizing the total cost of the routing. Cordeau, Laporte, and Mercier (2001) also proposed a TS procedure with the objective of minimizing the number of vehicles. An approximation to real industrial practice was studied by Parthanadee and Logendran (2006). In their problem, depots operate independently and solely within their own territories. The distributors may hence satisfy customers' requests by delivering products from other depots that hold more supplies. They proposed a mixed-integer linear programming model for the multi-product, multi-depot periodic distribution problem and presented three Tabu Search heuristics with different long-term memory applications. Results revealed that interdependent operations provide significant savings in costs over independent operations among depots, especially for large-size problems. More recently, Escobar, Linfati, Toth, and Baldoquin (in press) evaluated a Granular Tabu Search algorithm to minimize the total sum of vehicle traveled distances.

The first genetic algorithms were proposed by Filipec, Skrlec, and Krajcar (1997) for the problem of minimizing total travel distance, by Salhi, Thangiah, and Rahman (1998) and by Skok, Skrlec, and Krajcar (2000), Skok, Skrlec, and Krajcar (2001). An evolutionary algorithm coupled with local search heuristic was proposed by Vianna et al. (1999) in order to minimize the total cost. Thangiah and Salhi (2001) proposed the use of genetic algorithms to define clusters of clients and then routes are found by solving a traveling salesman problem (TSP) using and insertion heuristic. This approach is called Genetic Clustering (GenClust). Solutions are finally optimized using the post-optimization procedure of Salhi and Sari (1997). Recently, Yücenur and Demirel (2011a) proposed geometric shape based genetic clustering algorithm for the classical MDVRP. The procedure is compared with the nearest neighbor algorithm. Their experiments showed that their algorithm provides a better clustering performance in terms of the distance of each customer to each depot in clusters, in a considerably less computational time.

In the survey by Gendreau, Potvin, Bräumlaysy, Hasle, and Løkketangen (2008) focused on the application of meta-heuristics for solving various variants of the VRP, a short revision of the multi-depot problem is presented. The equivalence between the MDVRP and the PVRP is also analyzed. Among the meta-heuristics presented therein, we can highlight the use of Genetic Algorithms (Filipec, Skrlec, & Krajcar, 2000), Simulated Annealing (Lim & Zhu, 2006) of the case of fixed vehicle fleet, and Tabu Search (Angelelli and Speranza, 2002). Other works proposing meta-heuristics can be found in (Chao, Golden, & Wasil, 1993 and Chen, Takama, & Hirota, 2000).

The most studied variant of the problem has been the capacitated MDVRP. Among the meta-heuristics proposed in literature, we can highlight the Simulated Annealing algorithms of Wu, Low, and Bai (2002) and Lim and Zhu (2006), the Variable Neighborhood Search procedure proposed by Polacek, Hartl, Doerner, and Reimann (2005), Polacek, Benkner, Doerner, and Hartl (2008), Tabu Search algorithms from Lim and Wang (2005), Aras, Aksen, and Tekin (2011) and Maischberger and Cordeau (2011). Genetic Algorithms has been proposed as well for this problem variant, as illustrated in the works of Bae, Hwang, Cho, and Goan (2007), Vidal, Crainic, Gendreau, Lahrichi, and Rei (2010). All of these works seek for the minimization of total route distance or cost, except the work of Aras et al. (2011) in which the objective is the maximization of vehicle utilization rate. It is to note here that the work of Aras et al. (2011) is inspired by a particular case of reverse logistics problem in which the aim is to collect cores from an enterprise's dealers. The problem is called the selective MDVRP with price. In addition to the Tabu Search procedure, the authors also formulated two mixed-integer linear programming (MILP) models.

Other meta-heuristics, such as GRASP, are presented in the works of Villegas, Prins, Prodhon, Medaglia, and Velasco (2010) and Maya et al. (2012), respectively minimizing route cost and distance. Özyurt and Aksen (2007) solved the problem of depot location and vehicle routing using a hybrid approach based on Lagrangian relaxation (LR) and Tabu Search (TS). These procedures improve the best solutions found for the set of instances proposed by Tüzün and Burke (1999). A case study taken from waste collection system involving 202 localities in the city of Viseu, Portugal, is presented by Matos and Oliveira (2004). An Ant Colony Optimization (ACO) algorithm is proposed and compared with other procedures from the literature.

