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Invited Review

Rich vehicle routing problems: From a taxonomy to a definition

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ABSTRACT

Over the last years, several variants of multi-constrained Vehicle Routing Problems (VRPs) have been studied, forming a class of problems known as Rich Vehicle Routing Problems (RVRPs). The purpose of the paper is twofold: (i) to provide a comprehensive and relevant taxonomy for the RVRP literature and (ii) to propose an elaborate definition of RVRPs. To this end, selected papers addressing various cases are classified using the proposed taxonomy. Once the articles have been classified, a cluster analysis based on two discriminating criteria is performed and leads to the definition of RVRPs.

1. Introduction

The Vehicle Routing Problem (VRP), introduced by Dantzig and Ramser (1959), is a central problem in operations research applied to transportation sciences. Over the last three decades, the number of academic publications on the numerous variants of the VRP has increased extensively (see Eksioglu, Vural, & Reisman, 2009). These studies can be roughly divided into theoretical papers providing mathematical formulations and exact or approximate solution methods for academic problems and case-oriented papers. Several taxonomies and surveys devoted to the VRP have appeared, *e.g.*, Bodin (1975), Bodin and Golden (1981), Desrochers, Lenstra, and Savelsbergh (1990), and Laporte and Osman (1995) who provided a bibliography of 500 studies. More recently, Laporte (2009) reported on the last fifty years of academic vehicle routing from a historical perspective and Eksioglu et al. (2009) presented a taxonomy for the VRP literature. Many books or book chapters have been devoted to the VRP, its variants, and to exact and heuristic algorithms, see, *e.g.*, Toth and Vigo (2002a), Cordeau, Laporte, Savelsbergh, and Vigo (2007), and Golden, Raghavan, and Wasil (2008).

The most elementary VRP considered in the literature is the so-called *Capacitated* Vehicle Routing Problem (CVRP). Geographically scattered customers have demands for a homogeneous product. They have to be served by identical vehicles with a limited capacity based at one depot. The CVRP aims to determine a set of vehicles routes of minimum total cost over a single period such that: (i) each route starts and ends at the depot; (ii) each customer is served by only one vehicle; and (iii) the total demand on each route does not exceed the vehicle capacity. Most papers devoted to classical problems focus on idealized models and are motivated by unsolved theoretical problems. Nevertheless, in recent years methodological progress and the development of computer technologies has led to an increasing academic attention to new variants including more complex constraints and objectives. This trend is stimulated by the complex characteristics of real-life VRPs. The families of these extended problems are often called Rich Vehicle Routing Problems (RVRPs). Several works focusing on RVRPs have been published. In particular, two special issues were dedicated to works on rich combinatorial optimization problems (Hartl, Hasle, & Janssens, 2006; Hasle, Løkketangen, & Martello, 2006). Papers by Sörensen, Sevaux, and Schittekat (2008) and by Drexl (2012a) compare the VRPs in academic research versus the VRPs in the real-life and delineate the complexity of real-life VRPs. Based on identified gaps, they emphasize on the necessity of adapting commercial software systems to the evolution of customer needs, and of incorporating more intricate constraints. Doerner and Schmid (2010) present a survey devoted to hybrid math-heuristics for RVRPs and identify promising future avenues.

In most papers devoted to RVRPs, the authors claim that the problem addressed is rich, and then focus on the mathematical modeling and on the solution methods. Thus, the definitions of the RVRP are rather vague and not significantly different. For instance, Pellegrini (2005), Cruz Reyes et al. (2008), Rieck and Zimmermann (2010) and Drexl (2012a) suggest that the term rich vehicle routing is associated with problems that represent some or all aspects of a real-world application including optimization criteria, constraints, and preferences. Recently, some attempts have been made to propose unified models and algorithms tackling different classes of routing problems, see *e.g.* Røpke and Pisinger

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(2006), Subramanian, Uchoa, and Ochi (2011), Derigs and Vogel (2014) and Vidal, Crainic, Gendreau, and Prins (2013, 2014).

There is no precise definition either criterion which leads to determine whether or not a VRP is rich. Such definition has to rely on a relevant taxonomy which can help to distinguish among the numerous variants of the VRP. Therefore, the objective of this paper is twofold: (i) to provide a generic taxonomy for the RVRP literature with respect to relevant real-life issues and (ii) to propose a discriminating definition of the RVRP.

The remainder of this paper is organized as follows. Section 2 describes the taxonomy and introduces the key characteristics considered when it was built. Definitions of the hierarchical taxonomy attributes are provided. In Section 3, we survey several papers describing practical cases and addressing different issues related to RVRPs. They are classified on the basis of the taxonomy attributes. A cluster analysis of the selected papers is provided and discussed. Last, a RVRP definition is proposed. Section 4 concludes this paper by discussing some future research avenues.

2. RVRP taxonomy

Creating taxonomy is an efficient and effective way of consolidating knowledge (Reisman, 1992). It enables not only efficient and effective storage, sorting, and statistical analyses but also knowledge expansion and building (Eksioglu et al., 2009). Several surveys and classifications of the VRP have been used as guidelines for the RVRP taxonomy developed in this work. This taxonomy aims to build a relevant framework to classify any RVRP study without going into unnecessary details. It attempts also to highlight the different facets of richness encountered in the literature, and to distinguish RVRPs from standard VRPs.

To "validate" this taxonomy, we have selected papers devoted to RVRPs published since 2006. Real-life and academic works using as benchmarks randomly generated instances or real data have been considered. Surveys or theoretical articles without testbed have been omitted. Only papers devoted to node routing problems for road transportation have been retained. More than a half of them are based on real-life applications. We also have paid attention to take papers emanating from different countries. Indeed, each country has its geographical and political specificities and its own industrial practices. This may lead to introduce specific constraints on the routing plan. As a result, 41 papers published in different journals and conferences are examined attempting to be as exhaustive as possible. However, we apologize for any unintended omission of some relevant articles.

2.1. Taxonomy

In this section, we focus on the description of the taxonomy (see Table 1) and on the presentation of its main attributes. The taxonomy was iteratively built, due to the complexity of the distribution planning process. The taxonomy does not intend to highlight all differences between variants of the VRP in order to maintain its comprehensibility and its size. It is instead designed according to central concepts in routing that are often present in industrial applications. More precisely, the attributes mentioned are not necessarily the basic VRP features but are related to characteristics which alter the nature of the problem significantly. The purpose of the taxonomy is not to classify the papers according to all the details but rather to focus on relevant features. Indeed, we face the following dilemma. The omission of relevant variants of problems studied in the literature introduces some bias in the classification. Similarly, deepening the level of details may lead to an unmanageable taxonomy. Hence, we try to maintain a moderate level of granularity for the proposed RVRP taxonomy.

The taxonomy is constructed hierarchically with at most four subclasses. Problems are considered according to the Scenario Characteristics (SCs) and to the Problem Physical Characteristics (PPCs). Under each of these two classes, the most discriminating attributes are listed. They determine whether or not the problem under study can be classified as rich. The taxonomy is organized in an arborescent way with three levels associated with the *strategic* level, the *tactical* level and the *operational* level. Each of them is divided into sublevels. The difference between the three levels depends on the types of decision involved. The strategic and tactical levels are associated with the first branch of the taxonomy, *i.e.* the SCs. They correspond to the transportation strategy which describes the distribution system and designs its main components. At the strategic level, the company has to decide if the operational plan deals simultaneously with decisions related to different functions of the supply chain or if transportation planning issues are addressed. For instance, the strategic planning could include decisions related to the locations and the number of depots used. At the tactical level, the order type and the visit frequencies at customers over a given time horizon could be considered. The multi-use of vehicles or the data type leads to other extensions. Although these decisions are not related to daily transport activities, they affect the routing plan significantly.

