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Survey of Green Vehicle Routing Problem: Past and future trends

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ABSTRACT

Green Logistics has emerged as the new agenda item in supply chain management. The traditional objective of distribution management has been upgraded to minimizing system-wide costs related to economic and environmental issues. Reflecting the environmental sensitivity of vehicle routing problems (*VRP*), an extensive literature review of *Green Vehicle Routing Problems* (*GVRP*) is presented. We provide a classification of *GVRP* that categorizes *GVRP* into *Green-VRP*, *Pollution Routing Problem*, *VRP in Reverse Logistics*, and suggest research gaps between its state and richer models describing the complexity in real-world cases. The purpose is to review the most up-to-date state-of-the-art of *GVRP*, discuss how the traditional *VRP* variants can interact with *GVRP* and offer an insight into the next wave of research into *GVRP*. It is hoped that OR/MS researchers together with logistics practitioners can be inspired and cooperate to contribute to a sustainable industry.

1. Introduction

Green Logistics has recently received increasing and close attention from governments and business organizations. The importance of Green Logistics is motivated by the fact that current production and distribution logistics strategies are not sustainable in the long term. Thus environmental, ecological and social effects are taken into consideration when designing logistics policies, in addition to the conventional economic costs. The environmentally sensitive logistic policy itself requires changing the transportation scheme and shifting it onto a sustainable distribution network with fewer negative impacts on the environment and the ecology, owing to the undeniable fact that transportation accounts for the major part of logistics. There is a wide variety of problems concerning Green Transportation, such as the promotion of alternative fuels, next-generation electronic vehicles, green intelligent transportation systems, and other eco-friendly infrastructures. A better utilization of vehicles and a cost effective vehicle routing solution would more directly achieve sustainable transportation schemes. In this context, designing a green distribution network by means of vehicle routing models is the major task. Bloemhof-Ruwaard, van Beek, Hordijk, and Van Wassenhove (1995) and Daniel, Diakoulaki, and Pappis (1997) specified the close interaction and the contributions of Operations Research methods to environmental management and addressed some environmental issues related to routing, such as the reverse logistics in product recovery management and the routing of waste collection.

The studies of routing problems concern the fundeamental consideration in the distribution of goods from plant to warehouses to customers (Bodin, Golden, Assad, & Ball, 1983). In the traditional *Vehicle Routing Problem* (*VRP*), the focus is concentrated on the economic impact of vehicle routes on the organization that carries out the distribution service. Consideration of wider objectives and more operational constraints that are concerned with sustainable logistics issues pose new vehicle routing models and new application scenarios, which naturally lead to more complex combinatorial optimization problems. Green Logistics deals with the activities of measuring the environmental effects of different distribution strategies, reducing the energy consumption, recycling refuse and managing waste disposal (Sbihi & Eglese 2007a). Based on these dominating activities, we attempt to identify the *VRP* variants regarding these sustainable transportation issues in the literature from an operations research perspective and denote them as *Green Vehicle Routing Problems* (*GVRP*). *GVRP* are characterized by the objective of harmonizing the environmental and economic costs by implementing effective routes to meet the environmental concerns and financial indexes. As they have just arisen in the literature in recent years, there is a continuing need to enrich related studies either through theoretical contributions or by real applications. Sbihi and Eglese (2007a, 2007b) presented some research gaps that link the *VRP* with Green Logistics issues, such as employing the *Time-dependent VRP* as an approach to deal with the minimization of emissions during traveling. Salimifard, Shahbandarzaden, and Raeesi (2012) reported several recent articles

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published in 2010 and 2011 with direct consideration of environmental impact in the objective functions and stated that this topic is still at the beginning of being studied and is rather attractive. Despite their attempt of surveying relevant literature, they confined *VRP* with green transportation consideration to only those problems with explicit objectives of environmental costs. It seems that there is still room for investigation to explore *GVRP* in the area of energy consumption, emission control, and reverse logistics.

The contribution of this paper is to give an exhaustive literature review and clear classification of *GVRP*. More importantly, we have highlighted the lack of the existing studies and point out the future research directions for the *GVRP*. For academic purposes, a landscape of literature on *GVRP* is shown to shed light on this topic and help researchers find potential areas of further and deeper study. In particular, the classification of the traditional *VRP* variants is also summarized to inspire researchers to find out how these traditional variants can be related to the *GVRP*. For practical purposes, it is hoped that these idealized models can help governments, nonprofit organizations, and companies to evaluate the possible economic and environmental significance of real-world transportation problems and to take action at different levels to contribute to Green Logistics.

The remaining part of this paper is organized as follows. Section 2 concerns the survey methodology of this paper. A review of the traditional *VRP* variants, with a brief introduction and sub-categories for each variant, is presented in Section 3 to show the evolution of *VRP* literature. Section 4 gives an overview of the most important *VRP* variant, *VRP with Time Windows*. A brief introduction to the algorithms and main benchmark test instances for *VRP* is presented in Section 5. In Section 6, we review the existing research on *GVRP* in depth, with a classification categorizing *GVRP* into *Green-VRP*, *Pollution Routing Problem*, and *VRP in Reverse Logistics*. The future research opportunities for each *GVRP* category are also suggested. Section 7 contains a summary of important trends and perspectives of the future development of the research into *GVRP*. Finally, a conclusion is drawn in Section 8.

2. Survey methodology

2.1. Source of the literature

The literature surveyed in this paper was majorly selected from three sources: (1) a wide set of academic databases such as *Science Direct*, *Springer Link*, *EBSCO*, etc., accessed from the university library by using keywords such as vehicle routing, time windows, green, reverse logistics, etc.; (2) bibliographies of survey papers and book chapters on *VRP*; (3) additional articles that are addressed in the initial articles in (1) and (2). The literature we searched is normally scattered at different times ranging from 1959 to 2012. As we intend to survey the studies on *GVRP*, we mainly confined our search to articles published from 2006 to 2012. The searching process was conducted in two dimensions: horizontal and vertical. In the horizontal dimension, attention was paid to the evolution of *VRP* on the timeline, especially when finding *VRPs* of sustainability issues (i.e. *GVRP*). In the vertical dimension, different classes of *VRP* are employed to distinguish each article. The majority of the literature falls into journal articles in terms of operations research, management science, and transportation, in such journals as the *European Journal of Operational Research, Computers & Operations Research, Transportation Science, Transportation Research (Part A, B, C, D, E), Networks, Operations Research, Journal of the Operational Research Society*, etc. A small number of proceeding papers, working papers, technical reports and dissertations are also included in this overview as they were also taken as good references for some most up-to-date research directions or for the foundation of further study. In this study, about 280 papers were reviewed, which are shown in Fig. 1 and Table 1.

The fourth column of Table 1 summarizes the *VRP* variants that were studied in each year in our review work. It can be found that the research efforts before 2006 focused on the traditional *VRP*. Few studies on Green *VRP* had been conducted during this time period. After 2006, Green *VRP* covering energy consumption (*G-VRP*), pollution emissions (*PRP*), as well as recycling and reverse logistics (*VRPRL*) started to draw researchers' close attention and became a hot topic in the past several years. This trend can be re-

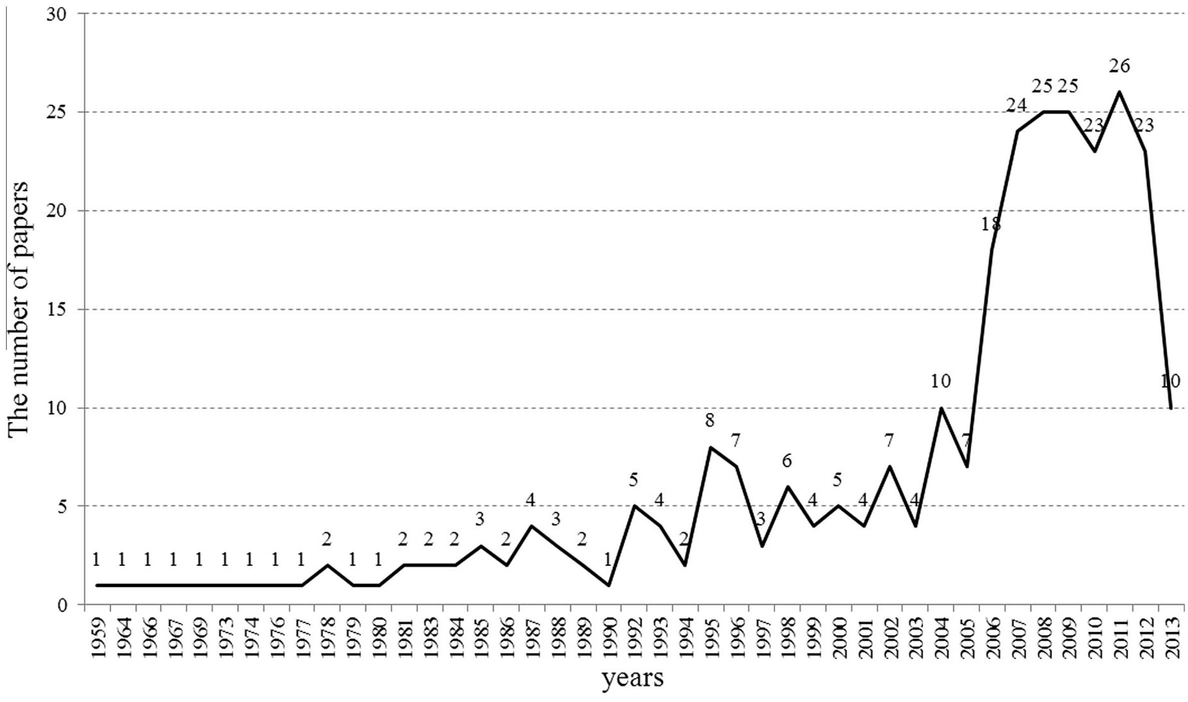


Fig. 1. The distribution of papers by year.