The great amount of heuristics algorithms proposed for the problem variant with heterogeneous fleet (HFMDVRP) has been focused on the design of meta-heuristics algorithms. We can highlight the works of Jeon, Leep, and Shim (2007), who proposed a hybrid genetic algorithm that minimizes the total distance traveled, and that of Flisberg, Lidén, and Rönnqvist (2009) who considered a Tabu Search procedure. Simulated Annealing (SA) has been employed as well. Wu et al. (2002) coupled SA with Tabu Search to solve the heterogeneous fleet case of the integrated location-routing problem. In their problem, location of depots, routes of vehicles and client assignment problems are solved simultaneously. The multi-depot heterogeneous vehicle routing problem with time windows (MDHVRPTW) was studied by Dondo and Cerdá (2009), who proposed a MILP and a Local Search Improvement Algorithm that explores the neighborhood in order to find the lowest cost feasible solution.

Other research papers have also been very interested in the analysis of the problem with time windows (MDVRPTW). This variant is studied in 25% of the single-objective focused papers considered in this review. The first meta-heuristics reported in literature was the Tabu Search procedure of Cordeau et al. (2001) in which the objective function is the minimization of the number of vehicles. Polacek, Hartl, Doerner, and Reimann (2005) proposed a Variable Neighborhood Search (VNS) algorithm for the MDVRP with time windows and with fixed distribution of vehicles. This problem was also studied by Lim and Wang (2005) with the characteristic of having exactly one vehicle at each depot. Jin, Mitsuo, and Hiroshi (2005), Yang (2008), Ghoseiri and Ghannadpour (2010) and Samanta and Jha (2011) proposed Genetic Algorithms, Pisinger and Ropke (2007) presented an Adaptive Large Neighborhood Search (ALNS) procedure with minimization of routing cost. Ting and Chen (2009) presented a hybrid algorithm that combines multiple ant colony systems (ACS) and Simulated Annealing (SA). Zarandi, Hemmati, and Davari (2011) presented a SA procedure to minimize routing cost, while Wang, Zhang, and Wang (2011) coupled SA with a modified Variable Neighborhood Search algorithm, and a clustering algorithm is used to allocate customers in the initial solution construction phase. A branch-and-cut-and-price algorithm for the multi-depot heterogeneous vehicle routing problem with time windows (MDHVRPTW) was recently proposed by Bettinelli, Ceselli, and Righini (2011). Computational experiments showed that this procedure is competitive in comparison with local search heuristics.

The variants with split delivery (MDVRPSD) or with pickup & delivery (MDVRPPD) have been considered by very few authors in the scientific literature. The work of Wasner and Zapfel (2004) presents an application to postal, parcel and piece goods service provider in Austria. The model employed is the MDVRPPD (MDVRP with pickup and deliveries) with the objective of determining the number and location of depots and hubs. Also, the client assignment problem is addressed. These authors develop a local search heuristic. As a real-life problem is solved, additional features are included in the algorithm in order to take into account the topography of the country (which is characterized by mountains) by considering maximum route length. The decision support system allowed the solution of large-sized instances with various millions of variables and constraints. The paper of Pisinger and Ropke (2007) studied the MDVRPPD, together with the variants of time windows and vehicle capacity constraint. These authors proposed an Adaptive Large Neighborhood Search procedure in order to minimize total routing cost. Flisberg, Lidén, and Rönnqvist (2009) also considered heterogeneous fleet of vehicles and time windows constraints, in addition to pickups and split deliveries: their case-study is taken from a forest company in Sweden. Schmid, Doerner, Hartl, and Salazar-González (2010) studied a realistic case inspired from companies in the concrete industry, and presented a mixed integer linear program (MILP) and a Variable Neighborhood Search (VNS) procedure to minimize routing cost for the variant with split deliveries. Mirabi, Fatemi Ghomi, and Jolai (2010) addressed the problem of minimizing the delivery time of vehicles. They compared three hybrid heuristics, each one combining elements from both constructive heuristic search and improvement techniques. The improvement techniques are deterministic, stochastic and simulated annealing (SA) methods.

Crevier et al. (2007) considered a MDVRP in which there are intermediate depots along vehicles' routes where they may be replenished. This problem was inspired from a real-life application at the city of Montreal, Canada. A heuristic combining adaptive memory, tabu search and integer programming was proposed. The model allows the assignment of vehicles to routes that may begin and finish at the same depot or that connect two depots to increase the capacity of vehicles to deliver goods. Zhen and Zhang (2009) considered a similar problem and proposed a heuristic combining the adaptive memory principle, a Tabu Search method for the solution of subproblems, and integer programming. Another variant of the MDVRP appears in the work of Zarandi et al. (2011). These authors studied the fuzzy version of the Capacitated Location-Routing Problem (CLRP) with multiple depots in which the location of depots have to be defined as well as the routes of vehicles. Fuzzy travel times between nodes and time window to meet the demand of each customer are considered. A simulation-embedded Simulated Annealing (SA) procedure was proposed. The framework was tested using standard data sets.