The operational level is associated with the PPCs. It describes the distribution planning including the vehicle and the driver schedules. At this level, short-term and daily decisions are handled considering each vehicle route. These decisions relate to the routing of goods using the distribution system designed at the strategic and tactical levels. These decisions are based on the characteristics of vehicles, and on specific constraints faced daily. These constraints are specified for a customer, a vehicle, a driver or a road.

2.1.1. Scenario characteristics

In this section, we describe the sublevels of the strategic and tactical levels presented in Table 1. We briefly define the characteristics of each sublevel and provide some relevant references.

2.1.1.1. Input data. The uncertainty and the variability of the data over the planning period are key factors for a classification of VRPs. Data can be subdivided into four classes: *deterministic, stochastic, static and dynamic.*

The *deterministic* routing problem assumes that the problem parameters are known with certainty while the *stochastic* data assumes that probability distributions are associated with them. In the *Stochastic* Vehicle Routing Problem (SVRP), the routes may not be followed as planned. The three most common stochastic parameters studied in the literature are: customers demands, service times and travel times (Hasle & Kloster, 2007). We refer to Gendreau, Laporte, and Séguin (1996), Flatberg, Hasle, Kloster, Nilssen, and Riise (2005), Cordeau et al. (2007), Louveaux and Laporte (2009) and Ritzinger and Puchinger (2013) for focused surveys.

A seminal work on the *Dynamic* Vehicle Routing problem (DVRP) is due to Psaraftis (1988). In the DVRP, the scheduling plan established at the beginning of the planning period may be adjusted. It allows the possibility of receiving additional information and changing some problems parameters. Then, the problem is solved repeatedly. For example, new customer requests may occur during the planning period and must be considered while the vehicles routes are being executed. For recent literature reviews, we refer to Psaraftis (1995), Powell, Shapiro, and Simão (2001), Malca and Semet (2006), Powell, Bouzaiene, and Simão (2007), Larsen, Madsen, and Solomon (2008), Berbeglia, Cordeau, and Laporte (2010), and Pillac, Gendreau, Guéret, and Medaglia (2013).

Table 1
A Taxonomy of RVRP.

1 Scenario characteristics	2 Problem physical characteristics
1.1 Input data	2.1 Vehicles
1.1.1 Static	2.1.1 Type
1.1.2 Dynamic	2.1.1.1 Homogeneous
1.1.3 Deterministic	2.1.1.2 Heterogeneous
1.1.4 Stochastic	2.1.2 Number
1.2 Decision management components	2.1.2.1 Fixed
1.2.1 Routing	2.1.2.2 Unlimited
1.2.2 Inventory and routing	2.1.3 Structure
1.2.3 Location and routing	2.1.3.1 Compartmentalized
1.2.4 Routing and driver scheduling	2.1.3.2 Not compartmentalized
1.2.5 Production and distribution planning	2.1.4 Capacity constraints
1.3 Number of depots	2.1.5 Loading Policy
1.3.1 Single	2.1.5.1 Chronological order
1.3.2 Multiple	2.1.5.2 No policy
1.4 Operation type	2.1.6 Drivers regulations
1.4.1 Pickup or delivery	2.2 Time constraints
1.4.2 Pickup and delivery	2.2.1 Restriction on customer
1.4.3 Backhauls	2.2.2 Restriction on road access
1.4.4 Dial-a-ride	2.2.3 Restriction on depot
1.5 Load splitting constraints	2.2.4 Service time
1.5.1 Splitting allowed	2.2.5 Waiting time
1.5.2 Splitting not allowed	2.3 Time window structure
1.6 Planning period	2.3.1 Single time window
1.6.1 Single period	2.3.2 Multiple time windows
1.6.2 Multi-period	2.4 Incompatibility constraints
1.7 Multiple use of vehicles	2.5 Specific constraints
1.7.1 Single trip	2.6 Objective function
1.7.2 Multi-trip	2.6.1 Single objective
	2.6.2 Multiple objectives

2.1.1.2. Decision management components. Supply chain management is a set of approaches utilized to integrate efficiently customers, manufacturers, warehouses and stores. It ensures producing the products and distributing them at the right quantities, to the right location and at the right time in order to minimize system wide costs while satisfying service level requirements (Simchi, Kaminsky, & Simchi, 2003). Hence, integrating decisions of different functions such as purchasing, inventory control, outsourcing, locating depots, production planning, and distribution management are a practice increasingly followed by many companies (Armentano, Shiguemoto, & Løkketangen, 2011). Nevertheless, the complexity of these functions may inhibit defining and solving a complete model including all decision variables. The related extensions of the VRP in the literature are inventory-routing, location-routing, production-routing and vehicle and driver scheduling. Schmid, Doerner, and Laporte (2013) propose an elaborated survey on relevant extensions of routing problems arising in the context of supply chain management. The authors describe a new family of integrated models considering the interdependencies between different types of decisions.

The *service type decision* is a strategic level of decision. Going back to the paper by Dantzig, Fulkerson, and Johnson (1954), each customer has to be served once and only once. However, profits may be associated with the customer service. In such cases, a subset of served customers must be determined to maximize an objective function which includes the total profit collected. This VRP variant is known as the VRP with profits, see Feillet, Dejax, and Gendreau (2005).

Boudia, Louly, and Prins (2007) states that, ideally, any cost reduction effort should encompass a production planning. First introduced by Glover, Jones, Kamey, Klingman, and Mote (1979), *production and distribution planning* aims to determine the quantity produced for each item, the distribution plans and the quantities of each item delivered to each customer. This variant was reviewed by Vidal and Goetschalckx (1997), Sarmiento and Nagi (1999), Chen (2004) and Adulyasak, Cordeau, and Jans (2013) while recent works are those of Chandra and Fisher (1994), Armentano et al. (2011) and Adulyasak, Cordeau, and Jans (2012).

In *Inventory Routing* Problems (IRP), the supplier defines, in addition to the routing plans, the quantities to deliver using inventory levels at consumers to avoid stock shortages. Fisher, Greenfield, Jaikumar, and Kedia (1982) and Bell et al. (1983) pioneered this variant when they studied the IRP at Air Products, a producer of industrial gases. Elaborate surveys are provided by Campbell, Clarke, Kleywegt, and Savelsbergh (1998), Cordeau et al. (2007) and Bertazzi, Savelsbergh, and Speranza (2008). Andersson, Hoff, Christiansen, Hasle, and Løkketangen (2010a) also describe industrial aspects of combined inventory management and routing in maritime and road transportation. They propose a classification and a comprehensive literature review of the current state of the research. Coelho, Cordeau, and Laporte (2014) describe this research area over the last thirty years. They categorize the IRP literature with respect to the structure of the problem and to the availability of information on customer demand. When production management, inventory management and transportation management are combined, the objective is to determine the quantities produced, the quantities delivered to customers and the vehicle schedules while minimizing the total costs. These costs include setup costs, holding costs and distribution costs. Some relevant references are Fumero and Vercellis (1999), Boudia et al. (2007), Boudia and Prins (2009), Bard and Nananukul (2009), Coelho, Cordeau, and Laporte (2011, 2012), Coelho (2013) and Coelho and Laporte (2013a, 2013b, 2014).

The *Location Routing* Problem (LRP) aims to determine the location of depots serving customers and the routes rooted at those depots simultaneously. Surveys on the LRP have been proposed by Balakrishnan, Ward, and Wong (1987), Laporte (1988, 1989), Berman, Jaillet, and Simchi-Levi (1995), Min, Jayaraman, and Srivastava (1998) and by Nagy and Salhi (2007).

