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# The Vehicle Routing Problem: State of the Art Classification and Review

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**Abstract:** Over the past decades, the Vehicle Routing Problem (VRP) and its variants have grown ever more popular in the academic literature. Yet, the problem characteristics and assumptions vary widely and few literature reviews have made an effort to classify the existing articles accordingly. In this article, we present a taxonomic review of the VRP literature published between 2009 and June 2015. Based on an adapted version of an existing comprehensive taxonomy, we classify 277 articles and analyze the trends in the VRP literature. This classification is the first to categorize the articles to this level of detail.

*Keywords:* vehicle routing, taxonomy, literature review, dynamic vehicle routing, time-dependent vehicle routing

*JEL code:* M1, M2

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## 1. Introduction

Dantzig & Ramser (1959) were the first to introduce the "Truck Dispatching Problem", modeling how a fleet of homogeneous trucks could serve the demand for oil of a number of gas stations from a central hub and with a minimum travelled distance. Five years later, Clarke & Wright (1964) generalized this problem to a linear optimization problem that is commonly encountered in the domain of logistics and transport: i.e., how to serve a set of customers, geographically dispersed around the central depot, using a fleet of trucks with varying capacities. This became known as the

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'Vehicle Routing Problem' (VRP), one of the most widely studied topics in the field of Operations Research.

Current VRP models, however, are immensely different from the one introduced by Dantzig & Ramser (1959) and Clarke & Wright (1964), as they increasingly aim to incorporate real-life complexities, such as for instance time-dependent travel times (reflecting traffic congestion), time windows for pickup and delivery, and input information (e.g., demand information) that changes dynamically over time. These features bring along substantial complexity. As the VRP is an NP-hard problem (Lenstra & Rinnooy Kan, 1981), exact algorithms are only efficient for small problem instances. Heuristics and metaheuristics are often more suitable for practical applications, because real-life problems are considerably larger in scale (e.g., a company may need to supply thousands of customers from dozens of depots with numerous vehicles and subject to a variety of constraints).

The number of solution methods introduced in the academic literature (for old as well as new variants of the VRP) has grown rapidly over the past decades. Moreover, the processing speed and memory capacity of current computers has increased exponentially, enabling to solve larger instances of the VRP which spurs the progression in the research field and the development of commercial software for the VRP. Nowadays VRP software is being used by thousands of companies, among others Coca-Cola Enterprises and Anheuser-Busch Inbev, in a large variety of industry sectors (Drexl, 2012a; Partyka & Hall, 2014).

The study by Eksioglu, Vural, & Reisman (2009) revealed 1021 journal articles with VRP as the main topic, published between 1959 and 2008. A number of books (e.g. Golden, Raghavan, & Wasil, 2008; Toth & Vigo, 2002, 2014) and a considerable amount of proceedings have also contributed to the VRP literature that exists today. According to Eksioglu et al. (2009), the VRP literature has been growing exponentially at a rate of 6% each year. This popularity makes it difficult to keep track of the developments in the field, and to have a clear overview of which variants and solution methods are relatively novel. Furthermore, taxonomies on vehicle routing are rather scarce (Eksioglu et al., 2009; Lahyani, Khemakhem, & Semet, 2015), while surveys/reviews of existing literature often only focus on specific variants or aspects of the VRP, e.g. the capacitated VRP (Laporte, 2009), periodic VRPs (Campbell & Wilson, 2014), the VRP with time windows (Bräysy & Gendreau, 2005a, 2005b; Gendreau & Tarantilis, 2010), dynamic VRPs (Pillac, Gendreau, Guéret, & Medaglia, 2013), pickup and delivery problems (Berbeglia, Cordeau, Gribkovskaia, & Laporte, 2007), vehicle routing with multiple depots (Montoya-Torres, Lopez France, Nieto Isaza, Felizzola Jimenez, & Herazo-Padilla, 2015), vehicle routing with split deliveries (Archetti & Speranza, 2012), green vehicle routing (C. Lin, Choy, Ho, Chung, & Lam, 2014) and synchronization aspects in vehicle routing (Drexl, 2012b). Additionally, these surveys often focus on reviewing the proposed solution methods, rather than identifying differences in assumptions and characteristics between VRP variants. For example, a categorized bibliography on metaheuristic approaches for different VRP variants is available in Gendreau, Potvin, Bräysy, Hasle, & Lokketangen (2008).

The purpose of this article is to classify the academic literature on the VRP, based on the detailed characteristics of the VRP problem studied. As we base our classification on the taxonomy by Eksioglu et al. (2009), we restrict our analysis to articles published between 2009 and June 2015 and as such, do not intend to provide an exhaustive overview of the VRP literature. To the best of our knowledge, this article provides the first structured classification of recent VRP literature. The main contribution of our paper is the resulting classification table which is made available online as supplementary material. This classification table enables future researchers to easily find relevant literature by eliminating or selecting characteristics in the taxonomy, leaving only articles tailored to their interests. Additionally, the classification table allows to analyze which characteristics and VRP variants are most popular, and which are promising topics for future research.

Section 2 defines the scope of the survey, and Section 3 introduces general notations for popular VRP variants. The proposed adaptations to the taxonomy of Eksioglu et al. (2009) are discussed in Section 4. In Section 5, an analysis of the classification results is presented. We highlight our findings and discuss a number of relatively novel topics (i.e., the Open VRP, the Dynamic VRP and the Time-dependent VRP) in further detail. Section 6 provides conclusions and avenues for future research.

## **2. Scope of the survey**

We structure the recent literature, published between 2009 and mid-2015, using a taxonomic framework. The classification is followed by a survey that uses the taxonomy to evaluate the trends in the field, and to identify which articles contribute to these trends.