A good manner of improving the performance of meta-heuristics is to generate good initial solutions. Ho, Ho, Ji, and Lau (2008) proposed the use of the well-known Clarke & Wright Savings (C&WS) algorithm (Clarke & Wright, 1964) to generate initial solutions, as commonly used for other vehicle routing problems (Juan et al., 2009). Once the solution is generated, the Nearest Neighbor (NN) heuristic is employed to improve such solution. In comparison with the random generation of initial solutions, their experiments showed that this hybrid C&WS + NN approach produces better results regarding total delivery time. Li and Liu (2008) considered the multi-depot open vehicle routing problem with replenishment during the execution of routes. They proposed a model and an Ant Colony Optimization resolution procedure. Other application of the Ant Colony Optimization paradigm can be found in the works of Wang (2013) and Narasimha, Kivelevitch, Sharma, and Kumar (2013). These last authors studied the MDVRP with minimization of the longest travel distance of a vehicle.

Vidal et al. (2010, 2011) proposed a general framework to solve a family of vehicle routing problems, including the multi-depot VRP, the periodic VRP and the multi-depot periodic VRP with capacitated vehicles and constrained route duration. Their meta-heuristic combines the exploration breadth of population-based evolutionary search, the aggressive improvement capabilities of neighborhood search based procedures and advanced population diversity management strategies. These authors improved the best-known solutions and even obtained optimal values for these three problem cases. Recent years on MDVRP research have witnessed the use of variable neighborhood search (VNS) algorithm for the resolution of various variants of the problem (Kuo & Wang, 2012; Salhi, Imran, & Wassan, 2014; Xu & Jiang, 2014; Xu, Wang, & Yang, 2012). A realistic application of MDVRP found in vessel routing was studied by Hirsch, Schroeder, Maggiar, and Dolinskaya (2014). These authors proposed the implementation of various heuristics, including GRASP (Greedy Randomized Adaptive Search Procedure). More recently, the trend has been focused on the use of hybrid meta-heuristics algorithms. Liu and Yu (2013) presented a hybridized genetic algorithm – ant colony optimization procedure to minimize the maximum travel distance of a vehicle in a system with heterogeneous fleet of vehicles. Liu (2013) proposed to couple the genetic algorithm with bee colony optimization and simulated annealing to solve the classical MDVRP. Rahimi-Vahed, Crainic, Gendreau, and Rei (2013) employed path relinking for the case of capacitated MDVRP with route duration constraint. Vidal, Crainic, Gendreau, and Prins (2014) proposed a hybrid genetic algorithm with iterated local search and dynamic programming was presented for the classical MDVRP with unconstrained vehicle fleet. Subramanian, Uchoa, and Ochi (2013) proposed a matheuristic procedure for the cases of the MDVRP and MDRVP with mixed pick up and deliveries. Their algorithm is based on iterated local search and exploits set partitioning models at certain stages of the procedure to obtain competitive solutions. Sitek, Wikarek, and Grzybowska (2014) presented a multi-agent system coupled with a mixed-integer linear programming (MILP) model and Constraint Programming (CP) for the multi-echelon capacitated vehicle routing problem.

3. The MDVRP with multiple objectives

An important characteristic of real-life logistics problems found in enterprises is that decision-makers, very often, have to simultaneously deal with multiple objectives. These objectives are sometimes contradictory (e.g., minimizing number of vehicles and maximizing service level). In the literature, there are very few papers on the MDVRP that consider multiple objectives (MOMDVRP): about 11.56% of the papers reviewed here. This percentage corresponds to a total of 17 papers reviewed here (see Table A2 in the Appendix).

The work of Lin and Kwok (2005) studies a realistic particular case of the MDVRP, named as location-routing problem (LRP) with multiple uses of vehicles. In this problem, decisions on location of depots, vehicle routing and assignment of routes to vehicles are considered simultaneously. Tabu search and simulated annealing procedures are designed and tested on both random-generated and real data. The objectives are the minimization of total operational cost and the balance on vehicle load. Both simultaneous and sequential procedures for the assignment of routes to vehicles are tested. Results show that the simultaneous versions have advantage over the sequential versions in problems where routes are capacity-constrained, but not in the time dimension. The simultaneous versions are also more effective in generating non-dominated solutions than the sequential versions.