The simultaneous determination of the *vehicle and driver schedules* represents a significant trend in transportation management. It implies to elaborate a crew assignment and the associated routes concurrently. The literature devoted to this challenging variant is scarce (Wen, Krapper, Larsen, & Stidsen, 2011). Nevertheless, recent papers have been published *e.g.*, Haase, Desaulniers, and Desrosiers (2001), Freling, Huisman, and Wagelmans (2003), Xu, Chen, Rajagopal, and Arunapuram (2003), Goel (2009), Zäpfel and Bögl (2008) and Wen et al. (2011). Note that the regulation of working hours can be modeled as additional constraints (see the section dedicated to driver regulations).

2.1.1.3. Depots. In the classic VRP, a *single depot* is in use which may be quite restrictive in practice. Thus, in real-life applications, there are often *multiple depots* and vehicles may have different starting and final locations. It may be required to allocate the customers to the appropriate depot. The depots may have different characteristics, regarding of their number, locations and capacities, which may affect the overall costs. Over the last four decades, many papers studied the multi-depots vehicle routing problem, for instance, Tillman (1969), Laporte, Nobert, and Arpin (1984), Laporte, Nobert, and Taillefer (1988), Salhi, Thangiah, and Rahman (1998), Surekha and Sumathi (2011), Vidal, Crainic, Gendreau, Lahrichi, and Rei (2012), Hemmelmayr, Doerner, Hartl, and Rath (2013), Rahimi-Vahed, Crainic, Gendreau, and Rei (2013), and Muter, Cordeau, and Laporte (2014).

2.1.1.4. Operation type. Four classes of routing problems can be distinguished: problems where goods are either delivered or picked-up, problems where goods are loaded and unloaded, problems where goods are loaded on board when the delivery part of the route is completed, and last dial-a-ride problems. The first class corresponds to the classical VRP. The goods are loaded at the depot and then unloaded at customer locations, or pickup tasks are performed at the customer sites and the unloading at the depot. The second class, where goods are transported between pickup and delivery locations, is named Vehicle Routing Problems *with Pickups and Deliveries* (VRPPD). In the VRPPD, goods can be loaded or unloaded at each customer. In the standard case, the pickup point and the delivery point must be served on the same route. There are many possible extensions to the VRPPD. The VRPPD was divided into other subclasses in Parragh, Doerner, and Hartl (2008b). A survey on this research area is due to Desaulniers, Desrosiers, Erdmann, Solomon, and Soumis (2002).

The Vehicle Routing Problems with *Backhauls* (VRPB) was introduced by Goetschalckx and Jacobs (1989). It consists in transporting goods from the depot to linehaul customers and from backhaul customers to the depot. The VRPB arises in various applications like in the grocery industry where supermarkets and shops are considered as the linehaul customers, and grocery suppliers are the backhaul customers (Toth & Vigo, 2002b). Four subtypes of the VRPB were considered and detailed in Parragh, Doerner, and Hartl (2008a).

The *Dial-A-Ride* Problem (DARP) refers to the situation where a shipment has to be transported between prespecified pickup and delivery locations under service restrictions. The DARP arises frequently in health related transportation like patient transportation or blood transportation. Recent solution methods and surveys on the DARP can be found in Berbeglia, Cordeau, Gribkovskaia, and Laporte (2007), Cordeau and Laporte (2007), Parragh et al. (2008b), Paquette, Cordeau, and Laporte (2009), Kirchler and Wolfer Calvo (2013), and Paquette, Cordeau, Laporte, and Pascoal (2013).

The difference between the above described problems is usually expressed through additional constraints. For the last three classes, there are always precedence constraints between the different types of nodes.

2.1.1.5. Load splitting. In the classical VRP, *each customer is served by only one vehicle*. The possibility of *multiple visits* to the same customer characterizes the VRP with *Split Deliveries* (SDVRP) introduced by Dror and Trudeau (1989). An intermediate level of splitting should also be identified when several products have to be delivered to a customer. In this case, several visits to the same customer may occur, each product being delivered during a unique visit. Archetti and Speranza (2007) and Archetti and Speranza (2012) proposed a state of the art for the SDVRP.

2.1.1.6. Planning period. The distribution plan may be computed over a *single period or* over *several periods*. In the *Periodic* Vehicle Routing problem (PVRP), all the input data is available at the beginning of the planning period. The customer requests are known in advance as well as the possible combinations for the visiting days. At each period, one has to decide which customers are served in this period and which orders are postponed to the next periods. The PVRP was first introduced in the paper of Beltrami and Bodin (1974). Since then it was extensively studied and enriched with several variants. A vast literature is dedicated to the PVRP, see *e.g.*, Cordeau, Gendreau, and Laporte (1997), Francis and Smilowitz (2006), Hemmelmayr, Doerner, and Hartl (2009), Wen, Cordeau, Laporte, and Larsen (2010), Baldacci, Bartolini, Mingozzi, and Valletta (2011), Gulczynski, Golden, and Wasil (2011), Vidal et al. (2012), and Michallet, Prins, Amodeo, Yalaoui, and Vitry (2014). Campbell and Wilson (2014) and Francis, Smilowitz, and Tzur (2008) have proposed a focused survey on modeling and solution methods.

2.1.1.7. Multiple use of vehicles. In the VRP with *multiple use of vehicles,* the same vehicle may perform several trips during the planning period while respecting additional temporal precedence constraints. Introduced by Fleischmann (1990), the multiple use of vehicles was addressed recently. Most papers appear in the last decade, see, *e.g.*, Petch and Salhi (2003), Olivera and Viera (2007), Salhi and Petch (2007), Alonso, Alvarez, and Beasley (2008), Azi, Gendreau, and Potvin (2010, 2012), Macedo, Alves, Valério de Carvalho, Clautiaux, and Hanafi (2011), and Cattaruzza, Absi, Feillet, and Vidal (2014). In this variant, it is common to add additional restrictions related to the vehicle use and to decompose the operating costs in loading/unloading costs and variable costs. The variable costs may be related to the vehicle cleaning service between tours as in Oppen and Løkketangen (2008), Oppen, Løkketangen, and Desrosiers (2010).

2.1.2. Problem physical characteristics

2.1.2.1. Vehicles. Vehicles with different characteristics better match customer needs related to physical restrictions, to environmental concerns, to specific logistic equipments or to demand variations, see, for example, Semet and Taillard (1993), Tarantilis, Kiranoudis, and Vassiliadis (2003, 2004), and Bräysy, Dullaert, Hasle, Mester, and Gendreau (2008). The first characteristics of the vehicles considered here are related to the types of vehicle available at the planning period. There are also physical characteristics related to the loading/unloading process. Last, social driver regulations may significantly affect the vehicle routes and are considered then as vehicle characteristics.

Dealing with the *fleet composition* goes back to the seminal paper by Kirby (1959). Since then, several variants of the *Heterogeneous Fleet* Vehicle Routing Problem (HFVRP) have been addressed in the literature. Recent surveys have been proposed by Andersson, Hoff, Christiansen, Hasle, and Løkketangen (2010b) and Baldacci, Battarra, and Vigo (2008). The primary decision related to the fleet consists to determine the size of the fleet, which is always limited in real life applications.