We restricted the reviewed literature as follows. Only relevant articles published in English-language journals are considered, i.e., books, conference proceedings and dissertations are excluded. To extract the most relevant literature and keep the number of articles manageable, the following search strategy was applied. First, only articles containing “vehicle routing” as a title word were selected. The search was limited to articles published in journals with an Impact Factor of at least 1.5 in the domains of Operations Research & Management Science, Transportation or Transportation Science & Technology (based on the Impact Factors of 2013 by Thomson Reuters). Articles published in Computers & Industrial Engineering (not in one of these categories) are included as well because of their relevance. Second, this set of articles was extended with highly cited articles published in any ranked journal. Articles were selected if they contain “vehicle routing” in the title or as a keyword, and they were cited at least five times per year, on average, since the year of publication. Third, the abstracts of the resulting articles were read to determine their relevance to the subject. Since the VRP already is an extensive research domain, the decision was made not to include any combined problems, such as inventory routing problems (see Bertazzi, Savelsbergh, & Speranza, 2008; Coelho, Cordeau, & Laporte, 2014), location-routing problems (see Prodhon & Prins, 2014), problems combining routing decisions with scheduling decisions related to other activities such as machine or

production scheduling (see H.-K. Chen, Hsueh, & Chang, 2009; Ullrich, 2013), multi-echelon routing (see Baldacci, Mingozzi, Roberti, & Calvo, 2013; Hemmelmayr, Cordeau, & Crainic, 2012), and routing with cross-docking (see C.-J. Liao, Lin, & Shih, 2010). Some papers take into account vehicle loading constraints which are more sophisticated than the traditional capacity constraints or simple precedence constraints appearing in e.g., the Vehicle Routing Problem with Pickup and Delivery (VRPPD, see Section 4). These papers are excluded as well since, in our opinion, they combine two separate, well-established and well-studied problems, i.e., vehicle routing problems and container loadings problems. For a recent survey on the integration of both problems, we refer to Pollaris, Braekers, Caris, Janssens, & Limbourg (2015).

This search strategy resulted in a final set of 277 articles which, while not exhaustive, contains the majority of recent articles on VRP and in our opinion can be considered as representative for the field. An overview per journal is given in Table 1 (Appendix A provides an overview of the selected references according to publication year). Table 1 shows that European Journal of Operational Research, Computers & Operations Research, and Expert Systems with Applications published most of the surveyed articles.

Journal	2013 Impact Factor	Number of selected articles
Transportation Research Part B: Methodological	3.894	3
Omega: The International Journal of Management Science	3.190	3
Transportation Research Part C: Emerging Technologies	2.820	9
Applied Soft Computing	2.679	3
International Journal of Production Economics	2.393	1
Transportation Science	2.294	21
Transportation Research Part E: Logistics and Transportation Review	2.193	21
Applied Mathematical Modelling	2.150	1
Decision Support Systems	2.036	4
Neurocomputing	2.005	1
Mathematical Programming	1.984	1
Expert Systems with Applications	1.965	38
Engineering Applications of Artificial Intelligence	1.962	2
Journal of Advanced Transportation	1.878	1
European Journal of Operational Research	1.843	65
Networks and Spatial Economics	1.803	2
Production and Operations Management	1.759	1
Computers & Operations Research	1.718	62
Computers & Industrial Engineering	1.690	18
Transportation Research Part D: Transport and Environment	1.626	3
International Journal of Systems Science	1.579	1
European Journal of Industrial Engineering	1.500	1
Operations Research	1.500	7
Manufacturing & Service Operations Management	1.450	1

Journal of Heuristics	1.359	1
Annals of Operations Research	1.103	1
Journal of the Operational Research Society	0.911	1
Networks	0.739	1
Discrete Applied Mathematics	0.677	1
Simulation – Transactions of The Society for Modeling and Simulation International	0.656	1
International Transactions in Operational Research	0.481	1

**Table 1:** Overview of the number of selected articles per journal

### 3. Terminology and notations

The classical VRP, also known as the Capacitated VRP (CVRP), designs optimal delivery routes where each vehicle only travels one route, each vehicle has the same characteristics and there is only one central depot. The goal of the VRP is to find a set of least-cost vehicle routes such that each customer is visited exactly once by one vehicle, each vehicle starts and ends its route at the depot, and the capacity of the vehicles is not exceeded.

This classical VRP has been extended in many ways by introducing additional real-life aspects or characteristics, resulting in a large number of variants of the VRP. It is possible to extend this problem by varying the capacities, which results in the Heterogeneous Fleet VRP (HFVRP), also known as the Mixed Fleet VRP. Another popular extension, the VRP with Time Windows (VRPTW), assumes that deliveries to a given customer must occur in a certain time interval, which varies from customer to customer.

In the VRP with Pickup and Delivery (VRPPD), goods need to be picked up from a certain location and dropped off at their destination. The pick-up and drop-off must be done by the same vehicle, which is why the pick-up location and drop-off location must be included in the same route (Tasan & Gen, 2012). A related problem is the VRP with backhauls (VRPB), where a vehicle does deliveries as well as pick-ups in one route (Pradenas, Oportus, & Parada, 2013). Some customers require deliveries (referred to as linehauls) and others require pick-ups (referred to as backhauls). The combination of linehauls and backhauls has been proven very valuable to the industry. The well-known ‘milk run’ concept is derived from the successes reached with VRPB: by employing milk runs, transportation costs and total distance travelled can be decreased significantly and the vehicle loading rate increases (Brar & Saini, 2011).

The Multi-Depot VRP (MDVRP) assumes that multiple depots are geographically spread among the customers (Montoya-Torres et al., 2015). The Periodic VRP (PVRP) is used when planning is made over a certain period and deliveries to the customer can be made in different days (Campbell & Wilson, 2014; Gulczynski, Golden, & Wasil, 2011b). For the PVRP, customers can be visited more than once, though often with limited frequency.

Recently, some of these variants have been combined into so-called “rich” vehicle routing problems, simultaneously including multiple real-life aspects (see Lahyani et al. (2015) for a recent discussion and survey).

## 4. Taxonomy

The applied taxonomy is an adapted version of the taxonomy proposed by Eksioglu et al. (2009). Five main characteristics are distinguished (type of study, scenario characteristics, problem physical characteristics, information characteristics and data characteristics), each with its own detailed categories and sub-categories (see Table 2). The (sub)categories indicated in bold are adapted from Eksioglu et al. (2009). These adaptations are discussed in the following paragraphs.