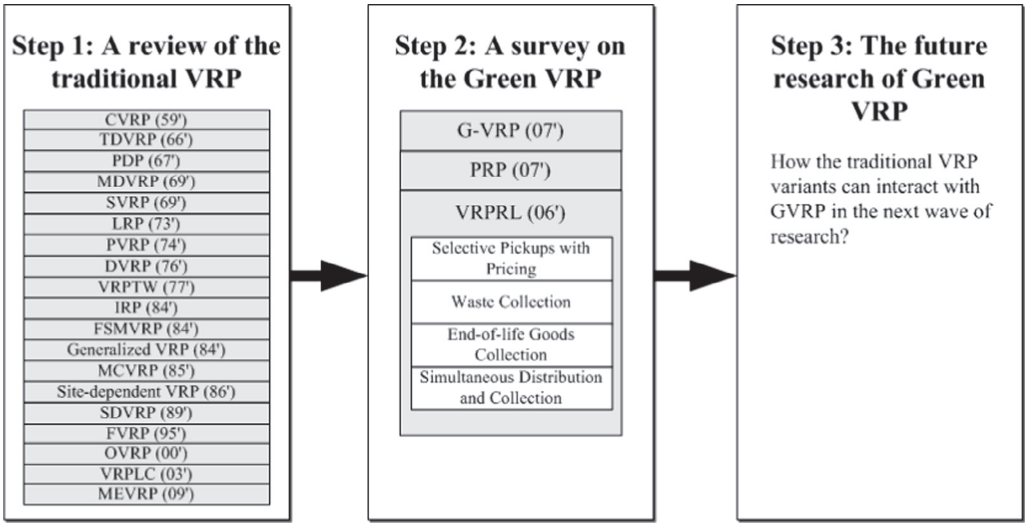
Table 1
The papers reviewed in this study.

Year	Number of papers	The list of the papers	The studied VRP variants
1959	1	Dantzig and Ramser	CVRP
1964	1	Clark and Wright	CVRP
1966	1	Cooke and Halsey	TDVRP
1967	1	Wilson and Weissberg	PDP
1969	1	Tillman	SVRP, MDVRP
1973	1	Watson-Gandy and Dohm	LRP
1974	1	Beltrami and Bodin	PVRP
1976	1	Speidel	DVRP
1977	1	Russell	VRPTW
1978	2	Cook and Russell; Golden and Stewart	SVRP
1979	1	Christofides et al.	
1980	1	Psaraftis	DVRP
1981	2	Fisher and Jaikumar; Schrage	VRPTW, CVRP
1983	2	Bell et al.; Bodin et al.	IRP, TSP
1984	2	Golden et al.; Tsiligirides	FSMVRP, Generalized VRP
1985	3	Christophides; Dror et al.; Jézéquel	MCVRP, SVRP
1986	2	Dror and Levy; Nag	IRP, Site-dependent VRP
1987	4	Dror and Ball; Jaillet; Sculli et al.; Solomon	IRP, SVRP, VRPTW
1988	3	Jaillet and Odoni; Powell; Psaraftis	SVRP, DVRP
1989	2	Balas; Dror and Trudeau	Generalized VRP, SDVRP
1990	1	Laporte and Martello	Generalized VRP
1992	5	Bertsimas; Laporte; Laporte et al.; Malandraki and Daskin; Min et al.	SVRP, MDVRP, TDVRP
1993	4	Dror et al.; Lambert et al.; Semet and Tailard; Taillard	SVRP, Site-dependent VRP
1994	2	Fisher; Rochat and Semet	Site-dependent VRP
1995	8	Bloemhof-Ruwaard et al.; Cheng et al.; Frizzell and Giffin; Gelinas et al.; Gendreau et al.; Madsen et al.; Psaraftis; Russell	FVRP, SDVRP, SVRP, PDP, DVRP, VRPTW
1996	7	Bertsimas and Simchi-Levi; Chao et al.; Gendreau et al.; Renaud et al.; Salhi and Fraser; Speranza; Teodorović and Pavković	Generalized VRP, SVRP, MDVRP, FSMVRP, IRP, FVRP, DVRP
1997	3	Daniel et al.; Fleischmann et al.; Salhi and Sari	MDVRP
1998	6	Cater and Ellram; Gendreau and Potvin; Golden et al.; Hadjiconstantinou and Baldacci; Mansini and Speranza; Min et al.	PVRP, MCVRP, LRP, DVRP
1999	4	Fagerholt; Gendreau et al.; Liu and Shen; Salhi and Nagy	FSMVRP, **G-VRP**, MDVRP, DVRP
2000	5	Ghiani and Improta; Irnich; Laporte et al.; Pronello and André; Sariklis and Powell	Generalized VRP, FSMVRP, OVRP
2001	4	Cordeau et al.; Dethloff; Ioannou et al.; Li and Lim	**VRPRL**, VRPTW
2002	7	Angelelli and Speranza; Bertazzi and Speranza; Cordeau et al.; Giosa et al.; Toth and Vigo; Wassan and Osman; Wu et al.	MDVRP, IRP, FSMVRP
2003	4	Blakeley et al.; Chajakis and Guignard; Ghiani et al.; Iori et al.	PVRP, MCVRP, VRPLC, DVRP
2004	10	Beullens et al.; Brandão; Campbell and Savelsbergh; Dekker et al.; Ho and Haugland; Moura and Oliveira; Polacek et al.; Sambracos et al.; Wasner and Zäpfel; Yang et al.	SDVRP, VRPLC, MDVRP, OVRP, IRP, **G-VRP**, DVRP
2005	7	Chao and Liou; Feillet et al.; Kallehauge et al.; Li; Nagy and Salhi; Bräysy and Gendreau (a); Bräysy and Gendreau (b)	Site-dependent VRP, Generalized VRP, MDVRP, VRPTW
2006	18	Archetti et al.; Bélanger et al.; le Blanc et al.; Bukchin and Sarin; Chen et al.; Chen and Xu; Dell'Amico, Monaci, et al.; Dell'Amico, Righini, et al.; Francis and Smilowitz; Francis et al.; Gendreau, Guertin, et al.; Gendreau, Iori, et al.; Jang et al.; Lee et al.; Min et al.; Privé et al.; Schultmann et al.; Zheng and Liu	**VRPRL**, SDVRP, PVRP, MCVRP, FSMVRP, VRPLC, MEVRP, FVRP, TDVRP, DVRP
2007	24	Alegre et al.; Alshamrani et al.; Archetti et al.; Cordeau et al.; Carrabs et al.; Crevier et al.; Doerner et al.; Dondo and Cerdá; Ichoua et al.; Iori et al.; Kara et al.; Laporte; Li et al. (a); Li et al. (b); Marinakis and Migdalas; McKinnon; Nagy and Salhi; Palmer; Repoussis et al.; Ropke et al.; Sbihi and Eglese (a); Sbihi and Eglese (b); Zhang and Tang; Zhao et al.	**G-VRP**, **PRP**, **VRPRL**, Site-dependent VRP, IRP, MDVRP, VRPLC, FSMVRP, OVRP, LRP, DVRP, PDP, VRPTW
2008	25	Alonso et al.; Apaydin and Gonullu; Baldacci, Battarra, et al.; Baldacci, Christofides, et al.; Bräysy et al.; Cheung et al.; El Fallahi et al.; Gendreau, Iori, et al.; Gendreau, Potvin, et al.; Golden et al.; Gribkovskaia et al.; Kallehauge; Krikke et al.; Krumke et al.; Malapert et al.; Marasš; Moura; Nanthavanij et al.; Oppen and Løkketangen; Paraskevopoulos et al.; Parragh et al. (a); Parragh et al. (b); Srivastava; Taveares et al.; Zhao et al.;	**G-VRP**, **VRPRL**, Site-dependent VRP, FSMVRP, MCVRP, VRPLC, VRPTW, IRP, PDP, IRP, DVRP
2009	25	Baldacci and Mingozzi; Baldacci et al.; Bräysy et al.; Crainic et al.; Erbao and Mingyong; Figliozzi; Fuellerer et al.; Khebbache et al.; Kim et al.; Laporte; Li, Mirchandani, et al.; Li, Tian, et al.; Liu et al.; Pirkwieser and Gunther; Potvin; Prescott-Gagnon et al.; Prins; Qureshi et al.; Soler et al.; Tang et al.; Tarantilis et al.; Wang and Lu; Wen et al.; Yu et al.; Zachariadis et al.;	**VRPRL**, FSMVRP, MEVRP, FVRP, VRPLC, DVRP, PVRP, MEVRP, VRPTW, OVRP, TDVRP
2010	23	Andersson et al.; Angelelli et al.; Azi et al.; Baldacci, Bartolini, et al.; Baldacci, Toth, et al.; Bauer et al.; Çatay; Christensen and Rousøe; Erbao and Mingyong; Fagerholt et al.; Figliozzi; Fuellerer et al.; Gajpal and Abad; Li et al.; Liao et al.; Maden et al.; Mendoza et al.; Muyldermans and Pang; Polimeni and Vitetta; Qureshi et al.; Rei et al.; Repoussis and Tarantilis; Kuo;	**G-VRP**, **VRPRL**, **PRP**, IRP, Generalized VRP, Site-dependent VRP, VRPLC, FVRP, SVRP, MEVRP, MCVRP, FSMVRP, DVRP, VRPTW, PDP
2011	26	Aras et al.; Archetti et al.; Baldacci et al.; Bektaş and Laporte; Belenguer et al.; Bortfeldt; Brandão; Cappanera et al.; Derigs et al.; Duhamel et al.; Faulin et al.; Leung et al.; Mar-Ortiz et al.; Mu and Eglese; Mu et al.; Pang; Perboli et al.; Ramos and Oliveira; Salani and Vacca; Tasan and Gen; Tricoire et al.; Ubeda et al.; Wen et al.; Xu et al.; Yu and Yang; Zachariadis et al.;	**VRPRL**, **PRP**, SDVRP, LRP, MDVRP, VRPLC, Site-dependent VRP, MCVRP, DVRP, MEVRP, FVRP, FSMVRP, VRPTW, PVRP