A real-life transportation problem consisting on moving empty or laden containers is studied by Tan, Chew, and Lee (2006). They called the problem as the truck and trailer vehicle routing problem (TTVRP), but in fact it corresponds to a variant of the MDVRP: the solution to the TTVRP consists of finding a complete routing schedule for serving the jobs with minimum routing distance

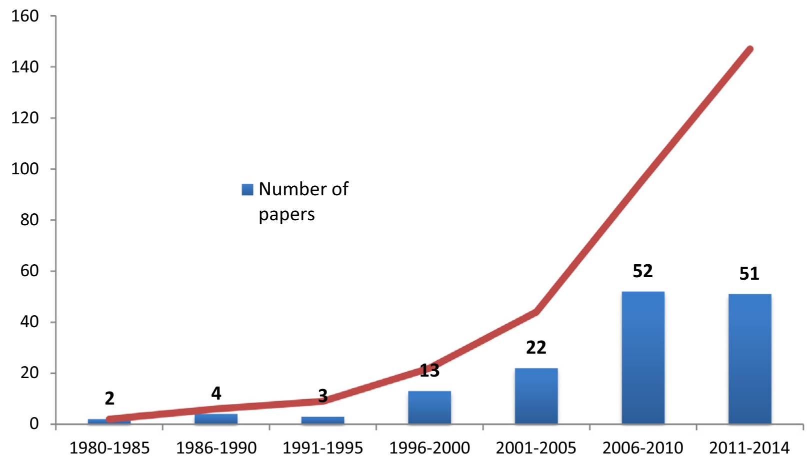

Fig. 3. Distribution of published papers per year for the MDVRP.

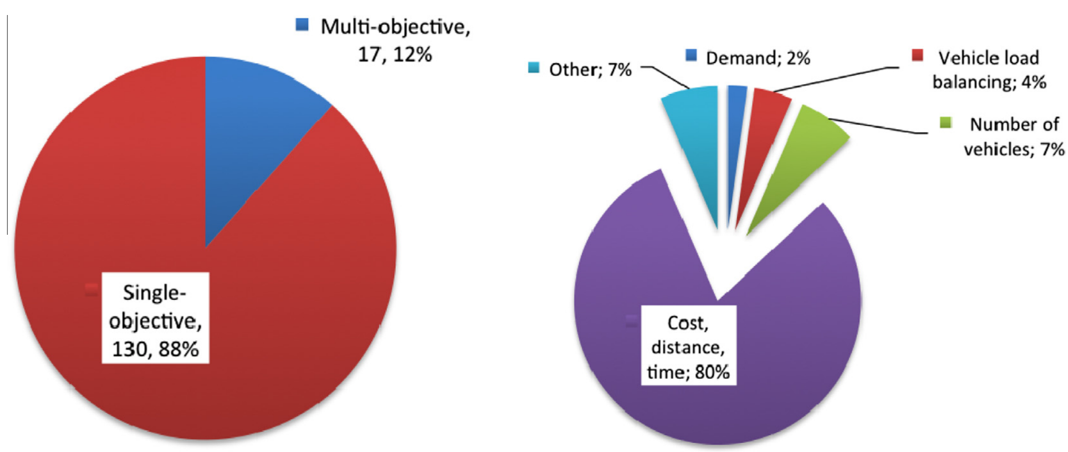

Fig. 4. Distribution of objective functions.

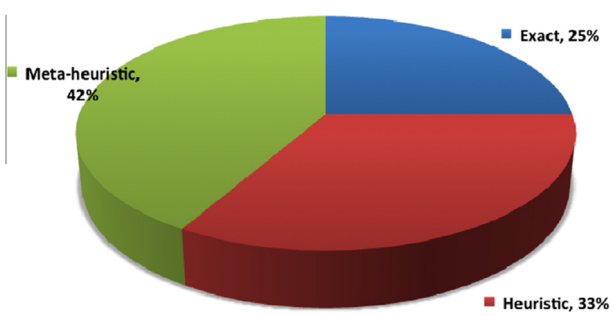

Fig. 5. Distribution of employed solution techniques.

and number of trucks, subject to time windows and availability of trailers. These authors solved the multi-objective case using a hybrid multi-objective evolutionary algorithm (HMOEA) with specialized genetic operators, variable-length representation and local search heuristic. Lau, Tang, Ho, and Chan (2009) considered the multi-objective problem in which the travel time is not a constraint but an objective function to be optimized in the model together with the total traveled distance. The proposed solution procedure is a hybrid meta-heuristic named fuzzy logic guided non-dominated sorting genetic algorithm (FL-NSGA2). The procedure uses fuzzy logic to dynamically adjust the probabilities of mutation and crossover. The algorithm is compared with the well-known algorithms non-dominated sorting genetic algorithms 2 (NSGA2), strength Pareto evolutionary algorithm 2 (SPEA2) with and without fuzzy logic and the micro-genetic algorithm (MICROGA) with and without fuzzy logic. Experiments showed that the proposed FL-NSGA2 procedure outperformed the other procedures. This technique was also used by Lau, Chan, Tsui, and Pang (2010) to solve the problem in which the cost due to the total traveling distance and the cost due to the total traveling time are minimized. In their work, several search methods, branch-and-bound, standard GA (i.e., without the guide of fuzzy logic), simulated annealing, and tabu search procedure are adopted to compare with FLGA in randomly generated data sets. Results of their experiments show that FLGA outperforms the other methods. Ombuki-Berman and Hanshar (2009) and Weise, Podlich, and Gorldt (2010) also proposed a genetic algorithm. The first authors considered the objectives of minimizing the total cost and the number of vehicles, while the latter authors considered the total distance, the idle capacity of vehicles and the number of externalized deliveries. A Simulated Annealing (SA) procedure was presented by Hasanpour, Mosadegh-Khah, and Tavakoli Moghadam (2009) for minimizing transportation costs and maximizing probability of delivery to customers.