1. Type of study	3.4. Number of points of loading/unloading facilities (depot)
1.1. Theory	3.4.1. Single depot
1.2. Applied methods	3.4.2. Multiple depots
1.2.1. Exact methods	<b>3.5. Time window type</b>
<b>1.2.2. Classical Heuristics</b>	3.5.1. Restriction on customers
<b>1.2.3. Metaheuristics</b>	3.5.2. Restriction on depot/hubs
1.2.4. Simulation	3.5.3. Restriction on drivers/vehicle
1.2.5. Real-time solution methods	3.6. Number of vehicles
1.3. Implementation documented	<b>3.6.1. Single vehicle</b>
1.4. Survey, review or meta-research	<b>3.6.2. Limited number of vehicles</b>
2. Scenario Characteristics	3.6.3. Unlimited number of vehicles
2.1. Number of stops on route	3.7. Capacity consideration
2.1.1. Known (deterministic)	3.7.1. Capacitated vehicles
2.1.2. Partially known, partially probabilistic	3.7.2. Uncapacitated vehicles
2.2. Load splitting constraint	3.8. Vehicle homogeneity (Capacity)
2.2.1. Splitting allowed	3.8.1. Similar vehicles
2.2.2. Splitting not allowed	3.8.2. Load-specific vehicles
2.3. Customer service demand quantity	3.8.3. Heterogeneous vehicles
2.3.1. Deterministic	3.8.4. Customer-specific vehicles
2.3.2. Stochastic	3.9. Travel time
2.3.3. Unknown	3.9.1. Deterministic
2.4. Request times of new customers	3.9.2. Function dependent (a function of current time)
2.4.1. Deterministic	3.9.3. Stochastic
2.4.2. Stochastic	3.9.4. Unknown
2.4.3. Unknown	<b>3.10. Objective</b>
2.5. Onsite service/waiting times	3.10.1. Travel time dependent
2.5.1. Deterministic	3.10.2. Distance dependent
<b>2.5.2. Dependent</b>	3.10.3. Vehicle dependent
2.5.3. Stochastic	3.10.4. Function of lateness
2.5.4. Unknown	3.10.5. Implied hazard/risk related
2.6. Time window structure	<b>3.10.6. Other</b>
2.6.1. Soft time windows	4. Information Characteristics
2.6.2. Strict time windows	4.1. Evolution of information
2.6.3. Mix of both	4.1.1. Static
2.7. Time horizon	4.1.2. Partially dynamic
2.7.1. Single period	4.2. Quality of information
2.7.2. Multi-period	4.2.1. Known (Deterministic)
2.8. Backhauls	4.2.2. Stochastic
2.8.1. Nodes request simultaneous pickups and deliveries	4.2.3. Forecast
2.8.2. Nodes request either linehaul or backhaul	

	service, but not both	4.2.4.	Unknown (Real-time)
2.9.	Node/Arc covering constraints	4.3.	Availability of information
2.9.1.	Precedence and coupling constraints	4.3.1.	Local
2.9.2.	Subset covering constraints	4.3.2.	Global
2.9.3.	Recourse allowed	4.4.	Processing of information
3.	Problem Physical Characteristics	4.4.1.	Centralized
3.1.	Transportation network design	4.4.2.	Decentralized
3.1.1.	Directed network	5.	Data Characteristics
3.1.2.	Undirected network	5.1.	Data used
3.2.	Location of addresses (customers)	5.1.1.	Real-world data
3.2.1.	Customer on nodes	5.1.2.	Synthetic data
3.2.2.	Arc routing instances	5.1.3.	Both real and synthetic data
3.3.	Number of points of origin	5.2.	No data used
3.3.1.	Single origin		
3.3.2.	Multiple origin		

**Table 2:** The proposed taxonomy (adapted from Eksioglu et al. (2009))

With respect to the applied methods (category 1.2), we propose to differentiate between classical heuristics and metaheuristics. Laporte (2009) defines classical heuristics as heuristics that do not allow the intermediate solution to deteriorate during the process of finding better (optimal) solutions. As a result, they often get trapped in local optima. Examples include construction heuristics such as the savings algorithm (Clarke & Wright, 1964), and improvement heuristics such as the  $\lambda$ -opt mechanism (S. Lin, 1965). Metaheuristics, on the other hand, include mechanisms that avoid getting trapped in local optima. Examples are Tabu Search (Glover, 1986) and Simulated Annealing (Kirkpatrick, Gelatt Jr., & Vecchi, 1983).

Onsite service or waiting times (category 2.5) indicate the exact time a vehicle has to wait at a customer before it can start the service or the amount of time it takes to perform the service. This is particularly relevant when dealing with time windows. In this category, we made an adaptation to the taxonomy provided by Eksioglu et al. (2009) by merging the two subcategories ‘time dependent’ and ‘vehicle type dependent’ into one subcategory ‘dependent’, as the service time can be dependent on many more aspects (such as the number of personnel in the vehicle (Pureza, Morabito, & Reimann, 2012), or the delivery quantity (Salani & Vacca, 2011)).

The time window type (category 3.5) classifies articles depending on the party that is restricted by the window (either customers, depots or drivers). Eksioglu et al. (2009) also included a time window restriction on roads. Since this is rare, it is excluded in this paper. Additionally, as it is often unclear which type of instances (randomly dispersed customers, clustered customers, or a combination of these) are used to test proposed solutions methods, we decided to remove category ‘geographical location’ from the taxonomy on problem physical characteristics as well.

VRP articles may also be classified according to the number of the vehicles available. Eksioglu et al. (2009) consider three categories based on the number of vehicles to be used: exactly  $n$  vehicles, up to  $n$  vehicles, and an unlimited amount of vehicles. However, situations in which exactly  $n$  vehicles should be used are rather uncommon, except for the single vehicle case (in a multi-vehicle context,



typically the option exists not to use some vehicles when this is beneficial). Therefore, we adapt category 3.6.1 to indicate articles on single vehicle problems only ( $n=1$ ). In case of multiple vehicles, either a limited or an unlimited amount may be available (categories 3.6.2 and 3.6.3, respectively). Note that the single vehicle case is commonly referred to as the Traveling Salesman Problem (TSP), for which in itself an extensive amount of literature is available (see e.g., Applegate, Bixby, Chvatal, & Cook, 2011; Gutin & Punnen, 2007; Lawler, Lenstra, Rinnooy Kan, & Shmoys, 1985). In this paper, it is not our intention to review the complete TSP literature; rather, we focus on the VRP. Hence, most of the reviewed articles address multi-vehicle problems.

Finally, in category 3.10, articles are categorized according to the selected objective function (either focusing on travel time, distance, number of vehicles, costs related to lateness, costs related to risks or hazards, any other objective type, or a combination of these). Compared to the original classification, the subcategory ‘other’ was added since several authors take into account objectives which are specific to the problem under study.