Table 1 (*continued*)

Year	Number of papers	The list of the papers	The studied VRP variants
2012	23	Baldacci et al.; Coelho et al.; Cordeau and Maischbergr; Demir et al.; ErdoÄŸan and Miller-Hooks; Figliozzi; Hemmelmayr et al.; Hong; Jin et al.; Kok et al.; Kritzinger et al.; Kuo and Wang; Li et al.; Marinakis; Mingozzi et al.; Moccia et al.; Pillac et al.; Qureshi et al.; Ribeiro and Laporte; Salimifard et al.; Schneider et al.; Vidal et al.; Xiao et al.;	**G-VRP**, **PRP**, IRP, OVRP, MDVRP, TDVRP, MEVRP, DVRP, VRPTW, PVRP
2013	10	Baldacci et al.; Baños et al.; Berbotto et al.; Dondo and Cerdá; Lecluyse et al.; Nguyen et al.; Polimeni and Vitetta; Salhi et al.; Stenger et al.; Vidal et al.;	MEVRP, VRPTW, SDVRP, TDVRP, MDVRP

Note: CVRP, Capacitated VRP; TDVRP, Time-dependent VRP; PDP, Pickup and Delivery Problem; MDVRP, Multi-depot VRP; SVRP, Stochastic VRP; LRP, Location Routing Problem; PVRP, Periodic VRP; DVRP, Dynamic VRP; VRPTW, VRP with Time Windows; IRP, Inventory Routing Problem; FSMVRP, Fleet Size and Mix Vehicle Routing Problem; MCVRP, Multi-compartment VRP; SDVRP, Split-delivery VRP; FVRP, Fuzzy VRP; OVRP, Open VRP; VRPLC, VRP with Loading Constraints; MEVRP, Multi-echelon VRP; G-VRP, Green-VRP; PRP, Pollution Routing Problem; VRPRL, VRP in Reverse Logistics.



Note. CVRP, Capacitated VRP; TDVRP, Time-dependent VRP; PDP, Pickup and Delivery Problem; MDVRP, Multi-depot VRP; SVRP, Stochastic VRP; LRP, Location Routing Problem; PVRP, Periodic VRP; DVRP, Dynamic VRP; VRPTW, VRP with Time Windows; IRP, Inventory Routing Problem; FSMVRP, Fleet Size and Mix Vehicle Routing Problem; MCVRP, Multi-compartment VRP; SDVRP, Split-delivery VRP; FVRP, Fuzzy VRP; OVRP, Open VRP; VRPLC, VRP with Loading Constraints; MEVRP, Multi-echelon VRP; G-VRP, Green-VRP; PRP, Pollution Routing Problem; VRPRL, VRP in Reverse Logistics.

Fig. 2. The philosophy of the review work.

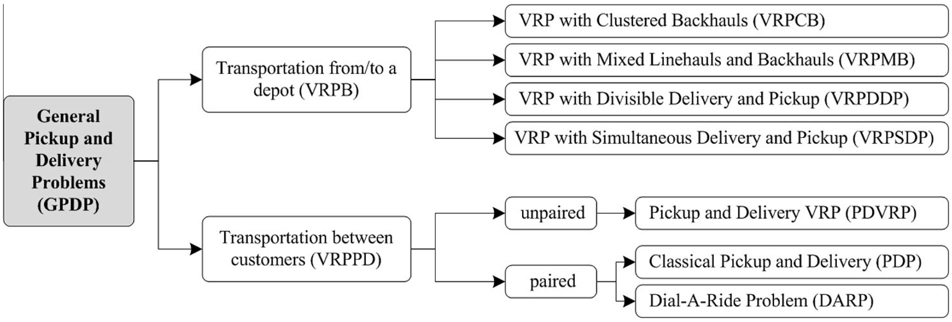


Fig. 3. Classification of the Pickup and Delivery Problem.

flected from the distribution of bold highlighted *VRP* variants in the last column of Table 1, where the bold highlighted variants, which concern Green *VRP*, mostly appear after 2006. To explore the past and new trends of *VRP* in order to better understand its evolution, our review work was performed from categorizing the traditional *VRP* to summarizing the Green *VRP*, which formed the fundamental philosophy of our review work.

2.2. The philosophy of the review work

As shown in Fig. 2, our review work includes three steps. Step 1 covers a review of the traditional *VRP* variants in the literature. It aims at providing a landscape of how different classes of problems evolved and varied in diverse application domains and operational constraints. In Step 2, the state-of-the-art of *GVRP* is summarized and criticized. Based on the traditional *VRP* variants we defined in Step 1, we discuss how the *GVRP* interacts with the traditional *VRP* variants to formulate more practical and complex models in Step 3 so as to suggest the next wave of research on *GVRP*.

2.3. Classification schemes

A comprehensive and feasible taxonomy of *VRP* is no doubt a tool to get the hang of the nature of the problem of *VRP* and to identify the future directions. There exist various classification schemes in the literature to categorize *VRP*. Using different algorithms (e.g. exact algorithm, heuristics, metaheuristics) and distinct characteristics of elements of the problem (e.g. time window structure, vehicle heterogeneity, quality of information) are the most common schemes in previous efforts by other researchers to produce a *VRP* taxonomy. Since we herein attempt to focus on the nature of the problem and application of *VRP*, our classification scheme is based on the problem characteristics and their application scenarios rather than the algorithms. One advantage of this scheme is that it enables in-depth classification of the problem, that is, sub-categories of each class can be revealed, which provides a much wider and clearer horizon to the scientific progress of this problem. Using this scheme, we identified the *GVRP* and its sub-categories.

3. A review of traditional VRP variants

At the outset, we present the traditional *VRP* variants that have been summarized and fruitfully studied in the literature, in order to demonstrate the evolution of *VRP*. One should note that although the variants are distinguishable they often stand closely related. An extensive survey of every variant would require very long paragraphs; we summarily introduce the definition, application, classification and related remarkable articles of each variant, on the basis of their first arrival on the timeline (see Fig. 5).

Since the seminal article of *VRP* by Dantzig and Ramser (1959), *VRP* has enjoyed close and extensive research attention for nearly 50 years. A variety of survey papers were published at different times to report the state-of-the-art up to that date (the latest surveys are by Cordeau, Laporte, Savelsbergh, & Vigo, 2007; Golden, Raghavan, & Wasil, 2008; Krumke, Saliba, Vredeveld, & Westphal, 2008; Laporte, 2007, 2009; Li, 2005; Marinakis & Migdalas, 2007; Potvin, 2009; Toth & Vigo, 2002). With its intrinsic relevance to the real-life applications and its growing complexity subject to operational constraints, concerns with *VRP* are still increasing and efforts are continually being made to develop more practical mathematical models and higher performance algorithms. Various classes of *VRP* have been identified and each class has received diverse scientific study. Some new *VRP* variants, such as *Multi-echelon VRP*, *VRP with Loading Constraints*, etc., have recently appeared. They incorporate new operational considerations into the problem, some of which even alter the structure of the nature of the problem.

3.1. Capacitated VRP (since 1959)

The vehicle routing problem was first introduced by Dantzig and Ramser (1959). They describe a real-world problem concerning dispatching gasoline delivery trucks between a bulk terminal and large numbers of service stations. When the number of the service stations becomes larger, options of routes increase dramatically, which thus makes the work of testing and finding an improved route to yield an optimal solution, a great burden. In order to replace this inapplicable procedure, they proposed an algorithm approach based on integer linear formulation to obtain a near optimal solution. In their truck dispatching problem, the capacity of each truck is explicitly considered (*Capacitated VRP*, *CVRP*). In the light of the properties of cost in the matrix of distance, *CVRP* can be further partitioned into *Symmetrical CVRP* (*SCVRP*) and *Asymmetrical CVRP* (*ACVRP*) (Toth & Vigo, 2002). An integer programming model of *CVRP* is presented in the appendix.

3.2. Time-dependent VRP (since 1966)

Traditional *VRP* assumes Euclidean distance as a constant. However, this contradicts the real conditions where the vehicles are moving on a real road network. The cost estimation is therefore unconvincing because the cost variability in relation to time is largely neglected (Polimeni & Vitetta, 2013). The distinctive characteristic of *Time-dependent VRP* (*TDVRP*) is that the travel time between any pair of points (customers and depots) depends on the distance between the points or on the time of day (e.g. rush hours, weather conditions). The feature of fluctuating traveling duration enables *VRP* to account for the actual conditions such as urban congestion, where the traveling speed is not constant due to variation in traffic density. As a consequence, *TDVRP* is a relevant and useful model to reveal the recurring traffic congestion problems (Lecluyse, Sörensen, & Peremans, 2013) and to explore how to avoid them (Kok, Hans, & Schutten, 2012).