The most common capacity constraints in freight transportation are expressed in terms of *weight, volume*, or number of *pallets*. Several capacity restrictions may be taken into account simultaneously. The vehicles may differ according to their capacities and the same vehicle may have several compartments with different capacities. Derigs et al. (2011a) have proposed a survey on VRP with multiple compartments. The use of *multiple compartments* is relevant when several products, which must remain separated during transportation, have to be loaded on the vehicles. For instance, multi-compartment vehicles are used, to perform selective waste collection (Muyldermans & Pang, 2010; Reed, Yiannakou, & Evering, 2014, to distribute food requiring different levels of refrigeration (Chajakis & Guignard, 2003), to distribute various types of fuel to petroleum companies (Brown & Graves, 1981; Cornillier, Boctor, Laporte, & Renaud, 2007, 2008) and to transport animals from farms to slaughterhouses (Oppen & Løkketangen, 2008). The optimization of routes to transport animals from farms to slaughterhouse is known as the livestock collection problem. It is a complex IRP combining animal welfare regulations and production and inventory constraints, and requiring vehicles with compartments.

Recently, loading and routing problems have been addressed jointly. Their combined optimization leads to the *Loading* Vehicle Routing Problem (LoVRP) dealing with more complex loading constraints than a simple weight or volume restriction. Routes are obtained thanks to the chronological order induced by the loading policy. The most common loading/unloading methods are based on the LIFO (Last-In-First-Out) and FIFO (First-In-First-Out) rules. If the vehicle picks up request i before request j, then it must deliver request j (i) before delivering request i (j) respectively (Carrabs, Cerulli, & Cordeau, 2007). Some references devoted to different variants of the LoVRP are Doerner, Fuellerer, Gronalt, Hartl, and Iori (2007), Fuellerer, Doerner, Hartl, and Iori (2009, 2010), and Tricoire, Doerner, Hartl, and Iori (2010). In other studies, the loading problem and the routing problem are solved separately. The loading problem is viewed as a Bin Packing Problem (Cruz Reyes et al., 2007) or as a Tank Truck Loading Problem (Cornillier, Boctor, Laporte, & Renaud, 2009; Cornillier, Boctor, & Renaud, 2012; Cornillier et al., 2007, 2008). Iori and Martello (2010) propose a recent survey on the VRP with loading constraints.

Although a vast literature is devoted to the VRP, constraints related to the legislation on driving and working hours were included infrequently. Such rules are either imposed by the company or legal regulations. Some examples are: daily working periods, number and duration of daily and weekly rest periods, maximum period of driving hours, overtime working hours and wages, etc. Driver *regulations* aim to provide safe driving, to reduce the number of accidents and to reduce the total costs. In recent years, there has been an increasing number of papers describing VRPs where a limited set of the European Union or United States regulations is taken into account (*e.g.*, Beaudry, Laporte, Melo, & Nickel, 2010; Derigs, Kurowsky, & Vogel, 2011b; Parragh, Cordeau, Doerner, & Hartl, 2012; Wen et al., 2011; Zäpfel & Bögl, 2008). Other studies include all parts of the mandatory legislation and the legal requirements, *e.g.*, Rancourt, Cordeau, and Laporte (2013) and Vidit (2008) who studied the US regulation in his thesis. Goel (2009), Kok, Meyer, Kopfer, and Schutten (2010), and Prescott-Gagnon, Desaulniers, Drexl, and Rousseau (2010) consider a VRP with time window respecting all driver rules imposed by the European Union. Recently, Goel and Vidal (2014) consider several sets of driver regulations in the United States, Canada, the European Union and Australia to provide an international evaluation of the impact of different rules on the road safety and on the minimization of transportation costs.

2.1.2.2. Time related constraints. The VRP with *time window* (VRPTW) was studied first in case studies by Pullen and Webb (1967), Knight and Hofer (1968), and Madsen (1976). Time window constraints impose that the service at every customer must start and end within a given time window. In the case of *hard time window*, the vehicle is allowed to arrive before the defined time window and waits until the customer becomes available, but it is not allowed to arrive late. In the case of *soft time window*, penalties are given for services starting after the allowed time windows. It leads to take into account the travel times between customer locations, the service times at customers and the loading/unloading times at the depot. Defining *time window at the depot* implies that the earliest departure time and the latest arrival time for each vehicle must lie within the interval time associated with the depot. A variant is the multiple time windows in which one of the time intervals associated with each customer has to be selected. In the last decades, time constrained routing problems have been extensively studied. Bräysy and Gendreau (2005a, 2005b), Kallehauge, Larsen, Madsen, and Solomon (2005), Kallehauge (2008), and Gendreau and Tarantilis (2010) propose recent surveys on this problem.

Often, the *route duration* is limited to a predefined parameter which may be equal to the total driver working hours or to the route access time. Indeed, a road segment may have a limited access given by an interval of time specifying when it can be entered. The time restriction can also be set by the number of customers visited on a route.

2.1.2.3. Incompatibility constraints. In real-life applications, many *(in)compatibility constraints* may occur between the problem entities specifically *customer, depot, vehicle compartment, products and driver,* as it was discussed in Hasle and Kloster (2007). These (in)compatibilities can be classified in two types depending on the causing factor: physical (in)compatibilities and temporal (in)compatibilities. Some of these constraints are described in what follows.

An extension of the VRPTW is the VRP with temporal dependencies, which includes synchronization and sequencing constraints between customers, vehicles, visits or depots. As Dohn, Rasmussen, and Larsen (2011) point out, many practical applications including such constraints were studied. Some examples are: (i) sequencing constraints related to technicians in the Port of Singapore, (*e.g.*, Li, Lim, & Rodrigues, 2005; Lim, Rodrigues, & Song, 2004); (ii) synchronization between visits in ground handling at airports, (*e.g.*, Dohn, Kolind, & Clausen, 2009); and (iii) coupled time windows for vehicles and schools in the design of school bus transportation services, *e.g.*, Fügenschuh (2006).

The *temporal incompatibilities are also present as* precedence constraints requiring synchronization between tours. The vehicle must visit some pick-up customers before visiting some delivery customers. This chronological order is a key point in the DARP, in the VRPPD, in the VRP with backhauls and sometimes in VRP. For example, in the transportation of livestock from farms to slaughterhouses, (Oppen & Løkketangen, 2008; Oppen et al., 2010), the health status associated with the farms may enforce an order for the visits. An elaborate and recent survey on vehicle routing problems with multiple synchronization constraints is due to Drexl (2012b).

There are also physical *inclusion and exclusion restrictions* as discussed in Desrochers et al. (1990). It may occur that a customer must (not) be served from a given depot, by a given vehicle (*e.g.*, Pellegrini, Favaretto, & Moretti, 2007) or a specific driver (*e.g.*, Rieck & Zimmermann, 2010). Indeed, the vehicle requirements and the driver qualifications, such as licensing, training for transporting specific materials and knowledge about a geographical area, may limit the compatibility between driver and vehicle. The VRP including incompatibilities between customers and vehicles types is known as the site dependent VRP (see *e.g.*, Baldacci et al., 2008).

Similarly, the vehicle characteristics or the product specificity may cause vehicle-request incompatibility, see *e.g.*, Goel and Gruhn (2008), Goel (2010), and Ceselli, Righini, and Salani (2009). In the distribution of multi-commodity loads, each vehicle can be used to handle specific types of cargos. Distribution to groceries is a relevant example where different types of food to deliver require vehicles with different temperature levels. In animal transportation, different animal types cannot be transported together in the same compartment (*e.g.*, Oppen & Løkketangen, 2008; Oppen et al., 2010). Similarly in a health application, the patient condition may prohibit sharing the ambulance with other patients to avoid the spread of diseases or to allow a medical staff assistance, see *e.g.*, Beaudry et al. (2010) and Parragh et al. (2012).