## **5. Results of the classification**

In this section, the results of the classification are discussed. The detailed classification results of the 277 articles are shown in the *electronic Appendix* of this manuscript. The .xlsx format allows the user (e.g., future researchers) to select any given combination of identifiers in order to retrieve the relevant articles. Moreover, the classification results may be used to analyze which characteristics and VRP variants are most popular, and which topics remain relatively underexamined. Note that some papers appear multiple times in this classification as they consider several VRP variants. As a result, the classification table contains 327 lines. In the remainder of this section we discuss our main findings (all percentages are calculated using this total of 327).

In Section 5.1, results are analyzed on the level of individual characteristics. Observations on combinations of characteristics are discussed in Section 5.2. Finally, in Section 5.3, we provide a more detailed discussion of three specific problem variants which have been studied extensively in recent years.

### **5.1. Individual characteristics**

Only a limited number of papers have a main focus on theory (category 1.1, 7.01%) or on reviewing existing literature (category 1.4, 3.66%). In the majority of papers (95.12%), at least one type of solution method is proposed or applied. An overview of these solution methods (category 1.2) is presented in Table 3. Next to the relative presence of a type of method over all reviewed articles, also the relative presence per publication year is shown. This may help to identify trends. However, it is hard to make strong statements due to the relatively short review period and the often limited number of papers per characteristic per publication year.

Table 3 indicates that metaheuristics are, by far, used most often. Exact methods and classical heuristics are applied less often (probably due to the fact that the former is computationally expensive for complex and large instances, while the latter can get stuck in local optima). Simulation and real-time solution methods are rarely used. Given their importance in solving realistic VRPs, the further development of metaheuristic methods provides an opportunity for further research.

Applied Method (1.2)	Number of models	Relative presence							
		Overall	2009	2010	2011	2012	2013	2014	2015
Metaheuristic (1.2.3)	233	71.25%	65%	63%	65%	77%	80%	76%	65%
Exact Method (1.2.1)	56	17.13%	17%	20%	26%	10%	13%	17%	19%
Classical Heuristic (1.2.2)	32	9.79%	11%	15%	15%	17%	4%	5%	10%
Real-time solution methods (1.2.5)	11	3.36%	6%	0%	6%	4%	5%	2%	0%
Simulation (1.2.4)	7	2.14%	4%	4%	6%	0%	2%	0%	0%

**Table 3:** Overview of applied methods in absolute and relative numbers

Table 4 gives an overview of the scenario and problem physical characteristics, extending the basic uncapacitated VRP, that have been considered most often in the reviewed articles. Again, percentages per publication year are presented as well. Clearly, most articles consider capacitated vehicles. Vehicles are rarely assumed uncapacitated, except in cases where one unit of demand is considered negligible in size (e.g., Ferrucci, Bock, & Gendreau, 2013). Moreover, vehicles are generally assumed to be identical. Load-specific or customer-specific vehicle types are not popular in recent literature (respectively 1.53% and 4.28%), although some authors have considered VRPs with multiple compartments (e.g., Lahyani, Coelho, Khemakhem, Laporte, & Semet, 2015; Mendoza, Castanier, Guéret, Medaglia, & Velasco, 2010, 2011). Time windows are considered in 37.92% of the articles. Most often these time windows are assumed to be strict (30.58%). Soft time windows have been considered as well (5.81%), while a mix of soft and strict time windows is rare (1.53%). These time windows are generally imposed on the visit time at customers (34.86%), while restrictions on depots and vehicles/drivers are considered less frequently (13.76% and 12.23%, respectively). Backhaul customers are considered in 18.65% of the articles, with almost even shares for the cases of nodes requesting simultaneous pickups and deliveries and nodes requesting either pickups or deliveries. Multiple depots are considered in 11.01% of the articles, while the different types of node covering constraints (category 2.9) appear in a slightly less than 10% of the articles. Other characteristics, such as multiple periods and splitting of requests, also appear in less than 10% of the surveyed articles.

Characteristic	Number of models	Relative presence							
		Overall	2009	2010	2011	2012	2013	2014	2015
Capacitated vehicles (3.7.1)	296	90.52%	91%	96%	91%	85%	88%	94%	87%
Heterogeneous vehicles (3.8.3)	54	16.51%	30%	11%	15%	13%	27%	9%	10%
Time windows (2.6)	124	37.92 %	28%	41%	44%	42%	43%	39%	23%
Backhauls (2.8)	61	18.65%	17%	22%	15%	10%	21%	11%	45%
Multiple depots (3.4.2)	36	11.01%	4%	4%	15%	13%	11%	14%	19%
Recourse allowed (2.9.3)	31	9.48%	7%	13%	15%	8%	5%	14%	3%
Multi-period time horizon (2.7.2)	29	8.87%	4%	11%	9%	13%	9%	6%	13%
Precedence and coupling constraints (2.9.1)	28	8.56%	7%	11%	6%	8%	13%	6%	10%
Subset covering constraints (2.9.2)	28	8.56%	2%	11%	12%	6%	9%	11%	10%
Split deliveries allowed (2.2.1)	20	6.12%	4%	9%	9%	0%	5%	5%	16%
Stochastic demands (2.3.2)	20	6.12%	4%	7%	12%	8%	5%	5%	3%
Unknown demands (2.3.3)	6	1.83%	2%	2%	0%	2%	4%	2%	0%
Time-dependent travel times (3.9.2)	10	3.06%	2%	4%	6%	6%	2%	2%	0%
Stochastic travel times (3.9.3)	9	2.75%	0%	2%	0%	2%	7%	5%	0%
Unknown travel times (3.9.4)	5	1.53%	2%	0%	6%	0%	2%	2%	0%
Dynamic requests (2.4)	8	2.45%	2%	2%	3%	4%	4%	0%	0%

**Table 4:** Overview of considered characteristics in absolute and relative numbers

A wide variety of objective functions is used in VRP literature, as is shown by the fact that almost one out of five articles (18.35%) considers a non-standard objective (category ‘3.10.6 Other’). The Cumulative VRP, for example, minimizes the sum of the arrival times at the customers (Ke & Feng, 2013; Lysgaard & Wøhlk, 2014; Mattos Ribeiro & Laporte, 2012; Ngueveu, Prins, & Wolfler Calvo, 2010). However, almost all articles include a routing cost (either based on distance or travel time) in the objective function (92.35%), while vehicle dependent costs are relatively common as well (38.23%).