Weise, Podlich, and Gorldt (2010) presented the use of evolutionary computation for a real-life problem inspired from a joint enterprise-academia research project. Results of the implementation are compared against the traditional routing structure

Table A1
Reviewed papers about the single-objective MDVRP.

Year	Reference	Constraints							Solution method		
		Time Windows	Heterogeneous fleet	Capacitated	Periodic	Pick up & Delievery	Split delivery	Other	Exact	Heuristic	Meta-heuristic
	% of papers	26%	21%	38%	12%	11%	5%	26%	31%	45%	57%
1984	Laporte et al. (1894)								X		
1985	Kulkarni and Bhave (1985)			X					X		
1987	Laporte and Nobert (1987)								X		
1988	Laporte et al. (1988)			X					X		
1989	Laporte (1989)								X		
	Carpaneto, Dell'amico, Fischetti, and Toth (1989)			X					X		
1992	Min et al. (1992)			X				X		X	
	Wilger and Maurer (1992)									X	
1993	Chao et al. (1993)									X	
1996	Renaud, Laporte et al. (1996)			X				X			X
1997	Filipec et al. (1997)			X							X
	Salhi and Sari (1997)		X							X	
	Cordeau et al. (1997)				X						X
1998	Salhi et al. (1998)										X
	Hadjiconstantinou and Baldacci (1998)				X					X	
1999	Vianna et al. (1999)				X					X	X
	Tüzün and Burke (1999)							X			X
	Salhi and Nagy (1999)							X		X	
2000	Irnich (2000)		X			X			X	X	
	Filipec et al. (2000)			X						X	X
	Skok, Skrlec, and Krajcar (2000)			X						X	X
	Yang and Chu (2000)				X					X	
2001	Thangiah and Salhi (2001)									X	X
	Skok, Skrlec, and Krajcar (2001)			X						X	X
	Cordeau et al. (2001)	X			X						X
	Chan, Carter, and Burnes (2001)							X		X	
2002	Wu et al. (2002)		X	X							X
	Angelelli and Speranza (2002)				X			X			X
	Zhang, Jiang, and Tang (2002)			X					X	X	
	Giosa, Tansini, and Viera (2002)	X								X	
2003	Dondo et al. (2003)	X	X						X		
	Kazaz and Altinkemer (2003)							X	X	X	
2004	Matos and Oliveira (2004)				X						X
	Wasner and Zapfel (2004)					X				X	
	Jin et al. (2004)									X	
2005	Mingozzi (2005)				X				X		
	Nagy and Salhi (2005)					X				X	
	Polacek et al. (2005)	X		X							X
	Lim and Wang (2005)			X					X		X
	Baltz, Dubhashi, Tansini, Srivastav, and Werth (2005)									X	
	Songyan, Akio, and Bai (2005)										X
	Jin et al. (2005)	X									X
	Songyan and Akio (2005)										X
2006	Parthanadee and Logendran (2006)				X						X
	Yang, Cui, and Cheng (2006)	X									X
	Chiu et al. (2006)	X								X	
	Lim and Zhu (2006)			X				X		X	X
2007	Dondo and Cerdá (2007)	X	X						X	X	
	Jeon et al. (2007)		X								X
	Crevier et al. (2007)								X		X
	Bae, Hwang, Cho, and Goan (2007)		X	X							X
	Pisinger and Ropke (2007)	X		X		X					X