The very early work related to time-dependent traveling duration includes Cooke and Halsey (1966), which extended the classical shortest path problem with static internodal time to consider varying internodal time. Nevertheless, multiple vehicles were not considered in this study. Malandraki and Daskin (1992) gave the mixed integer linear programming mathematical model of *TDVRP* and its special case, *TDTSP*. The variation of travel time was formulated as a step function within the period of a day. The travel time step function was then discussed in terms of how it influences the final solution. Two nearest neighbor heuristics were presented for solving *TDVRP* and *TDTSP* respectively. The extension of *TDVRP*, *TDVRP with Time Windows* (*TDVRPTW*), has gained great attention in the *TDVRP* literature. Based on the classical benchmark instances given by Solomon (1987) and Figliozzi (2012) introduced the benchmark problems in *TDVRPTW* for evaluating and comparing the solution quality and computational time of the algorithms in this field. An Iterative Route Construction and Improvement algorithm (IRCI) was also developed to universally tackle either constant or time-dependent speed problems with hard or soft time windows. Other research of *TDVRPTW* includes Chen, Hsueh, and Chang (2006), Kritzinger et al. (2012), and Soler, Albiach, and Martínez (2009).

TDVRP describes more real network optimization problems. More importantly, it makes it possible to use *VRP* to study the green issues in transportation, such as fuel consumption and emission, as the measurement of fuel consumption and emission is closely associated with the time-varying real-time speed in urban areas. We categorize these studies into the new variants of *VRP*: *Green-VRP* and the *Pollution Routing Problem*, which are summarized in Section 6.

3.3. Pickup and Delivery Problem (since 1967)

The *Pickup and Delivery Problem* (*PDP*) dates back to a dial-a-ride problem examined by Wilson and Weissberg (1967). In the research field of *VRP*, there are masses of studies in terms of *VRP with backhauls*, *VRP with pickup and delivery*, *VRP with simultaneously pickup and delivery*, *dial-a-ride problem*, etc. Some of them share a very similar structure of the nature of the problem but have slight differences that are difficult to distinguish and thus often cause confusion. In fact, all of these classes should be regarded as subcategories of *PDP*. To distinguish different sub-categories of *PDP*, Parragh, Doerner, and Hartl (2008a, 2008b) provided a literature synthesis for *PDP* and gave a very reasonable classification of *PDP*. According to their summary, the problem classes are shown in Fig. 3.

3.4. Multi-depot VRP (since 1969)

Multi-depot VRP (*MDVRP*), which was firstly studied by Tillman (1969), contains more than one depot and each customer is visited by a vehicle that is assigned to one of these depots (i.e. every vehicle route must start and end at the same depot). *MDVRP* naturally originates from a variety of physical distribution problems such as the delivery of meals, chemical products, soft drinks, machines, industrial gasses, packaged food, etc. and previous studies have shown the substantial economic savings in these cases achieved by the use of optimization techniques (Renaud, Laporte, & Boctor, 1996). Various extensions of *MDVRP* are discussed in the literature, including *MDVRP with Time Windows* (Dondo & Cerdá, 2007; Giosa, Tansini, & Viera, 2002; Polacek, Hartl, Doerner, & Reimann, 2004), *MDVRP with Backhauls* (Min, Current, & Schiling, 1992; Salhi & Nagy, 1999), *MDVRP with Pickup and Delivery* (Nagy & Salhi, 2005), *MDVRP with Mix Fleet* (Salhi, Imran, & Wassan, 2013; Salhi & Sari, 1997), *Multi-depot Location Routing Problem* (Wasner & Zäpfel, 2004; Wu, Low, & Bai, 2002), *MDVRP with Loading Cost* (Kuo & Wang, 2012),*MDVRP with Inter-depots* (Angelelli & Speranza, 2002; Crevier, Cordeau, & Laporte, 2007) where the intermediate depots act as either warehouses for replenishment in a distribution system, or as recycling facilities for vehicles to unload in a collection system.

3.5. Stochastic VRP (since 1969)

Stochastic VRP (*SVRP*) arises whenever some elements like customer demand, travel times, and even the set of customers in the routing problem are random (Gendreau, Laporte, & Séguin, 1996). Probability theory is the main tool to represent the uncertainty in mathematical models in this context. Gendreau et al. (1996) provided an extensive survey on *SVRP*. Based on the nature of different stochastic components, *SVRP* can be categorized into different variants: *VRP with Stochastic Demand* (Dror, Laporte, & Louveaux, 1993; Golden, Stewart, & Jr., 1978; Jaillet & Odoni, 1988; Mendoza, Castanier, Guéret, Medaglia, & Velasco, 2010; Rei, Gendreau, & Soriano 2010; Tillman, 1969), *VRP with Stochastic Customers* (Bertsimas, 1992; Jaillet, 1987; Jézéquel, 1985), *VRP with Stochastic Customers and Demands* (Gendreau, Laporte, & Séguin, 1995; Jézéquel, 1985;), *VRP with Stochastic Travel Time* (Lambert, Laporte, & Louveaux, 1993), *VRP with Stochastic Demand and Travel Time* (Cook & Russell, 1978), *VRP with Stochastic Travel Time and Service Time* (Laporte, Louveaux, & Mercure, 1992; Li, Tian, & Leung, 2010).

3.6. Location Routing Problem (since 1973)

It is observed that the separated design of depot location and vehicle routing often yields a suboptimal solution and generates extra cost, which motivates the advent of a *Location Routing Problem* (*LRP*) (Watson-Gandy & Dohm, 1973). In *LRP*, the joint decisions consist of opening a single or a set of depots and designing a number of routes for each opened depot, with the objectives of minimizing the overall cost comprising the fixed costs of opening the depots and the costs of the routes. The application of *LRP* can be found in waste collection, postbox location, parcel delivery, mobile communications access networks, and grocery distribution (Baldacci, Mingozzi, & Calvo, 2011). *LRP* is the generalization of *CVRP* (with single depot) or the *MDVRP* without addressing the location aspect (Belenguer, Benavent, Prins, Prodhon, & Calvo, 2011). Min, Jayaraman, and Srivastava (1998) provided a classification of *LRP* from different perspectives including deterministic or stochastic demand, capacitated or incapacitated depots, capacitated or incapacitated vehicles, etc. Another more recent review of *LRP* is referred to Nagy and Salhi (2007).

3.7. Periodic VRP (since 1974)

Beltrami and Bodin (1974) developed algorithms to solving routing problems for municipal waste collection with time constraints, in which locations (customers) required different numbers of visits and different day combinations for visits in a week. Given this visiting schedule requested by customers, the classical *VRP* is extended not only to determine a shortest route but also to assign the tours to certain days of the week. The objective is to find a feasible routing solution such that the total cost of the routes over the time horizon (week) is minimized. This problem is donated as the *Periodic Vehicle Routing Problem* (*PVRP*). The significance of studying *PVRP* is motivated by many real-world applications, such as waste collection, industrial gas distribution, grocery industry, picking up raw materials from suppliers (Alegre, Laguna, & Pacheco, 2007), and even the allocation of workforce (Blakeley, Arguello, Cao, Hall, & Knolmajer, 2003; Jang, Lim, Crowe, Raskin, & Perkins, 2006). In the literature, extensions of *PVRP* includes *Multi-depot PVRP* (Hadjiconstantinou & Baldacci, 1998), *PVRP with Service Choice* (Francis & Smilowitz, 2006; Francis, Smilowitz, & Tzur, 2006), *PVRP with Time Windows* (Bélanger, Desaulniers, Soumis, & Desrosiers, 2006; Pirkwieser & Gunther, 2009). *Site-dependent Multi-trip PVRP* (Alonso, Alvarez, & Beasley, 2008).

3.8. Dynamic VRP (since 1976)

The traditional *VRP* deals with a deterministic operational environment where all information is known (offline) before routes are constructed and remains static during the execution of the routing plan. However, the circumstances in the real-world is not always deterministic and static because uncertainty, such as breakdown of vehicles, traffic control, and continually arriving customer requests, frequently takes place. Reflecting such uncertainty in a dynamic operational environment, *Dynamic VRP* (*DVRP*), which dates back to Speidel (1976) and Psaraftis (1980), is featured by the ongoing fashion in which the information such as vehicle locations, customer orders are revealed over time. The typically studied *DVRP* concerns a dynamic operation in which the customer requests are released during the planning period (online requests) and should be assigned in real time to appropriate vehicles. It is motivated by a variety of real-life applications such as dynamic fleet management, vendor-managed distribution systems, courier service, repair or rescue service, dial-a-ride service, emergency service, as well as taxi cab service (Ghiani, Guerriero, Laporte, & Musmanno, 2003). So far, various classes of *DVRP* with different aspects of operational constraints have been investigated and reported in the literature, which fall into the main categories: *DVRP with Time Windows* (Chen & Xu, 2006; Gendreau, Guertin, Potvin, & Taillard, 1999; Hong, 2012; Madsen, Tosti, & Vælds, 1995) and *DVRP with Pickup and Delivery and Time Windows* (Cheung, Choy, Li, Shi, & Tang, 2008; Gendreau, Guertin, Potvin, & Séguin, 2006; Yang, Jaillet, & Mahmassani, 2004). The overview of *DVRP* with regards to its application and algorithm is presented by Angelelli, Bianchessi, Mansini, and Speranza (2010), Bertsimas and Simchi-Levi (1996), Gendreau and Potvin (1998), Ghiani et al. (2003), Ichoua, Gendreau, and Potvin (2007), Powell (1988), and Psaraftis (1988, 1995), and very recently by Pillac, Gendreau, Guéret, and Medaglia (2012).

Disrupted VRP is a variant of *DVRP* with real-time rerouting and rescheduling (Li, Mirchandani, & Borenstein, 2009; Mu, Fu, Lysgaard, & Eglese, 2011). Disruption to the original vehicle routing plans is sometimes caused by unforeseen events, such as traffic jams, breakdowns, or the postponed departure from depots or customer points (Mu & Eglese, 2011). As the original plans may not remain optimal due to the disruption, it needs timely adjustment to minimize the inevitable and negative effects. *Disrupted VRP* concerns disruption management during the execution stage of a dispatching plan. With the time window constraints, the problem aims at not only the least weighted sum of total distance, but also the minimization of deviations from the predefined time windows (Zhang & Tang, 2007).