With respect to information and data characteristics, problems with dynamic information (category 4.1.2) are modeled in 4.28% of the articles. Although the quality of information (category 4.2) is typically assumed to be deterministic in VRP literature (82.57%), several authors consider problems with stochastic or unknown (real-time) information (9.17% and 4.59%, respectively). Additionally, information is generally assumed to be available globally (89.30%) and processed centrally (96.64%). Finally, most authors use artificial data to test their solution methods (84.10%). Real-life data, or a combination of artificial and real-life data, are both used in 6.12% of the articles.

In general, results indicate that a large variety of VRP variants has been studied in the past years. We see a trend towards VRP variants that include real-life constraints and assumptions, which makes

the models more realistic and the solution approaches more applicable in practice. Given their importance in modeling real-life problems, we pay specific attention to the Open VRP, Dynamic VRP and Time-Dependent VRP in Section 5.3. Additionally, real-life settings such as cash transportation (Yan, Wang, & Wu, 2012), small package shipping (Stenger, Vigo, Enz, & Schwind, 2013), garbage collection (R. J. Kuo, Zulvia, & Suryadi, 2012) or social legislation for drivers' working hours (Goel, 2009; Kok, Meyer, Kopfer, & Schutten, 2010; Rancourt, Cordeau, & Laporte, 2013), have motivated researchers to develop specific mathematical formulations and solution methods. In fact, most authors still propose highly problem-tailored methods that are not applicable to other VRP variants, and in which parameters are manipulated to provide good performance for the given instance (or for benchmark instances). Consequently, many of the proposed solution methods cannot be easily applied to other problem settings or in real-life applications. In our classification, only a few articles (e.g., Cordeau & Maischberger, 2012; Subramanian, Uchoa, & Ochi, 2013; Vidal, Crainic, Gendreau, & Prins, 2013a, 2014a) propose a "general" algorithm that can solve multiple variants of the VRP. The parallel iterated tabu search metaheuristic in Cordeau & Maischberger (2012) is applicable to the classical VRP, PVRP, MDVRP, the site-dependent VRP and their variants with time windows. Subramanian et al. (2013) present a hybrid heuristic combining a set partitioning approach with an iterated local search heuristic which is applied to six different variants of the VRP. The genetic search algorithm in Vidal et al. (2013) can solve large scale VRPTW and extensions such as the periodic VRPTW, the multiple depot VRPTW, VRPTW with vehicle-site dependencies and their combinations, while the unified hybrid genetic search algorithm in Vidal et al. (2014) efficiently solves even up to 29 variants of the VRP. Next to further research on including (multiple) real-life assumptions in vehicle routing problems, the further development of such general solution approaches seems highly worthwhile.

## **5.2. Combinations of characteristics**

In this section, we present some insights on which characteristics often appear together, and which interesting combinations of characteristics have not yet been studied.

If stochastic information is considered, this is typically restricted to a single type of information, i.e., either stochastic demand quantities or stochastic travel times, not both. Such stochastic problems seem to be solved more often using exact methods or classical heuristics. Since it is hard to obtain stochastic information in real-life, almost solely artificial data is applied to test these methods. Additionally, stochastic problems more frequently consider only a single vehicle, probably due to problem complexity. In case of stochastic travel times, time windows appear more often (78%, compared to 38% on average). Typically these time windows are considered to be soft. In case of stochastic demand quantities, time windows appear less often (15%). For the latter problems, information is generally revealed locally (when arriving at the customer), and vehicles are assumed to travel back to the depot to be reloaded in case of route failures (recourse).

In problems in which information changes dynamically, other real-life aspects are often ignored, e.g., load splitting, multiple depots and heterogeneous vehicles never appear in dynamic problems, while backhauls are only considered in a single paper. Similar to problems with stochastic travel times, time windows are much more frequent (64% compared to 38% on average), and are more often assumed to be soft. Additionally, subset covering constraints are more common than on average (21% compared to 9%), since in many applications decisions makers may decline new requests in case they cannot be fulfilled (in a profitable way). Finally, no exact methods have been proposed for dynamic problems in the reviewed papers.

Backhauls are considered less than average in multi-vehicle and multi-period settings, and rarely in combination with dynamic or stochastic information. In case each customer requires either a linehaul or a backhaul service but not both, frequently precedence and coupling constraints are applied to indicate that linehaul customers should be visited before backhaul customers (57% compared to 9% on average). Precedence and coupling constraints itself, are also considered more often in single vehicle and single period problems, probably due to their complexity. In multiple period problems, multiple depots arise more frequently than on average, but vehicle capacities are taken into account less often. Finally, information is typically assumed to be deterministic in these multiple period problems.

In general, we observe that real-life characteristics are mostly considered either individually or with a limited number of other characteristics. Hence, many combinations of realistic characteristics are still unexplored. In order to make vehicle routing models even more realistic and readily applicable in practice, future research could focus on even ‘richer’ problems. Multiple real-life characteristics could be considered simultaneously, and efficient solution methods to solve these problems could be developed.

### **5.3. Specific problems**

In the following paragraphs, we further zoom in on three specific variants of the VRP which model real-life aspects and which started to receive more research attention in recent years: the Open VRP, the Dynamic VRP and the Time-Dependent VRP. We expect these variants to become even more popular in the coming years.