2.1.2.4. Specific constraints. In industrial real-life applications, managers face continuously various and non-standard challenging constraints coming from the problem specificities. For instance, decisions may be constrained by outsourcing resources, by environmental issues, by the prioritization of customers or by cross docking related restrictions. Other constraints are logistic restrictions encountered daily when the vehicle routes are designed. They are described in what follows.

- Outsourcing decisions

In some cases, decision has to be made whether a route is performed using the company resources or outsourcing services. The constraint set is then expanded, and the cost function includes cost terms for outsourced resources. Recent papers taking into account such decisions are due to Ileri et al. (2006), Zäpfel and Bögl (2008), Moon, Lee, and Seong (2012), Kovacs, Parragh, Doerner, and Hartl (2012), and Stenger, Vigo, Enz, and Schwind (2013).

- Environmental protection

During the last years, environmental concerns have been addressed in VRP studies. This research avenue is known as green routing problems in the literature. More precisely, the use of vehicles may be constrained by the release of gas and toxic effluents into the atmosphere. Reducing noise may also be a restriction on the types of vehicles used. Erdoğan and Miller-Hooks (2012) formulated and proposed solution methods for a green VRP arising in the refueling industry. Xiao, Zhao, Kaku, and Xu (2012) extend classical works on CVRP with the objective of minimizing fuel consumption and identified factors causing the variation in fuel consumption. The reader may refer to the book of McKinnon, Cullinane, Browne, and Whiteing (2010) and to the survey papers by Sbihi and Eglese (2007a, 2007b), Demir, Bektas, and Laporte (2014), and Lin, Choy, Ho, Chung, and Lam (2014) who examined the environmental issues related to vehicle routing and scheduling problem.

- Prioritization of customers

Additional transportation requests may have to be assigned to face some unexpected events such as out of stock situations at some customers or vehicle breakdowns. In such a case, priority tags are put on orders to determine which goods must be delivered first (see *e.g.*, Cornillier et al., 2008, 2009).

- Cross docking strategy

A cross dock terminal can be considered as a consolidation center having a short term inventory holding capacity. During a short time period incoming cargos are unloaded and sorted, and then goods are loaded on outgoing vehicles serving given areas, see *e.g.*, Lee, Jung, and Lee (2006), Liao, Lin, and Shih (2010), Wen, Larsen, Clausen, Cordeau, and Laporte (2009), Santos, Mateus, and Cunha (2011a, 2011b), Vahdani, Tavakkoli-Moghaddam, Zandieh, and Razmi (2012), and Van Belle, Valckenaers, and Cattrysse (2012). Such delivery systems are of interest for industries facing large distribution costs like pharmaceutical and food companies, see *e.g.*, Boysen (2010). Decisions related to the management of cross docking terminals are constrained by the design of the pickup and delivery routes.

- Open routes

A few papers have been devoted to the *Open* Vehicle Routing Problem (OVRP) introduced by Schrage (1981). In the OVRP, the driver must not return to the depot once the last customer on the route has been served. The route may terminate at a car park or at the driver home. Some relevant applications of the OVRP can be found in the home delivery of packages and newspapers (*e.g.*, Russell, Chiang, & Zepeda, 2008), when deliveries are outsourced to independent contractors or when drivers use their own vehicles. Some recent studies on the OVRP are due to Tarantilis and Kiranoudis (2002), Brandaõ (2004), Fu, Eglese, and Li (2005), Letchford, Lysgaard, and Eglese (2007), Rieck and Zimmermann (2010), and Ceselli et al. (2009).

- Accessibility constraints

Accessibility constraints differ from incompatibility constraints between vehicles and customer locations by imposing the use of different transportation means to serve customers. This corresponds to different real-life cases based on multimodal transportation systems. For example, in Semet and Taillard (1993) some routes are covered by trucks and trailers which have to be uncoupled to serve a subset of customers. Some references describing different truck and trailer routing applications are Gerdessen (1996), Hoff and Løkketangen (2007), Caramia and Guerriero (2010), Derigs, Pullmann, and Vogel (2013), and Villegas, Prins, Prodhon, Medaglia, and Velasco (2011, 2013).

- Simultaneous vehicles on site

In some industry sectors, many orders per day may have to be delivered at the same customer separately. Since queues may occur, a limit is set on the number of vehicles that are present simultaneously at the same location, *e.g.*, Cruz Reyes et al. (2007). This restriction occurs in the production and the delivery of newspapers where a fixed number of trucks may start their routes at the same time for the state edition, *e.g.*, Russell et al. (2008).

- Cleaning

To satisfy sanitary rules and to prevent contamination while transporting oil, chemicals products, lubricants, cattle food and animals, vehicle cleaning is an essential daily operation. Cleaning may be not necessary for some sequencing of products. Hence, in the VRP model we have to decide when cleaning operations are necessary for the proposed scheduling plan and how much it costs. For example, in Oppen and Løkketangen (2008) and Oppen et al. (2010), the authors impose the visits of the infected farms at the end of the route to avoid unnecessary cleaning.

Table 2
Selected papers devoted to pure routing problems.

Number	Paper	1	1.1	1.1.2	1.1.4	1.3	1.3.2	1.4	1.4.1	1.4.2	1.4.3	1.4.4	1.5	1.5.1	1.6	1.6.2	1.7	1.7.2	2	2.1	2.1.1.2	2.1.2.1	2.1.3.1	2.1.4	2.1.5.1	2.1.6	2.2	2.2.1	2.2.2	2.2.3	2.2.4	2.2.5	2.3	2.3.2	2.4	2.5	2.6	2.6.2	Formulation	Real case study	Rich	Methods
3	Beaudry *et al.* 2010			x			x					x									x	x		x				x	x	x	x				x					x		Tabu Search algorithm
7	Ceselli *et al.* 2009						x		x					x							x	x		x		x		x	x	x	x	x			x	x			x	x		Column Generation heuristic
10	Crainic *et al.* 2009						x		x							x								x				x	x												x	Integrative Cooperative Search based on metaheuristics
11	Cruz Reyes *et al.* 2007								x					x				x			x	x		x	x			x		x	x				x	x				x	x	Ant Colony System algorithm
12	Cruz Reyes *et al.* 2008						x		x					x				x			x	x		x	x			x		x	x			x	x	x				x	x	Ant Colony System algorithm
13	Derigs and Döhmer 2008									x														x				x			x	x			x						x	Classical heuristic
14	Fügenschuh 2006								x									x										x				x				x			x	x	x	Hybrid heuristic combining mixed integer preprocessing and metaheuristics
15	Goel 2010						x			x											x	x		x				x		x					x				x		x	Column Generation heuristic
16	Goel and Gruhn 2008			x			x			x											x	x		x				x		x					x				x	x	x	Variable Neighborhood Search algorithm and Large Neighborhood Search algorithm
18	Hvattum *et al.* 2006			x	x				x							x								x				x		x									x	x		Sample Scenario Hedging heuristic
19	Ileri *et al.* 2006									x														x		x		x						x	x	x			x	x	x	Column Generation heuristic
22	Magalhães and Sousa 2006			x					x					x		x		x			x	x		x	x				x											x	x	Four-phase heuristic
23	Mendoza *et al.* 2010				x				x														x	x					x						x				x			Memetic algorithm
24	Mendoza *et al.* 2009				x				x														x	x					x						x				x			Evolutionary algorithm
25	Mendoza *et al.* 2011				x				x														x	x					x						x				x			Classical heuristics
28	Parragh *et al.* 2012											x									x	x		x		x		x	x	x	x	x			x				x	x	x	Column Generation heuristic
29	Pellegrini *et al.* 2007								x							x					x			x	x	x		x	x					x	x	x		x		x	x	Ant Colony Optimzation algorithm
32	Reimann and Ulrich 2006										x													x				x	x	x	x				x			x			x	Ant Colony Optimization algorithm
33	Rieck and Zimmermann 2010						x			x								x			x	x		x				x	x	x	x				x	x		x	x		x	Exact solution using commercial solver
34	Røpke and Pisinger 2006						x				x											x		x				x		x	x				x			x			x	Large Neighborhood Search algorithm
35	Russell *et al.* 2008						x		x												x	x		x				x	x		x					x		x		x		Tabu Search algorithm
36	Schilde *et al.* 2011			x	x							x		x								x		x				x	x	x					x			x		x		Variable Neighborhood Search algorithm/Multiple Scenario approach/Multiple Plan approach
37	Schmid *et al.* 2009						x		x					x							x			x				x			x				x	x			x	x		Hybrid heuristic combining Variable Neighborhood Search algorithm and integer programming
39	Wen *et al.* 2010			x					x							x						x		x					x		x	x						x	x	x	x	Three-phase rolling horizon heuristic
40	Wen *et al.* 2009									x												x		x				x			x				x	x			x	x	x	Tabu Search algorithm
90	**CVRP**								x															x																		
91	**DCVRP**								x															x					x													
92	**VRPTW**								x															x				x			x	x										
93	**VRPB**										x													x											x							
94	**VRPPD**									x														x											x							