3.9. Inventory Routing Problem (since 1984)

The *Inventory Routing Problem* (*IRP*) was first considered by Bell et al. (1983) to deal with the distribution of air products in terms of integrated inventory management and vehicle dispatching. A distinguishing feature of *IRP* is to guarantee that there are no stockouts at each customer (Dror, Ball, & Golden, 1985; Dror & Levy, 1986). Several early studies (Bertazzi & Speranza, 2002; Dror & Ball, 1987; Speranza, 1996) addressed *IRP* of only a single vehicle or a single customer, which cannot entirely describe the complexity in real-world problems and do not match the nature of *VRP*. Archetti, Bertazzi, Laporte, and Speranza (2007) proposed the first exact algorithm for *IRP* in the context of Vender-managed Inventory (VMI). They used a branch-and-cut algorithm to successfully tackle the problem with up to 50 customers when the time horizon was equal to 3. Coelho, Cordeau, and Laporte (2012) very recently considered more practical cases in VMI in which the goods can be transshipped from supplier to customer or from customer to customer. They employed the large neighborhood search heuristic combined with a network flow algorithm to simultaneously decide the optimal inventory and routing solution. However, both of these 2 studies only handled a single vehicle case in the VMI system. Zhao, Wang, and Lai (2007) and Zhao, Chen, and Zang (2008) took into account multi-vehicle cases in VMI and employed different approaches to tackle the inventory/routing problem. Another interesting study by Campbell and Savelsbergh (2004) was motivated by an industrial gasses company which implements VMI with their customers. Considering a long planning horizon and customer consumption rates in the vehicle routing model, the study determined the timing, sizing, and routing of the deliveries so that the average distribution cost during the planning period is minimized and no stockouts occur. By leveraging a two-phase algorithm that is composed of an integer program in phase 1 and an insertion heuristic in phase 2, large-scale real-life instances (up to 100 customers) were tested. Andersson, Hoff, Christiansen, Hasle, and Løkketangen (2010) presented an excellent and exhaustive literature survey of *IRP*. Implications of trends both in industry and in research were also provided.

3.10. Fleet Size and Mix Vehicle Routing Problem (since 1984)

Clark and Wright (1964) developed an effective saving heuristic algorithm to improve the Datzig-Ramser approach. They relaxed the assumption of identical vehicle capacity in Datzig and Ramser's model. Extending *VRP* with heterogeneous vehicles is practically relevant because vehicles differ in speed, carrying capacity, equipment as well as cost structure. In reality, the common problem that bothers the logistics decision makers is: How many and what size of vehicles are necessary to accommodate the demand at the least expense (Golden, Assad, & Dahl, 1984)? The *Fleet Size and Mix VRP* (*FSMVRP*) (Baldacci, Battarra, & Vigo, 2009; Liu, Huang, & Ma, 2009) is to solve this question to determine the most economic combination of vehicles in the fleet when considering the trade-off between the fixed vehicle costs and the variable costs proportional to the distance traveled. A more complex case in the fleet size problem is to consider heterogeneous vehicles with different capacities and traveling cost. *FSMVRP with Time Windows* (Bräysy, Dullaert, Hasle, Mester, & Gendreau, 2008; Bräysy, Porkka, Dullaert, Repoussis, & Tarantilis, 2009; Dell'Amico, Monaci, Pagani, & Vigo, 2006; Li, Golden, & Wasil, 2007; Liu & Shen, 1999; Paraskevopoulos, Repoussis, Tarantilis, Ioannou, & Prastacos, 2008; Repoussis & Tarantilis, 2010; Wassan & Osman, 2002) has been well studied as an extension of *FSMVRP*. *FSMVRP with Multi-depot* (Irnich, 2000; Salhi & Fraser, 1996; Salhi & Sari, 1997) is another natural extension of *FSMVRP* to determine which customers are to be associated with different depots in addition to the optimum fleet composition and routes. Dondo and Cerdá (2007) considered a combined multi-depot and time window version in *FSMVRP*.

3.11. Generalized VRP (since 1984)

In *Generalized VRP* (Ghiani & Improta, 2000), the customers are partitioned into clusters and vehicles are obligated to visit only one customer in each cluster (i.e. each cluster should be visited exactly once). The prototype of *Generalized VRP* dates back to the orienteering problem introduced by Tsiligirides (1984) and extended as a team orienteering problem by Chao, Golden, and Wasil (1996). They are characterized by the case that visiting customers is associated with different scores (or profits) and due to the time limitation, it is impossible to traverse all of the customers. What subset of the customers is to be visited, how to assign these selected customers to vehicles, and how to dispatch the vehicles so as to achieve maximum total profit become the objectives and thus make a multi-level optimization problem concerning routing. Very similar problems and studies in the literature include prize collecting traveling salesman problems (Balas, 1989), the selective traveling salesman problem (Laporte & Martello, 1990), the traveling salesman problem with profits (Feillet, Dejax, & Gendreau, 2005), *VRP* with selective backhauls (Gribkovskaia, Laporte, & Shyshou, 2008; Privé, Renaud, Boctor, & Laporte, 2006). Baldacci, Bartolini, and Laporte (2010) provided an exhaustive survey on *Generalized VRP* and its applications.

3.12. Multi-compartment VRP (since 1985)

VRP with multiple compartments (*MCVRP*) (Christophides, 1985) differs from the traditional *VRP* in that goods in *MCVRP* are inhomogeneous and non-intermixable in the sense that they have to be delivered in multiple compartments on the same vehicle. In *MCVRP*, each customer requests one or more types of products; each product required by a customer must be delivered by only one vehicle (i.e. the demand of a customer for one given product cannot be split); however, multiple visits are allowed to deliver different requested products so as to fulfill the demand set of products. *MCVRP* naturally arises in several industries, such as delivery of food to convenience stores and fuel distribution. Chajakis and Guignard (2003) proposed optimization models with the consideration of two possible cargo space layouts. Bukchin and Sarin (2006) attempted to determine a loading policy which minimizes the number of required shipments per unit of time, by the comparison between two loading policies: the continuous and static loading policy and the discrete and dynamic loading policy. El Fallahi, Prins, and Wolfler Calvo (2008) developed a genetic algorithm hybridized with a local search procedure, namely, the Memetic Algorithm, and a tabu search for solving *MCVRP*. Mendoza et al. (2010) introduced uncertainty of customer demands to *MCVRP* and developed the optimization model as *MCVRP with Stochastic Demands*. Other applications in co-collecting different types of waste, collecting milk of different types and qualities can be found in the work of Muyldermans and Pang (2010) and Oppen and Løkketangen (2008). An overview of *MCVRP*, including a benchmark suite of 200 instances and a discussion of heuristics for *MCVRP*, is provided by Derigs et al. (2011).

3.13. Site-dependent VRP (since 1986)

In *Site-dependent VRP* (Nag, 1986), there are compatible independencies between customers (sites) and vehicle types. Each customer is allowed to be visited by only one set of vehicle types rather than by all types. One customer has to select only one type of this set of allowable vehicle types. A comprehensive definition and illustration can be found in the work of Chao and Liou (2005). Many real-life application problems, such as refuse collection (Sculli, Mok, & Cheung, 1987), grocery delivery (Semet & Tailard, 1993), pet food and flour distribution (Rochat & Semet, 1994), can be formulated as *Site-dependent VRP* models. A survey of the studies of *Site-dependent VRP* before 2005 is provided in Chao and Liou (2005). *Site-dependent VRP* was mentioned as a variant of the general heterogeneous *VRP* in Baldacci, Battarra, and Vigo (2008) and Baldacci, Toth, and Vigo (2010). The *Skill VRP*, which originates from a real-world problem concerning dispatching technicians with different skill levels to conduct the after-sales service, is a special case of *Site-dependent VRP* (Cappanera, Gouveia, & Scutellà, 2011). Alonso et al. (2008) presented an explicit and direct research on *Site-dependent VRP*.

3.14. Split-delivery VRP (since 1989)

In the majority of the aforementioned *VRP*, each customer is assumed to be visited by a vehicle exactly only once. However, this confinement is not always realistic because sometimes the customer demand exceeds the vehicle capacity. In this case, this constraint should be relaxed to allow each customer to be serviced by more than one vehicle. *Split-delivery VRP* (*SDVRP*), the extension of *VRP* that deals with this real-life operation, was first introduced by Dror and Trudeau (1989) who demonstrated that remarkable cost savings with regard to the number of vehicles utilized and the total traveling distance can be achieved by split deliveries. Archetti, Savelsbergh, and Speranza (2006) showed that these savings can reach up to 50%. The research in this field mainly focuses on algorithms for tackling this complex problem. *SDVRP with Time Windows* (Archetti, Bouchard, & Desaulniers, 2011; Frizzell & Giffin, 1995; Ho & Haugland, 2004; Salani & Vacca, 2011) is the main extension of *SDVRP* in the literature.

3.15. Fuzzy VRP (since 1995)

In real-life application, time windows and customer demand are frequently set by ambiguous linguistic statements like "14:00 to 16:00 is highly preferred", "approximately between 200 and 300 items are needed". In this context, fuzzy logic is used in *VRP* to formulate the uncertain, subjective, ambiguous, and vague elements. *VRP with Fuzzy Time Windows* (*VRPFTW*) directly investigates how service time preference influences the logistics service level. Cheng, Gen, and Tozawa (1995) replaced fixed time window with a fuzzy due-time, the fuzzy membership function of which is correlative to the degree of customer satisfaction of service time. They used genetic algorithm to find the maximum average satisfaction as well as other traditional objectives of *VRP*. To cope with the fuzziness of time windows, Tang, Pan, Fung, and Lau (2009) considered linear and concave fuzzy membership functions for the fuzzy soft time window and formulated a multi-objective model for the *VRPFTW* so as to minimize the routing cost and to maximize the overall customer satisfaction level. A two-stage algorithm is proposed to decompose *VRPFTW* into a traditional vehicle routing problem with time window and a service improvement problem and then solve these two sub-problems sequentially. Xu, Yan, and Li (2011) proposed a global–local-neighbor particle swarm optimization with exchangeable particles to tackle a very similar problem. Other versions of *FVRP* include *VRP with Fuzzy Demand* (Erbao & Mingyong, 2009, 2010; Teodorović & Pavković, 1996) and *VRP with Fuzzy Travel Time* (Zheng & Liu, 2006).