#### **5.3.1. Open VRP (OVRP)**

In the Open VRP (OVRP) vehicles are not required to return to the central depot after visiting the last customer. If they do return, they must visit the same customers in the reverse order. Additionally, the OVRP often has two optimization objectives: minimizing the number of vehicles used and (given this number of vehicles) minimizing the total distance (or sometimes time) travelled (e.g., Fleszar, Osman, & Hindi, 2009; MirHassani & Abolghasemi, 2011; Subramanian et al., 2013; Zachariadis & Kiranoudis, 2010b), although some exceptions exist (e.g., Cao, Lai, & Yang, 2014; Norouzi,

Tavakkoli-Moghaddam, Ghazanfari, Alinaghian, & Salamatbakhsh, 2012). In practice, the OVRP occurs when the vehicle fleet is not owned by the company itself or when the available vehicle fleet is unable to satisfy the demand of its customers, such that (part of) the distribution activities is contracted to a third party logistics (3PL) provider (Repoussis, Tarantilis, Bräysy, & Ioannou, 2010). The OVRP solution then indicates the amount of vehicles that is needed. In addition, the OVRP might be used in case of pick-up and delivery, when after delivering goods to given customers, the vehicles pick up goods from the same customers, but in reverse order (Salari, Toth, & Tramontani, 2010). In real-life the OVRP occurs for instance with home delivery of packages and newspapers (Repoussis et al., 2010), school bus routing (López-Sánchez, Hernández-Díaz, Vigo, Caballero, & Molina, 2014; Salari et al., 2010), routing of coal mines material (S. Yu, Ding, & Zhu, 2011) or shipment of hazardous materials (R. Liu & Jiang, 2012).

Thirteen of the classified articles that have OVRP as (main) subject. Overall, all articles include capacity constraints for the vehicles. Additionally, more than half of the articles include distance (or time) constraints. All articles, except for one (X. Li, Leung, & Tian, 2012), assume a homogeneous fleet of vehicles and all but two (Cao et al., 2014; Cao & Lai, 2010) assume deterministic demands. All proposed solution methods are metaheuristics, except for one (Salari et al., 2010), and all but one (S. Yu et al., 2011) are tested on benchmark instances, either gathered from literature or generated by the authors. López-Sánchez et al. (2014) test their metaheuristic both on benchmark instances and on real data.

### 5.3.2. Dynamic VRP (DVRP)

The evolution of real-time technologies, such as Intelligent Transformation Systems (ITS), Advanced Fleet Management Systems (AFMS) and Global Positioning Systems (GPS), has made dynamic VRPs a relatively hot topic in recent years (Psaraftis, 1995): 14 (4.28%) of the classified articles discuss a DVRP. In a DVRP (also referred to as online or real-time VRP), the inputs are revealed or updated continuously. Based on these new inputs, vehicle routes are then adapted dynamically. A comprehensive review of the DVRP was recently presented by Pillac et al. (2013).

Dynamism is mostly considered with respect to customer requests. New requests are assumed to arrive in problems studied by e.g., Barkaoui & Gendreau (2013); Hong (2012); Khouadjia, Sarasola, Alba, Jourdan, & Talbi (2012); Lorini, Potvin, & Zufferey (2011); Wen, Cordeau, Laporte, & Larsen (2010). Mostly no information about future requests is assumed, although stochastic information (Albareda-Sambola, Fernández, & Laporte, 2014) or forecasts (Ferrucci et al., 2013) may be available. Pillac, Guéret, & Medaglia (2012) consider dynamic routing decisions as a consequence of actual demand only being revealed when arriving at the customers (although stochastic information is known beforehand). Dynamic travel times are considered by e.g., T.-Y. Liao & Hu (2011).

Strikingly, no standard problem definitions or formulations are available for dynamic VRPs (Hong, 2012; Psaraftis, 1995). Additionally, to the authors' knowledge, no benchmark instances are available to test and compare the proposed solution methods objectively.

### 5.3.3. Time Dependent VRP (TDVRP)

Most VRPs assume that the travel times between depots and customers are deterministic and constant (e.g., Kok et al., 2010) or equal to the distance between customers (e.g., Lei, Laporte, & Guo, 2011; X. Li et al., 2012). In real life, variable travel times (due to congestion) are prevalent. The TDVRP assumes that the travel times are deterministic but no longer constant, i.e., they are a function of current time. As such, the effects of congestion on the total route duration, the number of vehicles and transportation cost can be determined.

All ten TDVRP articles in our classification (see electronic Appendix) satisfy the non-passing property, also known as the First-In First-Out (FIFO) property (Ichoua, Gendreau, & Potvin, 2003), which states that a vehicle that leaves earlier from some customer will arrive earlier at its destination. The time-dependent travel times are generally modelled following the example of Ichoua et al. (2003), where the workday is partitioned into several periods and a constant travel speed is assigned to each time interval, resulting in speed being a step function of the departure time for all the arcs. The higher the number of time intervals, the more realistic the model will be, because the travel speeds will change more gradually (Kok, Hans, & Schutten, 2012). The travel time between two customers is then dependent on the departure time from the first customer and the time-dependent speed on the associated arc between the two customers.

Six TDVRP articles in our classification assume time windows. Most of these time windows are strict (4 articles) and restrict the time of service at the customers. All TDVRP are deterministic except for the variant proposed by Lorini et al. (2011), who also take unforeseen events into account. All articles address single period problems with a single depot. Dabia et al. (2013) are the only authors to solve the TDVRP with time windows using an exact method. Their branch-and-price method was tested on the Solomon instances with speeds derived from real life.

## 6. Conclusions

This paper classifies 277 VRP articles published between 2009 and mid-2015 according to an adapted taxonomy based on Eksioglu et al. (2009). The resulting classification table (in electronic Appendix) enables future researchers to find relevant literature by eliminating or selecting characteristics in the taxonomy, leaving only articles tailored to their interests. Additionally, the classification allowed to analyze which characteristics and combinations of characteristics are most popular.

Results indicate that the vehicle routing literature consists of a broad range of problem variants. Researchers pay more and more attention to VRP variants that include real-life characteristics and assumptions, thereby making their models more realistic and their solution approaches more applicable in practice. However, real-life characteristics are often considered either individually or with a limited number of other characteristics. Future research could therefore focus on even ‘richer’ problems by simultaneously considering multiple real-life characteristics, and developing efficient solution methods to solve these problems. On the other hand, many researchers still propose highly problem-tailored solution methods which are not directly applicable to other problem variants. In our classification, only a few articles propose more general algorithms which can solve multiple variants. The further development of such general solution approaches seems highly worthwhile.