	Özyurt and Aksen (2007)								X		X
	Carlsson, Ge, Subramaniam, Wu, and Ye (2007)									X	
	Hu, Chen, and Guo (2007)					X				X	
	Wang, Gao, Cui, and Chen (2007)										X
	Lou (2007)							X		X	X
	Tsirimpas et al. (2007)			X				X	X		
2008	Ho et al. (2008)									X	X
	Kek et al. (2008)			X		X			X		
	Dondo et al. (2008)	X	X			X			X	X	
	Polacek, Benkner, Doerner, and Hartl (2008)	X		X							X
	Dai, Chen, Pan, and Hu (2008)									X	X
	Li and Liu (2008)										X
	Chen, Guo, and Fan (2008)							X		X	
	Yang (2008)	X	X								X
	Chen, Sheng-Zhang, and Shi (2008)	X	X	X							
	Goela and Gruhn (2008)	X	X	X		X	X	X		X	
2009	Flisberg et al. (2009)	X	X			X	X		X		X
	Dondo and Cerdá (2009)	X	X						X	X	
	Baldacci and Mingozzi (2009)								X		
	Ting and Chen (2009)	X									X
	Zhen and Zhang (2009)							X	X		X
2010	Schmid et al. (2010)		X				X		X		X
	Mirabi et al. (2010)									X	X
	Liu et al. (2010)			X			X			X	
	Vidal et al. (2010)		X	X	X						X
	Ma and Yuan (2010)										X
	Sombunthama and Kachitvichyanukulb (2010)	X				X				X	
	Sepehri and Kargari (2010)							X	X		
	Gajpal and Abad (2010)					X				X	
	Villegas et al. (2010)			X				X		X	X
	Garaix, Artigues, Feillet, and Josselin (2010)			X				X	X	X	
	Ghoseiri and Ghannadpour (2010)	X							X	X	X
	Kansou and Yassine (2010)									X	X
2011	Gulczynski et al. (2011)						X		X	X	
	Bettinelli et al. (2011)	X	X	X					X	X	
	Yücenur and Demirel (2011a)										X
	Aras et al. (2011)			X							X
	Zarandi et al. (2011)	X		X							X
	Yang, Zhou, Cui, and He (2011)							X	X		X
	Wang et al. (2011)	X							X	X	X
	Samanta and Jha (2011)	X						X			X
	Yücenur and Demirel (2011b)									X	X
	Yu, Yang, and Xie (2011)										X
	Lei, Xing, Wu, and Wen (2011)									X	
	Fard and Setak (2011)							X		X	X
	Zhang, Tang, and Fung (2011)							X			X
	Surekha and Sumathi (2011)									X	X
	Maischberger and Cordeau (2011)	X		X	X			X		X	X
2012	Cornillier et al. (2012)	X	X					X	X	X	
	Kuo and Wang (2012)			X				X			X
	López Franco and Nieto Isaza (2012)			X						X	
	Maya et al. (2012)			X	X					X	X
	Nieto Isaza et al. (2012)	X	X						X		
	Xu et al. (2012)	X	X	X							X
2013	Ben Alaia, Dridi, Bouchriha, and Borne (2013)			X		X					X
	Benavent and Martínez (2013)								X		
	Liu (2013)	X		X							X
	Liu and Yu (2013)	X	X	X							X
	Venkata et al. (2013)			X				X			X

(continued on next page)

Table A1 (*continued*)

Year	Reference	Constraints							Solution method		
		Time Windows	Heterogeneous fleet	Capacitated	Periodic	Pick up & Delievery	Split delivery	Other	Exact	Heuristic	Meta-heuristic
	Rahimi-Vahed et al. (2013)			X	X						X
	Seth et al. (2013)			X		X		X	X		
	Subramanian et al. (2012)			X		X					X
	Wang (2013)			X							X
2014	Adelzadeh et al. (in press)	X	X						X	X	
	Afshar-Nadjafi and Afshar-Nadjafi (in press)	X	X	X				X		X	
	Braekers et al. (2014)		X	X				X	X		X
	Contardo and Martinelli (2014)				X			X	X		
	Contardo et al. (2014)				X			X	X		
	Escobar et al. (in press)			X				X			X
	Hirsch et al. (2014)							X		X	X
	Li, et al. (in press)	X		X					X		X
	Luo and Chen (2014)	X		X							X
	Ray et al. (in press)						X	X	X	X	
	Salhi et al. (2014)		X	X						X	X
	Sitek et al. (2014)			X				X		X	
	Vahed et al. (in press)		X		X			X		X	
	Vidal et al. (2014)		X	X							X
	Xu and Jiang (2014)	X	X	X							X

employed by the enterprises associated with the research. The multi-objective MDVRP with time windows and split delivery is studied by Dharmapriya and Siyambalapitiya (2010). The objectives to be optimized were defined to be the total transportation cost, the total distance traveled, full use of vehicle capacity and load balancing. The problem is solved using Tabu Search, Simulated Annealing and a Greedy algorithm. Tavakkoli-Moghaddam, Makui, and Mazloomi (2010) studied the multi-objective problem in which depot location and routes of vehicles have to be defined simultaneously. This problem is known in the literature as the Multi-Depot Location-Routing Problem. Traditionally, this problem is solved sequentially: first, the location of depots is addressed and then the routing of vehicles is approached. These authors proposed a scatter search algorithm that seeks to maximize total demand served and to minimize the total operational cost (cost of opening depots and variable delivery costs). Computational experiments showed that the proposed multi-objective scatter search (MOSS) algorithm outperformed an Elite Tabu Search (ETS) procedure. Scatter Search operates on a set of solutions, the reference set, by combining these solutions to create new ones. Then, a subset is non-randomly selected from this reference set and selected solutions are combined to get starting solutions to run an improvement mechanism. The reader interested in more details of the multi-objective of Scatter Search can refer to the works of Beausoleil (2001), Beausoleil (2004, Beausoleil (2006). On the other hand the ETS algorithm considered by Tavakkoli-Moghaddam et al. (2010) first determines the minimum number of required facilities and then evaluates all combinations of facilities by incorporating an elite tabu search procedure at the routing phase.