Table 3
Selected papers devoted to combined routing problems.

Number	Paper	1	1.1	1.1.2	1.1.4	1.2	1.2.1	1.2.2	1.2.3	1.2.4	1.2.5	1.3	1.3.2	1.4	1.4.1	1.4.2	1.4.3	1.4.4	1.5	1.5.1	1.6	1.6.2	1.7	1.7.2	2	2.1	2.1.1.2	2.1.2.1	2.1.3.1	2.1.4	2.1.5.1	2.1.6	2.2	2.2.1	2.2.2	2.2.3	2.2.4	2.2.5	2.3	2.3.2	2.4	2.5	2.6	2.6.2	Formulation	Real case study	Rich	Methods
1	Armentano *et al.* 2011							x			x				x							x						x		x					x							x			x			Tabu Search algorithm with Path Relinking heuristic
2	Bard and Nananukul 2009							x			x				x							x						x		x												x			x			Tabu Search algorithm with Path Relinking heuristic
4	Bolduc *et al.* 2006							x							x					x		x					x	x		x							x					x			x		x	Classical heuristics
5	Boudia and Prins 2009							x			x				x							x						x		x												x						Memetic algotithm
6	Boudia *et al.* 2007							x			x				x							x						x		x												x			x			Greedy Randomized Adaptive Search algorithm with Path Relinking heuristic
8	Cornillier *et al.* 2009							x							x									x			x	x	x	x				x	x		x	x			x	x			x	x		Classical heuristics
9	Cornillier *et al.* 2008							x							x							x		x			x	x	x	x					x		x				x	x			x	x		Multi-phase heuristic
17	Hemmelmayr *et al.* 2010				x			x							x							x													x		x					x			x	x		Variable Neighborhood Search algorithm
20	Kok *et al* . 2010									x					x															x		x		x	x		x							x				Dynamic Programming heuristic
21	Lin and Kwok 2006								x				x		x									x						x		x			x							x		x		x	x	Tabu Search algorithm and metaheuristics
26	Oppen and Løkketangen 2008							x							x					x		x		x			x	x	x	x	x				x	x	x				x	x				x	x	Tabu Search algorithm
27	Oppen *et al.* 2010							x							x					x		x		x			x	x	x	x	x				x	x	x				x	x			x	x	x	Branch and Price algorithm
30	Prodhon and Prins 2008								x				x		x							x						x		x																		Memetic algorithm
31	Rancourt *et al.* 2013									x					x												x			x		x		x	x	x	x	x		x	x			x			x	Tabu Search algorithm
38	Wen *et al.* 2011									x					x							x					x	x		x		x		x	x		x				x	x			x	x	x	Variable Neighborhood Search algorithm
41	Zäpfel and Bögl 2008									x						x						x					x			x		x		x		x	x				x	x				x		Genetic algorithm and Tabu Search algorithm

(See above-mentioned references for further information.)

2.1.2.5. Objective function. The objectives can be *multiple* and diverse. The most common objectives include minimizing some or all of these criteria: the total traveled distance, the total time, the total tour cost, the fleet size, and/or maximizing the service quality, the collected profit. When multiple objectives are identified, the different objectives are often in conflict. Hence, adequate algorithms have to ensure some trade-off between them. For a survey on the multi-objective VRPs, we refer to Jozefowiez, Semet, and Talbi (2008).

3. Taxonomy analysis

Considering the 41 selected papers, we have to mention that some authors first consider a simplified version of a VRP and then tackle a more complicated variant by considering additional constraints. For instance, Parragh (2011) first solves a restricted and simplified version of the heterogeneous DARP. Then Parragh et al. (2012) take into consideration the medical requirements of patients and modeled them as incompatibilities constraints. Similarly, Pellegrini (2005) focuses on a VRP with heterogeneous vehicles and multiple time windows for customers. Later on, in Pellegrini et al. (2007) the authors consider multiple visits to some customers over a periodic horizon, hierarchical objectives, and additional customer requirements.

In Tables 2 and 3, papers addressing different variants of the VRP are listed. Table 2 is devoted to papers addressing pure routing problems. Therefore, the sublevels of the level decision management component (1.2) are omitted. In Table 3, we consider papers that combine routing vehicles with other strategic or tactic facets. Each article is classified according to the attributes defined in the above taxonomy (see Table 1). The subclasses and branching classes are shaded. When the attribute is present in the corresponding paper, 'X' is reported in the associated cell. The column headed *Number* provides the numbers, we assigned, to each selected paper. In what follows, we give the number of the selected paper into square brackets. The columns headed *Formulation, Real case study* indicate whether or not the article includes a mathematical formulation and/or a set of instances based on a real-life application. In the column headed *Rich*, we report whether or not the authors consider the problem under study as a RVRP. The last column headed *Method* refers to the types of designed method(s).

In Tables 2 and 3, all described attributes are present in one paper at least. This shows that no unnecessary node has been introduced in the taxonomy. In selected papers, the routing based problems with pickups or deliveries were studied more deeply than the other variants. Indeed, 61% of the papers selected addressed routing issue only (1.2.1), and 70.7% of them are devoted to pickup or delivery (1.4.1) problems. At the opposite, little attention has been paid to routing problems dealing with other decisions, such as location (1.2.3), driver scheduling (1.2.4) and production (1.2.5). This suggests some promising future research avenues. Even if stochastic and dynamic problems are quite challenging, they constitute almost 15% of the selected papers which illustrate the key role played by these problem characteristics. Different types of temporal and physical incompatibilities between the basic entities (2.4) are present in the considered papers (63.4%) as well as specific restrictions (2.5) related to real-life applications (53.7%). Moreover, the time constrained routing problems have been studied intensively. In more than half of the selected papers, the VRPs tackled take into account time window restrictions for customers and/or road accesses (2.2.2). Opening hours for depots (2.2.3) are defined in almost 40% of the papers. Last, it is noteworthy to mention that the social constraints such as legislation rules on driving and working hours are considered in 22% of the papers (2.1.6). This illustrates that social driver regulations increasingly are taken into account in the VRP literature since 2006.