3.16. Open VRP (since 2000)

In*Open VRP* (*OVRP*), which was firstly introduced by Sariklis and Powell (2000), each route is Hamiltonian path rather than a Hamiltonian cycle as vehicles are not required to return to the depot after servicing all the affiliated customers. This key feature was described in Schrage (1981) mentioning real-life routing problems. It is naturally encountered in the newspaper or mail delivery service. In particular, this problem is faced by the companies that outsource the deliveries to the third party logistics provider (3PL) as the external vehicles are not obligated to return to the depot. Brandão (2004) proposed a tabu search for *OVRP*. The initial solution was derived by using a nearest neighbor heuristic and a pseudo lower bound based approach, while the solution was improved by using the nearest neighbor method and the unstringing and stringing procedure. The extensive computational experiments showed that the proposed tabu search was very competitive in its ability to find very good solutions within a very short computation time, remarkably outperforming Sariklis and Powell's (2000) algorithm. Li, Golden, and Wasil (2007b) provided a survey on the algorithms for solving the *OVRP*. Repoussis, Tarantilis, and Ioannou (2007) addressed *OVRP with Time Windows* and conducted a survey on the related studies in real-world cases, such as the delivery of school meals, school bus routing, the plans of passing through tunnels of trains, etc. Very recently, Li, Leung, and Tian (2012) studied a heterogeneous fixed fleet *OVRP*, in which vehicles are heterogeneous and of a limited number and with different costs per unit distance. This problem more closely describes the real situation of the transportation in outsourcing carriers. A multi-start adaptive memory programming meta-heuristic combined with modified tabu search was proposed to solve the problem.

3.17. VRP with Loading Constraints (since 2003)

VRP with Loading Constraints (*VRPLC*) jointly determines the optimal routes and packing patterns (Zachariadis, Tarantilis, & Kiranoudis, 2012). Ladany and Mehrez (1984) presented a traveling salesman problem with pickup and delivery and Last-In-First-Out (LIFO) loading constraint. The most frequently studied problem in the literature is the *Two-dimensional Capacitated VRP* (*2L-CVRP*) (Duhamel, Lacomme, Quilliot, & Toussaint, 2011; Fuellerer, Doerner, Hartl, & Iori, 2009; Gendreau, Iori, Laporte, & Martello, 2008; Iori, Salazar-González, & Vigo, 2003, 2007; Khebbache, Prins, Yalaoui, & Reghioui, 2009; Leung, Zhou, Zhang, & Zheng, 2011; Zachariadis, Tarantilis, & Kiranoudis, 2009). In *2L-CVRP*, customer demand consists of rectangular two-dimensional weighted items. The problem calls for the minimization of total cost of routes, with a feasible orthogonal packing pattern of the items onto the two-dimensional loading surface of each vehicle, without exceeding the vehicle weight capacity. Other extensions of *VRPLC* include *Two-dimensional Pickup and Delivery Routing Problem* (Malapert, Guéret, Jussien, Langevin, & Rousseau, 2008), *Three-dimensional Capacitated VRP* (Bortfeldt, 2012; Christensen & Rousøe, 2010; Fuellerer, Doerner, Hartl, & Iori, 2010; Gendreau, Iori, Laporte, & Martello, 2006; Tarantilis, Zachariadis, & Kiranoudis, 2009), *Vehicle Routing with Time Windows and Loading Problem* (Moura, 2008; Moura & Oliveira, 2004), *Multi-Pile Routing Problem* (Doerner, Fuellerer, Gronalt, Hartl, & Iori, 2007; Tricoire, Doerner, Hartl, & Iori, 2011), *The Pallet-Packing Vehicle Routing Problem* (Zachariadis et al., 2012), *Pickup and Delivery TSP with LIFO Loading* (Carrabs, Cordeau, & Laporte, 2007).

3.18. Multi-echelon VRP (since 2009)

Multi-echelon VRP (*MEVRP*) is to study the movement of flows in a multi-echelon distribution strategy, where the delivery of freight from the origin to the customers is compulsorily delivered through an intermediate depot (Perboli, Tadei, & Vigo, 2011). It aims at minimizing the total transportation cost of the vehicles involved at all levels. Multi-echelon transportation systems naturally originate from many different real-world industries, such as newspaper and press distribution, e-commerce and home delivery service, and express postal service. The most common instance is *Two-echelon VRP* (*2EVRP*) with the first level linking the depot to the intermediate depots (named satellites) and the second level connecting the satellites to the customers, which is also known as cross-docking (Lee, Jung, & Lee, 2006; Liao, Lin, & Shih, 2010; Wen, Larsen, Clausen, Cordeau, & Laporte, 2009). Crainic, Ricciardi, and Storchi (2009) investigated *Two-echelon Capacitated VRP* (*2E-CVRP*) in a two-tier distribution facility structure in the context of city logistics planning. Multiple trips, multiple depots, multiple products, heterogeneous vehicles, soft time windows (at customers) and hard time windows (at satellites) were considered. In Perboli et al. (2011), *2E-CVRP* was explicitly examined by a flow-based mathematical model and two math-based heuristics were derived from the model. An instance with the size of 50 customers and 4 satellites was tested.

4. VRP with Time Windows (since 1977)

Heuristic approaches for *VRP* did not consider service time intervals or due dates as constraints of the model until Russell (1977) presented an effective heuristic for the M-tour traveling salesman problem. He accommodated the time window restrictions in his model and extended Lin and Kernighan's heuristic to propose a MTOUR heuristic that could give better-quality solutions. Before Russell's study, *VRP* with time windows had dealt mainly with case studies (Solomon, 1987). Generally, there are two types of time windows that are extensively studied in the literature:

(1) Hard Time Windows, where a vehicle must arrive and be ready to serve the customer before or right before the specified time interval. Late arrival is not allowed. If the vehicle arrives earlier than the time window, it has to wait.
(2) Soft Time Window, where the violation of the time window constraint is acceptable at the price of some penalty (Kallehauge, 2008).

The hard time window constraint seems to naturally describe the real-world situation, but sometimes no feasible or executable solution can be obtained if all time window constraints need to be satisfied. Relaxing this strict restriction might result in a better solution with respect to total distance or to the total number of vehicles. Furthermore, a tiny deviation from the customer-specified time window is acceptable in real life (Tang et al., 2009). The adoption of soft time window constraints deals with this practical violation and it receives close attention in many practical scenarios. Relaxing hard time windows might lead to lower cost without significantly hurting customer satisfaction (Figliozzi, 2010). In particular, Semi Soft Time Windows (Qureshi, Taniguchi, & Yamada, 2009, 2010), as a variant of Soft Time Windows, refers to the scenario where early arrival is allowed at no cost while late arrival incurs a penalty cost.

VRP with Time Windows (*VRPTW*) is the most common variant in the literature. The introduction of time windows has led to the growth of research interest in various real scenarios concerning routing. Recent surveys of *VRPTW* have been conducted by Bräysy and Gendreau (2005a, 2005b), Kallehauge (2008), and Kallehauge, Larsen, Madsen, and Solomon (2005). A typical mathematical model of *VRPTW* is presented in the appendix. Recent studies of *VRPTW* tend to not merely focus on the minimization of transportation cost. A variety of new research angles have been pursued to keep pace with the new service strategies (e.g. make-to-order) of the growing industry. Figliozzi (2009) reflected how time window constraints and customer demand levels influence the average distance of *VRP*, which is an important indicator associated with the decisions in network design, facility location and fleet sizing, especially for delivering high value-high time sensitive products. Instead of using traditional optimization heuristics, the study developed a probabilistic modeling approach to approximate the average length of the routes traveled. Polimeni, Russo, and Vitetta (2010) integrated a demand model (commodity flow) and a routing model (vehicle flow) with time windows so as to present a macro-architectural view of goods movement in the context of city logistics. Door-to-door delivery, which is a growing industry of city logistics, often suffers from the great pressure from both the customer-defined service time intervals and the unexpected disruption of traffic conditions in urban places. To cope with the dynamic re-routing problems caused, Qureshi, Taniguchi, and Yamada (2012) proposed a *Dynamic Vehicle Routing Problem with Soft Time Windows* model to help freight carriers avoid extra cost as well as lateness of goods delivery.

5. Algorithms and main benchmark test instances

VRP is a NP-hard combinatorial optimization problem. The optimal or near-optimal solution is generally obtained by using *exact algorithms* or *approximate algorithms*. *Exact algorithms* can only tackle problems of a relatively small scale. According to Laporte (1992), *exact algorithms* for *VRP* are classified into three broad categories: (1) direct tree search methods; (2) dynamic programming; (3) integer linear programming. The related papers in these three categories were also discussed to present the rationale of the algorithms.