Jiang and Ding (2010) minimized the distribution cost, the customer dissatisfaction and the changes of routes in a disruption measurement model and an immune algorithm. The procedure is tested using a simple example. Ghoseiri and Ghannadpour (2010) considered the problem of simultaneously optimizing total fleet size and total distance deviation by using a genetic algorithm coupled with goal programming. Finally, Venkatasubbaiah, Acharyulu, and Chandra Mouli (2011) proposed the use of a Fuzzy Goal Programming Method to solve the multi-objective problem. A fuzzy max-min operator is also proposed to improve the effectiveness of the procedure. The algorithm is tested on simple transportation problems from literature, and compared with previous works, while Li and Liu (2011) proposed a genetic algorithm so as to minimize the number of vehicles and the total travel distance. Adelzadeh et al. (in press) proposed a mathematical model and a fuzzy-based heuristic for the particular case of the MDVRP with fuzzy time windows and heterogeneous fleet of vehicles. Martínez-Salazar et al. (2014) studied the location-routing problem (LRP) with transportation considerations in order to minimize transport cost and load balancing. The bi-objective problem is formalized using mathematical programming and then solved with both a Scatter Tabu Search procedure and the well-known NSGA-II (Non-dominated Sorting Genetic Algorithm II). Mirabi (2014) proposed a hybrid meta-heuristic algorithm coupling simulated annealing and electromagnetism to minimize travel distance and customer waiting time for service. Finally, Rodrigues Pereira Ramos, Gomes, and Barbosa-Póvoa (2014) simultaneously evaluated travel distance and level of carbon emissions in a multi-depot vehicle routing problem found in waste collection supply chain.

4. Analysis of literature

As pointed out before, since the first publication on multi-depot vehicle routing problem appeared in 1984. Since there, more than 145 papers have been published up to date in the scientific literature about this problem and its variants. Between the middle

Table A2
Reviewed papers about the multi-objective MDVRP.

Year	Reference	Constraints							Solution method		
		Time windows	Heterogeneous fleet	Capacitated	Periodic	Pick up & Delievery	Split delivery	Other	Exact	Heuristic	Meta-heuristic
	% of papers	29%	12%	41%	12%	12%	6%	41%	12%	35%	82%
2005	Lin and Kwok (2005)							X			X
2006	Tan et al. (2006)	X	X								X
2009	Lau et al. (2009)										X
	Hasanpour et al. (2009)							X			X
	Ombuki-Berman and Hanshar (2009)			X				X		X	X
2010	Dharmapriya and Siyambalapitiya (2010)	X					X				X
	Tavakkoli-Moghaddam et al. (2010)			X							X
	Jiang and Ding (2010)					X		X		X	
	Lau et al. (2010)								X		X
	Weise et al. (2010)	X		X	X	X		X		X	X
	Ghoseiri and Ghannadpour (2010)	X								X	X
2011	Venkatasubbaiah et al. (2011)									X	
	Li and Liu (2011)										X
2014	Adelzadeh et al. (in press)	X	X	X						X	X
	Martínez-Salazar et al. (2014)			X				X			X
	Mirabi (2014)			X	X						X
	Rodrigues Pereira Ramos et al. (2014)			X				X	X		

of the 1980's (when the first works on the MDVRP were published) and the end of the twentieth century, very few papers were proposed in the literature (see Fig. 3): only 18 publications (excluding those published in 2000), giving an average of 1.12 papers per year. Between 2000 and 2005, there was an increase in the number of publication on MDVRP with an average of 4.33 publications per year. This gives a total of 44 publications until 2005 inclusive. The most impressive growing on the number of papers published is observed between 2006 and 2014 with a total 103 publications, giving an average of 10.4 papers per year in the period 2006–2010 and 12.75 paper per year in the period 2011–2014 inclusive.