In 56% of the papers, mathematical formulations are provided even if approximate methods are then designed to solve the problem under study. The models typically aim to provide a complete description of the problem. With respect to the solution methods, exact algorithms are proposed in two papers while heuristics and metaheuristics are described in the remaining 39 papers. This is due to the ability of approximate methods to find near-optimal solutions for large instances of complex problems.

To obtain a more accurate partition of the selected papers, we classify them using a cluster analysis. The cluster analysis consists in gathering the observed data having many similarities into significant structures. The formed groups must be as different as possible while the degree of similarity of the data clustered in the same group must be maximal. The clustering method used is the *K*-means algorithm. The clustering is based on the paper score according to 2 criteria: the number of scenario characteristics and the number of the operational characteristics. To calculate the scores, we follow 2 main principles. First, we count at least 1 for each paper according to the attributes (1.2) and (1.4). These attributes are necessary to describe the problem under study. Second, we add one to the score only if the problem addressed has one additional feature compared to the basic variant of the deterministic VRP (see below). Each of these attributes may be considered as dichotomous either the score increases by one or zero. The basic variant of VRP, we defined, is a single depot pickup (or delivery) routing problem. The planning horizon is one period. All vehicles are identical and covered one route only. Their number is unlimited. All data are known a priori. This basic variant has a score of 2 for the SCs and of 0 for the PPCs. For the clustering analysis, we include standard VRPs (see Toth & Vigo, 2002a) in addition to the VRPs described in the 41 selected papers. The standard versions are: the CVRP [90], the Distance Constrained VRP (DCVRP) [91], the VRPTW [92], the VRPB [93] and the VRPPD [94]. The greatest dissimilarity between clusters is obtained for 3 clusters using the *K*-means method. These clusters are depicted in Fig. 1.

Cluster *C1* contains papers having a significant degree of similarity. It includes 13 papers with the largest scores for the PPCs: [3, 7, 8, 9, 11, 12, 26, 27, 28, 29, 31, 33, 38]. All papers except the article by Rieck and Zimmermann (2010) [33] are devoted to variants of the VRP with many complicating optimization criteria and constraints coming from different real-life applications. In all papers of *C1*, a capacitated heterogeneous fleet is used, and (in) compatibility constraints (2.4) are present. In most of them, time window constraints are imposed and/or a restriction on the number of vehicles (2.1.2.1) is present. Nine papers address variants with a wide variety of specific constraints (2.5).

The papers of *C1* are devoted to VRPs with eight operational characteristics at least. They are considered by their authors as RVRP studies. For example, in the papers of Oppen and Løkketangen (2008) and Oppen et al. (2010)) [26, 27], an inventory routing problem is tackled. It consists in collecting animals from farms for slaughterhouses. This real-world case extends standard routing problems by defining multiple trips, multiple periods and split deliveries. Several PPCs are considered. They are related to

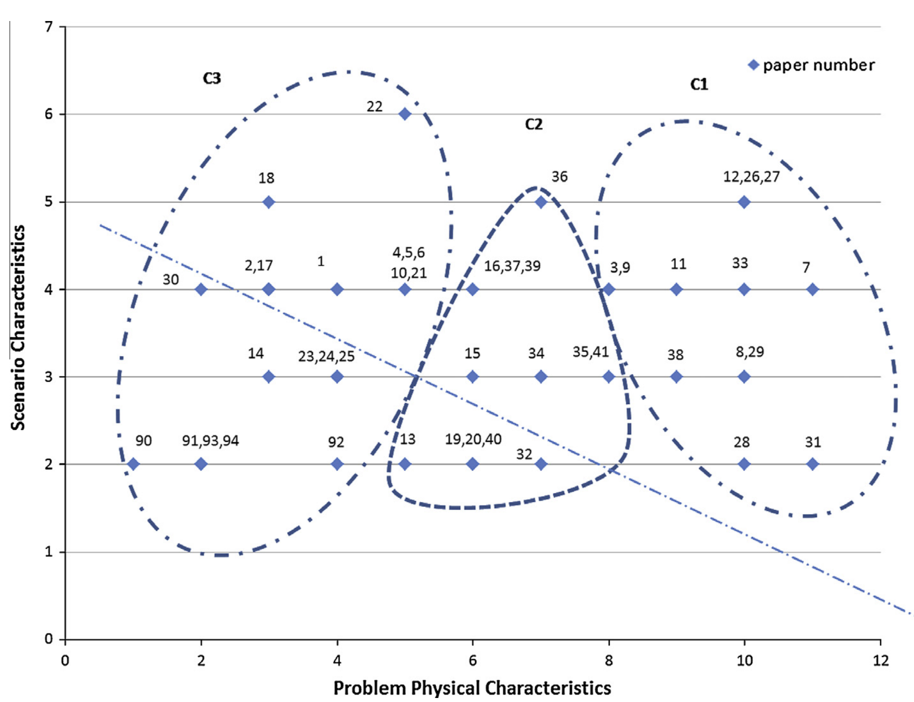

Fig. 1. Cluster analysis.

the heterogeneous capacitated and multi-compartment vehicles, to loading rules for animals, to cleaning constraints, to incompatibilities constraints between animal types, farms and animals, etc. The variety of the real-life features considered assesses the richness of the problem addressed in these papers.

The papers by Cruz Reyes et al. (2007, 2008) [11, 12] describe the distribution of bottled products for a Mexican company. The problem tackled includes 6 variants of the VRP in [11] and 11 variants in [12]. Many practical aspects are considered such as a heterogeneous capacitated and limited fleet, the assignment of several trips to vehicles, the loading plan, time window restrictions and incompatibilities between products. Additional constraints are included. First, the positions of the loaded products are optimized according to their weights. Second, the number of vehicles simultaneously present on the same location is limited. An extended version, which includes multiple depots and the assignment of orders to the depots, is studied in [12]. In their paper, Ceselli et al. (2009) [7] consider several operational constraints that arise in a real life situation. In this application, the routes performed thanks to a heterogeneous fleet may start from different depots, and may be open paths and not closed paths. Time windows are associated with the depots and the customers, which may be served according to a split delivery policy. The authors consider also social driver regulations and incompatibilities between products, depots, vehicles and customers. Last, outsourcing is made possible by using express courier services. Parragh et al. (2012) [28] and Beaudry et al. (2010) [3] study dial-a-ride problems enriched by several complicating operational constraints which arise in the hospital context. For instance, these constraints required for patient transportation are: precedence constraints, the desired pickup or delivery time restrictions for patients and hospitals, etc. Last, the paper by Rancourt et al. (2013) [31] has a score of 2 according to SCs, but it considers various driver safety rules imposed for long-haul trips in North America under different objectives. The authors consider many PPCs such as multiple time windows at customers and different subsets of heterogeneous vehicles, which served subsets of customers.