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## Appendix A: Overview of classified literature per year

Year of publication	References	Number of articles per year
2015	Allahyari, Salari, & Vigo (2015); Avci & Topaloglu (2015); Bertazzi, Golden, & Wang (2015); Dayarian, Crainic, Gendreau, & Rei (2015a, 2015b); Garcia-Najera & Bullinaria (2011); Z.-H. Hu, Sheu, Zhao, & Lu (2015); J. Janssens, Van den Bergh, Sörensen, & Cattrysse (2015); Lahyani, Coelho, Khemakhem, Laporte, & Semet (2015); Lahyani, Khemakhem, et al. (2015); J. Li, Pardalos, Sun, Pei, &	23

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- Zhang (2015); Z. Luo, Qin, Che, & Lim (2015); McNabb, Weir, Hill, & Hall (2015); Montoya-Torres et al. (2015); Mouthuy, Massen, Deville, & Van Hentenryck (2015); Nagy, Wassan, Speranza, & Archetti (2015); Polat, Kalayci, Kulak, & Günther (2015); Rahimi-Vahed, Crainic, Gendreau, & Rei (2015); Silva, Subramanian, & Ochi (2015); Tang, Yu, & Li (2015); Vidal, Battarra, Subramanian, & Erdogan (2015); C. Wang, Mu, Zhao, & Sutherland (2015); Zachariadis, Tarantilis, & Kiranoudis (2015)
- 2014 Abdallah & Jang (2014); Albareda-Sambola, Fernández, & Laporte (2014); Allahviranloo, Chow, & Recker (2014); Amorim & Almada-Lobo (2014); Archetti, Bianchessi, & Speranza (2014); Azi, Gendreau, & Potvin (2014); Maria Battarra, Erdoğan, & Vigo (2014); Belhaiza, Hansen, & Laporte (2014); Bhusiri, Qureshi, & Taniguchi (2014); Cacchiani, Hemmelmayr, & Tricoire, (2014); Cao et al. (2014); Cattaruzza, Absi, Feillet, & Vidal (2014); Cattaruzza, Absi, Feillet, & Vigo (2014); Q. Chen, Li, & Liu (2014); Chiang & Hsu (2014); Ćirović, Pamučar, & Božanić (2014); Demir, Bektaş, & Laporte (2014); Á. Felipe, Ortuño, Righini, & Tirado (2014); Gauvin, Desaulniers, & Gendreau (2014); Hà, Bostel, Langevin, & Rousseau (2014); Han, Lee, & Park (2014); Jiang, Ng, Poh, & Teo (2014); Jin, Crainic, & Løkketangen (2014); A. A. Juan, Faulin, Caceres-Cruz, Barrios, & Martinez (2014); Krichen, Faiz, Tlili, & Tej, (2014); Küçükoğlu & Öztürk (2014); Letchford, Nasiri, & Oukil (2014); C. Lin et al. (2014); López-Sánchez et al. (2014); J. Luo & Chen (2014); Lysgaard & Wøhlk (2014); Michallet, Prins, Amodeo, Yalaoui, & Vitry (2014); Morais, Mateus, & Noronha (2014); Muter, Cordeau, & Laporte (2014); Palhazi Cuervo, Goos, Sörensen, & Arráiz (2014); Prins, Lacomme, & Prodhon (2014); Salhi, Imran, & Wassan (2014); Schneider, Stenger, & Goeke (2014); Taş, Dellaert, van Woensel, & de Kok (2014); Taş, Gendreau, et al. (2014); Taş, Jabali, & Van Woensel (2014); Tu, Fang, Li, Shaw, & Chen (2014); Vidal et al. (2014a); Vidal, Crainic, Gendreau, & Prins (2014b); M. Yu & Qi (2014); S. Zhang, Lee, Choy, Ho, & Ip (2014); Zhu, Rousseau, Rei, & Li (2014) 47
- 2013 Agra et al. (2013); Almoustafa, Hanafi, & Mladenovic (2013); Avella, Boccia, & Vasilyev (2013); Baños, Ortega, Gil, Fernández, & de Toro (2013); Baños, Ortega, Gil, Márquez, & de Toro (2013); Barkaoui & Gendreau (2013); Belfiore & Yoshizaki (2013); Dabia et al. (2013); Derigs, Pullmann, & Vogel (2013a, 2013b); Drexl (2013); Ferrucci et al. (2013); Fleming, Griffis, & Bell (2013); Goksal, Karaoglan, & Altıparmak (2013); Gounaris, Wiesemann, & Floudas (2013); X. Hu et al. (2013); Ke & Feng (2013); Kergosien, Lenté, Billaut, & Perrin (2013); Kwon, Choi, & Lee (2013); Leung, Zhang, Zhang, Hua, & Lim (2013); R. Liu, Xie, Augusto, & Rodriguez (2013); S. Liu (2013); Marinakis et al. (2013); Nguyen, Crainic, & Toulouse (2013); Osaba, Carballedo, Diaz, & Perallos (2013); Pandelis, Karamatsoukis, & Kyriakidis (2013); Penna, Subramanian, & Ochi (2013); Pillac et al. (2013); Pop, Matei, & Sitar (2013); Pradenas et al. (2013); Rancourt et al. (2013); Salhi, Wassan, & Hajararat (2013); Schneider, Sand, & Stenger (2013); Sörensen & Schittekat (2013); Stenger et al. (2013); Subramanian et al. (2013); Tang, Ma, Guan, & Yan (2013); Tarantilis, Anagnostopoulou, & Repoussis (2013); Taş, Dellaert, van Woensel, & de Kok (2013); Vidal et al. (2013a); Vidal, Crainic, Gendreau, & Prins (2013b); Villegas, Prins, Prodhon, Medaglia, & Velasco (2013); Wy, Kim, & Kim (2013); Wy & Kim (2013); Xiao & Lo (2013); Yao, Hu, Zhang, & Wang (2013); Zachariadis, Tarantilis, & Kiranoudis (2013); J. Zhang, Lam, & Chen (2013); Z. Zhang, Che, Cheang, Lim, & Qin (2013) 49
- 2012 Anbuudayasankar, Ganesh, Lenny Koh, & Ducq (2012); Archetti & Speranza (2012); Baldacci, Mingozzi, & Roberti (2012); Chardy & Klopfenstein (2012); X. Chen, Feng, & Soon Ong (2012); Cordeau & Maischberger (2012); Demir, Bektaş, & Laporte (2012); Drexl (2012b); Erdoğan & Miller-Hooks (2012); Figliozzi (2012); Goodson, Ohlmann, & Thomas (2012); Hong (2012); Jabali, Van Woensel, & de Kok (2012); Jin, Crainic, & Løkketangen (2012); Khouadjia et al. (2012); Kok et al. (2012); Y. Kuo & Wang (2012); X. Li et al. (2012); R. 41