As can be seen, there is a clearly increasing trend showing the growing interest in this field. It is reasonable to expect that in the coming years the MDVRP will receive an ever large amount of attention. There are however some remarks to be made. As shown in Fig. 4, most of the works have been focused on the minimization of cost, distance or time. The papers dealing with vehicle load balancing are in fact papers that seek to optimize multiple objectives simultaneously (very often cost and vehicle load). As presented in previous sections of this review (see also Fig. 4), the majority of published works deals with the single objective problem. While this problem is of theoretical interest, very often decision-makers are faced to optimize multiple (contradictory) objectives. Very few published works deals with multi-objective problem. Hence, this gap in current research could be closed by proposing efficient and effective solution approaches for multi-objective environments.

It is also interesting to study the different methodologies and techniques that the authors apply in the reviewed literature. Fig. 5 shows two pie charts with this distribution: it first classifies the approaches as exact, heuristics and meta-heuristics algorithms, while the second pie presents a distribution of the different approximate algorithms employed in the reviewed literature. We first observe that exact algorithms (branch and bound, mathematical programming) are employed in 25% of reviewed papers. We have to consider that these techniques have proven to be useful for simplified combinatorial optimization problems, specific settings and/or small instances. Hence, a larger focus is needed on approaches able to solve larger instances. Because of the NP-hardness of the MDVRP, approximate heuristics have also been proposed. Under the category of heuristic algorithms, we have classified many different algorithms and *ad-hoc* methods that are specific and do not contain a well-known meta-heuristic template. This represents 33% of the reviewed papers. For the other 42% a meta-heuristic algorithm is proposed. Among the available procedures, Tabu Search (TS), genetic algorithms (GA) and simulated annealing (SA) have been the most employed in the reviewed literature. The other meta-heuristics have been less employed: ant colony optimization and variable neighborhood search. Clearly, there is a large opportunity for research here. Meta-heuristics have long ago established themselves as state-of-the-art methodologies for the vast majority of vehicle routing problems.

5. Conclusions and lines for future research

Finding an optimal (or at least very good) route for vehicles delivering products to customers is one of the key functions in any logistics systems. Since the first works proposed in literature in the late 1959, the literature on vehicle routing problems has been highly increasing. A lot of works, as well as state-of-the-art surveys, have been published. In this paper, we focused on one of the less reviewed variants: the vehicle routing problem with multiple depots (MDVRP). We presented a complete analysis of scientific literature since the first works about this problem were published in the mid 1980s.

Early works on MDVRP mainly proposed exact algorithms (mathematical models, branch-and-bound methods). With the development of computers and the increasing popularity of meta-heuristics, researches then focused on proposing genetic algorithms, tabu search procedures, simulated annealing, ant colony optimization algorithms or even variable neighborhood procedures to efficiently solve the problem. Some hybrid procedures have been proposed and their effectiveness has been proved by using benchmark instances. It is to note that several meta-heuristics (like GRASP), matheuristics, simheuristics and other hybrid procedures can be exploited to solve the problem. Also, as complex realistic problems appear to be of interest for researchers, additional constraints (product pickup and delivery, vehicle capacity constraints, delivery time windows, etc.) have been added to the original problem.

Most of the first works on MDVRP looked at the minimization of travel cost, distance or time. Very few papers considered nontraditional objective functions. There is an interesting gap in literature here since many other objective functions are of industrial relevance. In addition, logistics problems are multi-objective (MO) by nature, which means that several criteria, very often in conflict with each other, have to be considered at a time. Very few published works on multi-depot vehicle routing problems deals with multiple objectives. Research in multi-objective optimization is concerned with the generation of solutions in which none of the objective functions can be improved without paying a cost in other objective(s) (usually referred to as non-dominated solutions). Hence, researches must focus on proposing efficient and effective decision-making tools for multi-objective environments. The deal is not to consider several objectives and to optimize them sequentially (e.g., by concentrating on optimizing one objective and then, with that solution, considering the other objectives as secondary. The attempt is to find non-dominated solutions.

Finally, with the increasingly worldwide concern on the optimal use of scarcer natural resources, enterprises and supply chains need to be re-aligned to adjust to this trend. In order to go further from the classical economic optimization, the inclusion of social and environmental metrics in optimization problems becomes highly relevant. The paper of Montoya-Torres (2014) presents a general framework to take into account sustainability issues in supply chain decision-making, including logistics distribution process (i.e. vehicle routing decisions), while the work of Montoya-Torres, Muñoz-Villamizar, and Vega-Mejía (2014) seeks at proposing the application of the MDVRP in city logistics for the minimization of travel costs and carbon emissions. Some first attempts to consider sustainable issues (i.e. economic, environmental and social issues simultaneously) when solving logistic distribution problems have been presented in literature, see e.g. (Sbihi & Eglese, 2007). This certainly leads to solve more complex multi-objective routing problems.

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Appendix A.

(see Tables A1 and A2).

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