Cluster *C3* includes papers dealing with variants of the VRP with the lowest scores for the PPCs and different scores for the SCs. 15 papers are in *C3*: [1, 2, 4, 5, 6, 10, 14, 17, 18, 21, 22, 23, 24, 25, 30] as well as the 5 standard VRPs defined in Toth and Vigo (2002a). Since they are in the same group as the standard VRPs, the problems addressed in these papers have a low level of richness a priori. Indeed, only 5 papers out of 15 are case studies and most of the diverse real-life constraints considered in the papers of *C1* are not present. For instance, the articles by Mendoza, Castanier, Guéret, Medaglia, and Velasco (2009, 2010, 2011) [24, 25, 23] are the only ones in which incompatibility constraints are taken into account. Split deliveries is an option in 2 papers only, Magalhães and Sousa (2006) [22] and Bolduc, Renaud, and Montreuil (2006) [4]. Magalhães and Sousa (2006) [22] study a pharmaceutical case-study in a dynamic multi-period environment using a heterogeneous fleet. Each vehicle may cover several routes and is loaded according to a chronological order. In [4], the authors address an inventory routing problem on a multi-period horizon using a heterogeneous limited fleet and a multiple use of vehicles. Fügenschuh (2006) [14] consider a real world bus scheduling problem taking into account school starting times and public bus schedule. The assignment of several trips to buses is the unique additional SC imposed. In their work, Prodhon and Prins (2008) [30] tackle a VRP variant closed to a standard one. The paper by Crainic, Crisan, Gendreau, Lahrichi, and Rei (2009) [10] addresses a multi-depot periodic VRP including time constraints and using a homogeneous unlimited fleet. Last, in their works, Mendoza et al. (2009, 2010, 2011) [24, 25, 23] describe routing problems for compartmentalized vehicles in a stochastic environment which are close to the classic VRPs. Hvattum, Løkketangen, and Laporte (2006) [18] consider an extended variant of the VRP to take into account some aspects of a real case faced by a major distribution company in Norway. The problem is modeled as a periodic dynamic and stochastic problem with temporal constraints for customers and the depot. This paper is slightly different from those included in *C3*.

Last, Armentano et al. (2011) [1], Boudia et al. (2007) [6], Boudia and Prins (2009) [5], and Bard and Nananukul (2009) [2] integrate two types of strategic decision by coordinating the production, inventory and routing decisions over a multi-period horizon. The customer demands are satisfied either from inventory and/or thanks to the daily production of a single facility. The integration of two levels of decision illustrates the complexity of real-life supply chain management problems. It adds various constraints to the basic model to ensure the balance between demand, production, inventory and deliveries at the facility and at customers.

Cluster *C2* includes the following papers: [13, 15, 16, 19, 20, 32, 34, 35, 36, 37, 39, 40, 41]. It lies between cluster *C1,* which gathers articles devoted to real cases and multi-constrained problems, and cluster *C3,* which contains papers addressing VRPs which seem not to be rich. In *C2*, we can identify variants of the VRP closed to those tackled in the papers of *C1* or of *C3* in terms of SCs and PPCs. Thus, Reimann and Ulrich (2006) [32] and Ileri et al. (2006) [19] describe problems which are not entirely different from the standard VRPs. The problem studied in [32] differs from the basic VRPB [93] by imposing time windows at customers and depots, by bounding the route length and by defining a lexicographic objective function. In [19], the problem addressed is a variant of the VRPPD [94] where multiple time windows are associated with customers, possible additional stops between the origin and the destination are considered, and the social rules for the drivers are satisfied. In their paper, Derigs and Döhmer (2008) [13] have addressed a pickup and delivery problem with time window using an unlimited homogeneous capacitated fleet. The work of Wen, Larsen, Clausen, Cordeau, and Laporte (2009) [40] on the vehicle routing with cross-docking differs from the VRPPD by adding restrictions to synchronize inbound and outbound flows. However, the terminal management is not modeled since constraints related to the resource limitations are not included. For instance, the authors do not take into account the capacity of the cross-dock, the number and the availability of docks, and the scheduling of trucks processed at the dock doors, see *e.g.,* Kreng and Chen (2008), Boysen and Fliedner (2009), and Miao, Lim, and Ma (2009). Last, Kok et al. (2010) [20] study a routing and crew scheduling problem with time window. In this work, the European social legislation on drivers' working hours is considered, but basic physical and the scenario characteristics are included.

Papers devoted to VRPs with 6 to 8 PPCs are also present in *C2*. Such problems could be considered as RVRPs. For instance, in their paper, Schmid, Doerner, Hartl, Savelsbergh, and Stoecher (2009) [37] develop a hybrid solution approach for a rich application in the concrete industry. It consists in delivering concrete produced at different plants to construction sites at their preferred periods. Multiple visits using a heterogeneous capacitated fleet are allowed. Different incompatibility constraints between products, vehicles and customers must be satisfied as well as specific constraints related to the delivery process at construction sites. Schilde, Doerner, and Hartl (2011) [36] study the patient transportation problem faced by the Austrian Red Cross daily. The problem is modeled as a multi-objective DARP which aims to satisfy dynamic and stochastic requests in their specified time intervals using a fixed fleet. Zäpfel and Bögl (2008) [41] combine a multi-period vehicle routing problem with a crew scheduling problem to address a postal case-study. They consider pickup and delivery routes and time constraints at the customers and the depots. Driver outsourcing is also considered.

The analysis of the three clusters shows that the multi-constrained VRPs are considered in papers included mainly in *C1* or *C2*. At the opposite, problems close to standard VRPs are addressed in papers belonging to clusters *C3* and *C2*. The foregoing discussion leads us to define a frontier which discriminate the selected papers (see Fig. 1). Below the frontier, there are standard variants of the VRP [90, 91, 92, 93, 94] and papers describing problems closed to those variants. Above the frontier, papers are devoted to multi-constrained problems.

With respect to the two clustering criteria, we note that multi-constrained problems have at least 4 SCs and 6 PPCs in the papers included in *C1*. Rich combinations contain more PPCs than SCs. This is not a general rule, but it indicates combinations leading to rich vehicle routing studies. In addition, the previous discussion put into highlights that other combinations may lead to RVRPs. Those are studies above the frontier and can be characterized as follows: (i) papers in which the strategic level includes several constraints related to the distribution system (5 SCs or more), see, *e.g.*, [18], [22] and (ii) papers addressing variants in which the strategic and tactical levels remain standard but the operational characteristics of the route planning are increased (9 PPCs or more), see, *e.g.*, [8, 29, 31, 38]. It is noteworthy that some VRPs based on real case studies could not be viewed as RVRPs as illustrated by papers [14, 19, 40].

The definition of RVRPs based on the taxonomy relies on the characteristics of the selected papers. In the literature, the RVRP is defined as a problem which simultaneously includes several types of challenging and complicating features. It is associated with the complexity of real-life routing problems. Now, we propose a more precise definition:

Definition. A RVRP extends the academic variants of the VRP in the different decision levels by considering at least four strategic and tactical aspects in the distribution system and including at least six different daily restrictions related to the physical characteristics. When a VRP is mainly defined through strategic and tactical aspects, at least five of them are present in a RVRP. When a VRP is mainly defined through physical characteristics, at least nine of them are present in a RVRP.

Clearly, the state of the art of RVRPs has changed since 2006. Some variants described as rich by their authors in 2006 may not be considered as such anymore whereas recent papers contain more complex aspects of reality.

4. Conclusions

In this paper, a general taxonomy for RVRPs has been proposed. Several papers have been classified and analyzed. A more elaborate definition of the RVRP than the existing ones results from this analysis. The taxonomy has been proven to be valid since some variants of the VRP are classified. Nevertheless, this taxonomy may be limited and not applicable for some *exotic* VRPs. In some countries, the distribution process includes primarily specific operational constraints. It may end up, rarely, with an uncommon problem that contains mainly particular constraints (2.4). Whether such problem should be classified according to the taxonomy, it could be not considered as a RVRP according to our taxonomy. Moreover, the RVRP taxonomy developed should not remain unchanged over time. It should be updated as new industrial challenges arise and new attributes may be added. Last, as the RVRPs incorporate complex features of real-life routing problems, there should be unified approximate methods to provide good solutions for these problems. Such heuristics should be generic and able to solve several VRP variants studied in the literature. A first step in this direction has been made by Røpke and Pisinger (2006), Subramanian et al. (2011), Derigs and Vogel (2014), and Vidal et al. (2013, 2014).

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