Approximate algorithms are able to find very near-optimal solutions for large-scale problems within a very satisfactory computation time, and thus commonly used in practice. A variety of *approximate algorithms*, including *classical heuristics* and *metaheuristics* since 1980s, are proposed in the literature to efficiently solve different variants of *VRP*. Based on the survey by Cordeau, Gendreau, Laporte, Potvin, and Semet (2002) and Laporte, Gendreau, Potvin, and Semet (2000), there are mainly several categories of *classical heuristics*: (1) Saving algorithms; (2) Sequential improve-

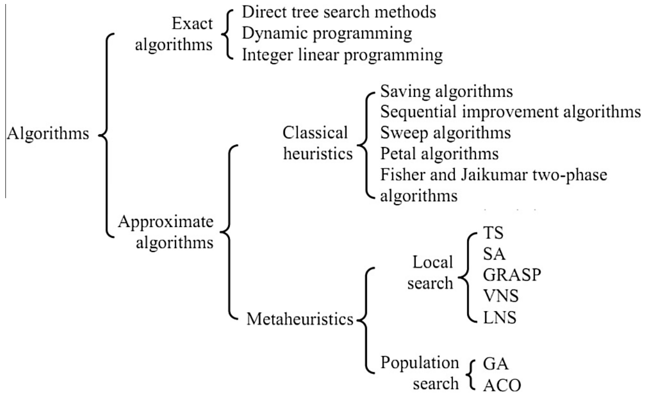


Fig. 4. The algorithms for *VRP* and their relation.

Table 3
The main benchmark instances for *VRP*.

VRP variants	Benchmark test instances
Capacitated VRP	Christofides, Mingozzi, and Toth (1979) Taillard (1993) Fisher (1994) Golden, Wasil, Kelly, and Chao (1998)
VRP with Time Windows	Solomon (1987) Russell (1995)
Pickup and Delivery Problem with Time Windows	Li and Lim (2001) Ropke, Cordeau, and Laporte (2007)
Multi-depot VRP with Time Windows	Cordeau, Laporte, and Mercier (2001)
Periodic VRP with Time Windows	Cordeau et al. (2001)
VRP with Backhauls and Time Windows	Gelinas, Desrochers, Desrosiers, and Solomon (1995)

ment algorithms; (3) Sweep algorithms; (4) Petal algorithms; (5) Fisher and Jaikumar two-phase algorithms; (6) Improvement heuristics. Compared with the *classical heuristics*, *metaheuristics* carry out a more thorough search of the solution space, allowing inferior and sometimes infeasible moves, in addition to re-combining solutions to create new ones. As a result,*metaheuristics* are capable of consistently producing high quality solutions, in spite of its greater computation time than early *heuristics*. (Cordeau et al., 2002). *Metaheuristics* can be categorized into two main types:

(1) *Local search.* Local search based methods keep exploring the solution space by iteratively moving from the current solution to another promising solution in its neighborhood. The main local search based metaheuristics for *VRP* include: (1) tabu search (TS); (2) simulated annealing (SA); (3) Greedy Randomized Adaptive Search Procedure (GRASP); (4) Variable Neighborhood Search (VNS); (5) Large Neighborhood Search (LNS).
(2) *Population search.* Population search based methods maintain a pool of good parent solutions, by continually selecting parent solutions to produce promising offspring so as to update the pool. Typical examples are: (1) Genetic Algorithms (GA); (2) Ant Colony Optimization (ACO).

Fig. 4 summarizes the relation among the above-mentioned algorithms. Table 2 lists the papers related to the exact and approximate algorithms for *VRP* in the recent decade, with a focus on *metaheuristics*. For the research work of metaheuristics, Gendreau, Potvin, Bräysy, Hasle, and Løkketangen (2008) have listed the bibliography of metaheuristics for solving *VRP* and its extensions. Only the papers since 2008 are cited in this table.

In the literature, benchmark test instances for various *VRP* variants have been created. These instances provide a data set for a variety of solution methods that solve a certain *VRP* variant and conduct extensive computational experiments. In this way, the performance of different algorithms and the solution results can be evaluated and compared. Table 3 presents the main benchmark instances for *VRP*.

Though the *VRP* variants discussed above have covered a large number of subjects, few studies of them investigated the environmental and ecological impact that is caused in the real-world Vehicle Routing Problems. The recent advent of a limited number of papers on *VRP* that concerns the optimization of green impact bridges the gap, which is discussed in the next section.

6. Green Vehicle Routing Problem (since 2006)

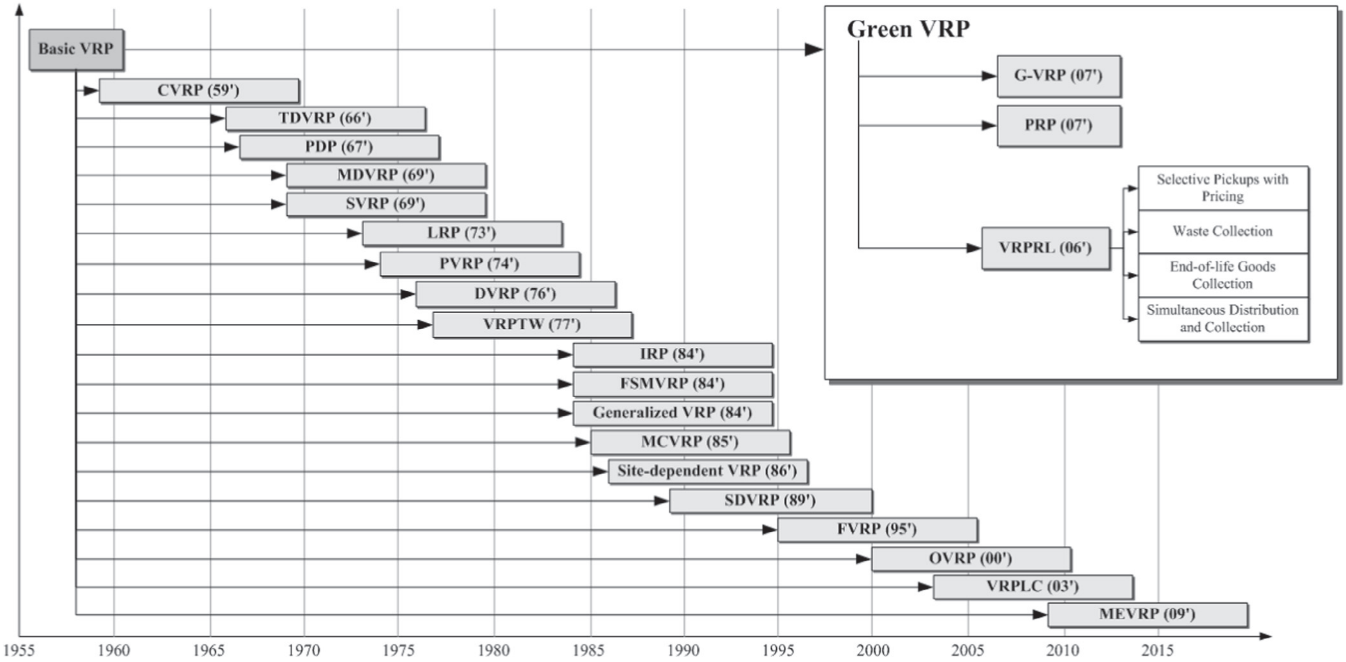
Fig. 5 provides a landscape of the state-of-the-art of *VRP*, which renews the existing taxonomy of *VRP* by adding the *GVRP* variants. The *GVRP*, which was mainly investigated since 2006, are reviewed and criticized in this section. Based on the classification scheme, we define three major categories of *GVRP*, including *Green-VRP*, *Pollution Routing Problem*, and *VRP in Reverse Logistics*. We also discuss their future interesting research areas for those who are dedicated to research into *GVRP*.

6.1. Green-VRP

The research on *Green-VRP* (*G-VRP*) deals with the optimization of energy consumption of transportation. The review begins with illustrating (i) transportation and energy consumption, followed by the survey on (ii) the current studies on *G-VRP* during 2007–2012. (iii) The future research directions in *G-VRP* are then suggested.

Table 2
The algorithms for *VRP* and recent related papers.

Algorithms	Papers
Exact algorithms	Azi, Gendreau, and Potvin (2010), Baldacci, Christofides, and Mingozzi (2008), Baldacci and Mingozzi (2009), Baldacci, Mingozzi, and Roberti (2012), Baldacci, Mingozzi, Roberti, and Calvo (2013), Mingozzi, Roberti, and Toth (2012), and Qureshi et al. (2009)
Classical heuristics	Dondo and Cerdá (2013), Figliozzi (2010), Gajpal and Abad (2010), Li et al. (2007a), and Pang (2011)
TS	Berbotto, García, and Nogales (2013), Brandão (2011), Cordeau and Maischberger (2012), Jin, Crainic, and Løkketangen (2012), Moccia, Cordeau, and Laporte (2012), and Nguyen, Crainic, and Toulouse (2013)
SA	Baños, Ortega, Gil, Fernández, and de Toro (2013) and Kuo (2010)
GRASP	Marinakis (2012) and Prins (2009)
VNS	Kuo and Wang (2012), Paraskevopoulos et al. (2008), Salhi et al. (2013), Stenger, Vigo, Enz, and Schwind (2013), and Wen, Krapper, Larsen, and Stidsen (2011)
LNS	Hemmelmayr, Cordeau, and Crainic (2012), Prescott-Gagnon, Desaulniers, and Rousseau (2009), and Ribeiro and Laporte (2012)
GA	Liu et al. (2009), Vidal, Crainic, Gendreau, Lahrichi, and Rei (2012), Vidal, Crainic, Gendreau, and Prins (2013), and Wang and Lu (2009)
ACO	Fuellerer et al. (2009), Li, Tian, and Leung (2009), Yu and Yang (2011), and Yu, Yang, and Yao (2009)



Note. CVRP, Capacitated VRP; TDVRP, Time-dependent VRP; PDP, Pickup and Delivery Problem; MDVRP, Multi-depot VRP; SVRP, Stochastic VRP; LRP, Location Routing Problem; PVRP, Periodic VRP; DVRP, Dynamic VRP; VRPTW, VRP with Time Windows; IRP, Inventory Routing Problem; FSMVRP, Fleet Size and Mix Vehicle Routing Problem; MCVRP, Multi-compartment VRP; SDVRP, Split-delivery VRP; FVRP, Fuzzy VRP; OVRP, Open VRP; VRPLC, VRP with Loading Constraints; MEVRP, Multi-echelon VRP; G-VRP, Green-VRP; PRP, Pollution Routing Problem; VRPRL, VRP in Reverse Logistics.