- Liu & Jiang (2012); Lu & Yu (2012); Ma, Cheang, Lim, Zhang, & Zhu (2012); Marinakis (2012); Mattos Ribeiro & Laporte (2012); Moghaddam, Ruiz, & Sadjadi (2012); Moon, Lee, & Seong (2012); Nazif & Lee (2012); Norouzi et al. (2012); Pandelis, Kyriakidis, & Dimitrakos (2012); Pillac et al. (2012); Pureza et al. (2012); Qi, Lin, Li, & Miao (2012); Rasmussen, Justesen, Dohn, & Larsen (2012); Rodríguez & Ruiz (2012); Subramanian, Penna, Uchoa, & Ochi (2012); Tarantilis, Stavropoulou, & Repoussis (2012); Tasan & Gen (2012); Vidal, Crainic, Gendreau, Lahrichi, & Rei (2012); Yan et al. (2012); Zachariadis & Kiranoudis (2012); T. Zhang, Chaovalitwongse, & Zhang (2012); Z. Zhang, Qin, Zhu, & Lim (2012)
- 2011 Alabas-Uslu & Dengiz (2011); Aras, Aksen, & Tuğrul Tekin (2011); Archetti, Bouchard, & Desaulniers (2011); Baldacci, Bartolini, Mingozzi, & Valletta (2011); Baldacci, Mingozzi, & Roberti (2011); Balseiro, Loiseau, & Ramonet (2011); Bektaş, Erdogan, & Ropke (2011); Bektaş & Laporte (2011); Bettinelli, Ceselli, & Righini (2011); Brandão (2011); Felipe, Ortuño, & Tirado (2011); Garcia-Najera & Bullinaria (2011); Gulczynski, Golden, & Wasil (2011a); Gulczynski et al. (2011b); A. Juan et al. (2011); Lei et al. (2011); T.-Y. Liao & Hu (2011); C. K. Y. Lin (2011); Lorini et al. (2011); Macedo, Alves, Valério de Carvalho, Clautiaux, & Hanafi (2011); Mendoza et al. (2011); Minis & Tatarakis (2011); MirHassani & Abolghasemi (2011); Pang (2011); Salani & Vacca (2011); Santos, Coutinho-Rodrigues, & Antunes (2011); Szeto, Wu, & Ho (2011); Valle, Martinez, da Cunha, & Mateus (2011); Villegas, Prins, Prodhon, Medaglia, & Velasco (2011); Xu, Yan, & Li (2011); B Yu, Yang, & Xie (2011); Bin Yu, Yang, & Yao (2011); Bin Yu & Yang (2011); S. Yu et al. (2011); Yücenur & Demirel (2011)
- 2010 Azi, Gendreau, & Potvin (2010); Baldacci, Toth, & Vigo (2010); Benjamin & Beasley (2010); Bolduc, Laporte, Renaud, & Boctor (2010); Cao & Lai (2010); Çatay (2010); P. Chen, Huang, & Dong (2010); Cortés, Matamala, & Contardo (2010); Desaulniers (2010); Erera, Morales, & Savelsbergh (2010); Figliozzi (2010); Ghoseiri & Ghannadpour (2010); Gulczynski, Golden, & Wasil (2010); Gutiérrez-Jarpa, Desaulniers, Laporte, & Marianov (2010); Kok et al. (2010); Y. Kuo (2010); X. Li, Tian, & Aneja (2010); X. Li, Tian, & Leung (2010); R. Liu, Jiang, Fung, Chen, & Liu (2010); Lysgaard (2010); Maden, Eglese, & Black (2010); Marinakis, Marinaki, & Dounias (2010); Marinakis & Marinaki (2010); Mendoza et al. (2010); Müller (2010); Muyldermans & Pang (2010); Nagata, Bräysy, & Dullaert (2010); Ngueveu et al. (2010); Prescott-Gagnon, Desaulniers, Drexler, & Rousseau (2010); Rei, Gendreau, & Soriano (2010); Ren, Dessouky, & Ordóñez (2010); Repoussis et al. (2010); Repoussis & Tarantilis (2010); Salari et al. (2010); Subramanian, Drummond, Bentes, Ochi, & Farias (2010); Tang, Zhang, & Pan (2010); Wen et al. (2010); Yazgı Tütüncü (2010); Yurtkuran & Emel (2010); Zachariadis & Kiranoudis (2010a, 2010b); Zachariadis, Tarantilis, & Kiranoudis (2010)
- 2009 Ai & Kachitvichyanukul (2009a, 2009b); Baldacci & Mingozzi (2009); M. Battarra, Monaci, & Vigo (2009); Belfiore & Yoshizaki (2009); Brandão (2009); Bräysy, Porkka, Dullaert, Repoussis, & Tarantilis (2009); Ceselli, Righini, & Salani (2009); Cheng & Wang (2009); Eksioglu et al. (2009); Figliozzi (2009); Fleszar et al. (2009); Gajpal & Abad (2009a, 2009b); Goel (2009); Groër, Golden, & Wasil (2009); Hemmelmayr, Doerner, & Hartl (2009); Hoff, Gribkovskaia, Laporte, & Løkketangen (2009); Imran, Salhi, & Wassan (2009); G. K. Janssens et al. (2009); Jozefowicz, Semet, & Talbi (2009); Karlaftis, Kepaptsoglou, & Sambracos (2009); Kim, Yang, & Lee (2009); Y. Kuo et al. (2009); Laporte (2009); S.-W. Lin, Lee, Ying, & Lee (2009); S.-W. Lin, Yu, & Chou (2009); S. Liu, Huang, & Ma (2009); Mendoza, Medaglia, & Velasco (2009); Moretti Branchini et al. (2009); Novoa & Storer (2009); Prescott-Gagnon, Desaulniers, & Rousseau (2009); Prins (2009); Qureshi, Taniguchi, & Yamada (2009); Ropke & Cordeau (2009); Secomandi & Margot (2009); C.-H. Wang & Lu (2009); Yazgı Tütüncü, Carreto, & Baker (2009); Bin Yu, Yang, & Yao

(2009); Zachariadis, Tarantilis, & Kiranoudis (2009)

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**Table A.1:** Overview of classified literature per year