Fig. 5. A landscape of the state-of-the-art of *VRP*.

6.1.1. Transportation and energy consumption

As the overuse of energy and air pollution have imposed a threat on our ecological environment, governments, non-profit organizations, as well as private companies have started to take the initiative to participate in this green campaign. The US government has made some energy policies for reducing fossil fuel consumption and for supporting alternative fuel, though barriers to implementing these sustainable solutions still exist. Private companies have started to make some changes at the operational level in their business to prevent too much damage to the environment. Logistics activities, such as product development, production process, transportation, waste management, can have a great impact on the environment and thus call for more environmentally-friendly practices.

Transportation, which is one of the most important parts of logistics, is the irreplaceable fundamental infrastructure for economic growth. However, it is also one of the hugest petroleum consumers and accounts for a large part of the overall pollutants (Salimifard et al., 2012). Researchers and entrepreneurs tend to pay close attention to the role that transportation will play in achieving positive environmental effects. The new green transportation solution may clash with the designated economic objectives. Exploring the relationship between environmental effect and transportation through route planning will be able to provide practical and valuable suggestions regarding this green campaign.

6.1.2. The current studies on G-VRP during 2007–2012

G-VRP is the Vehicle Routing Problems concerning energy consumption. Fuel cost accounts for a significant part of the total cost of the petroleum-based transportation (Xiao, Zhao, Kaku, & Xu, 2012). Reducing the fuel consumption and improving the transportation efficiency at an operational level would be the most straightforward course of action. It is also desirable that a decrease petroleum-based fuel consumption can correspondingly reduce the greenhouse gas emission significantly (ErdoÄŸan & Miller-Hooks, 2012; Xiao et al., 2012). Therefore, fuel consumption is an important index in the *G-VRP* (Kuo, 2010). In order to include the fuel consumption in the routing model, the formulation of computing fuel consumption with respect to the condition of a traveling vehicle is essential. According to the report by the US Department of Energy. (2008), travel speed, the weight of the load as well as the transportation distance are the factors that affect the fuel consumption. Some studies about the fuel consumption model in terms of transportation exist in the literature, which provide relevant reference to the research on *G-VRP*.

The existing research on *VRP* with the aim of minimizing the fuel consumption seems rare. Kara, Kara, and Yetis (2007) considered a more realistic cost of transportation that is affected by the load of the vehicle as well as the distance of the arc traveled. They define *Energy Minimizing Vehicle Routing Problem* (*EMVRP*) as the *CVRP* with a new objective of cost, in which the cost function is a product of the total load (including the weight of the empty vehicle) and the length of the arc. However, they used work to represent the energy so as to simplify the relationship between minimizing the consumed energy and the variables of the vehicle conditions. Details of the formulation of fuel consumption are not provided. A formulation of fuel consumption is provided in Xiao et al. (2012). They proposed a Fuel Consumption Rate (FCR) considered CVRP (*FCVRP*), which extends *CVRP* with the objective of minimizing fuel consumption. In their paper, both the distance traveled and the load are considered as the factors which determine the fuel costs. FCR is taken as a load dependent function, where FCR is linearly associated with the vehicle's load. Besides the transportation distance and the loading weight that are addressed in the above two papers, Kuo (2010) added the transportation speed to the fuel consumption calculation model in time-dependent *VRPs*. Other *VRP*-related studies that aim at minimizing total fuel consumption include Apaydin and Gonullu (2008), Fagerholt (1999), Maraš (2008), Nanthavanij, Boonprasurt, Jaruphongsa, and Ammarapala (2008), Sambracos, Paravantis, Tarantilis, and Kiranoudis (2004), and Taveares, Zaigraiova, Semiao, and da Graca Carvalho (2008).

Another problem of *G-VRP* deals with the recharging or refueling of the vehicles, particularly, the alternative-fuel powered vehicle (AFV). Government agencies, nonprofit organizations, municipalities and some private companies have started to convert their fleets of trucks to AFVs so as either to satisfy the energy policies or environmental regulations, or to voluntarily reduce the environmental impact (ErdoÄŸan & Miller-Hooks, 2012). The above papers concerning fuel consumption merely come up with the formulation for computing the fuel consumption, assuming that the fuel is adequate for coving the whole tour. They do not consider the distance limitation that depends on fuel tank capacity. In this problem, recharging stations in the tour to overcome the capacity limitation of fuel tank are considered. To the best of our knowledge, there are only 2 research papers in the literature that address refueling or recharging problems. ErdoÄŸan and Miller-Hooks (2012) is the first to consider the possibility of recharging or refueling a vehicle on the route in *VRP*. They denoted this problem as *Green-VRP* (*G-VRP*), in which AFV are allowed to refuel on the tour to extend the distance it can travel. With the objective of minimizing the total distance, the model seeks to eliminate the risk of running out of fuel. They consider service time of each customer and the maximum duration restriction was posed on each route. Schneider, Stenger, and Goeke D. (2012) extended *G-VRP* with time windows.

6.1.3. Future research directions in G-VRP

As shown in Table 4, the existing *G-VRP* studies only cover vehicle capacity and time window constraints. There exist extensive *VRP* variants that can be combined with the *G-VRP* model and make it comprehensive and closer and more applicable to real-world problems. Heterogeneous vehicles are still not explored in the existing literature. As the fuel consumption model is closely related to the condition of the vehicle, the flexibility offered by using different types of vehicles may result in more reduction of fuel consumption. But it is still not yet known to what extent a mixed fleet might contribute to reducing the energy consumption. In the recharging problems, some restrictions in the real world have not yet been accommodated in the routing model. For example, the availability and the fuel capacity of the recharging stations will cause some change to the optimal routes. The stochastic service time of the recharging stations is also worth attention as it influences the time traveled and the arrival time at each point. Techniques like queuing models seem suitable for tackling the service time problem in this context.

6.2. The Pollution Routing Problem

The road transport sector accounts for a large percentage of Greenhouse Gas (GHG) and in particular CO_2 emissions. The pollution from the emissions has direct or indirect hazardous effects on humans and on the whole ecosystem. The growing concerns about such negative impacts of transportation on the environment require re-planning of the road transport network and flow by explicitly considering GHG emission (Bektaş & Laporte, 2011). Putting the *VRP*, at the center of transportation planning, opens opportunities for reducing emissions by including broader objectives that reflect environmental cost. The *Pollution Routing Problem* (*PRP*) aims at choosing a vehicle dispatching scheme with less pollution, in particular, reduction of carbon emissions. The review of *PRP* firstly investigates (i) the current studies on *PRP* during 2007–2012, and then gives (ii) the future research directions in *PRP*.

Table 4
Recent studies of *G-VRP* during 2007–2012.

VRP variants	Papers (Total: 5)
Basic VRP or TSP	ErdoÄŸan and Miller-Hooks (2012)
Capacitated VRP	Kara et al. (2007), Kuo (2010), and Xiao et al. (2012)
VRP with Time Windows	Schneider et al. (2012)

6.2.1. The current studies on PRP during 2007–2012

Reducing CO_2 emissions by extending the traditional *VRP* objectives of economic costs to consider relevant social and environmental impact is achievable (Bektaş & Laporte, 2011; Maden, Eglese, & Black, 2010; McKinnon, 2007; Palmer, 2007; Sbihi & Eglese, 2007a). However, related studies on *VRP* from the perspective of minimizing emissions are seldom found. The traditional *VRP* objective of reducing the total distance will in itself contribute to a decrease of fuel consumption and environmental pollutant emissions. But this relationship needs to be directly measured using more accurate formulations. Pronello and André (2000) suggested that reliable models to measure the pollution generated by vehicle routes need to take into account more factors, such as the traveling time when the engine is cold. Only with these models can the environmental benefits in *VRP* be quantified. Sbihi and Eglese (2007a) considered a *TDVRP* in the context of traffic congestion. Since less pollution is produced when the vehicles are at best speeds, directing them away from congestion tends to be more environmental-friendly, even though it leads to longer traveling distance. Maden et al. (2010) also presented a *TDVRP* with congestion and reported about a 7% reduction of CO_2 emissions based on an emission measurement function was observed after planning routes according to the time-varying speeds. However, the objective of their *VRP* model remains the minimization of the total travel time rather than the reduction of emissions. Palmer (2007) developed an integrated routing and carbon dioxide emissions model and calculated the amount of CO_2 emitted on the journey as well as the traveling time and distance. The paper examined how the speed affects the reduction of CO_2 emissions in different congestion scenarios with time windows. The results showed that about 5% of reduction of CO_2 emissions could be achieved. Bauer, Bektaş, and Crainic (2010) explicitly focus on minimizing greenhouse gas emissions in a model of intermodal freight transport, showing the potential of intermodal freight transport for reducing greenhouse emissions. Fagerholt, Laporte, and Norstad (2010) tried to reduce the fuel consumption and fuel emissions by optimizing speed in a shipping scenario. Given the fixed shipping routes and the time windows, the speed of each segment of a route is optimized in order to yield fuel savings.

Some studies sought to formulate a comprehensive objective function which measures economic costs and environmental costs so as to meet efficiency objectives and green criteria simultaneously. Ubeda, Arcelus, and Faulin (2011) conducted a case study in which minimization of both the distances and pollutant emissions is the objective. The results also revealed that backhauling seems more effective in controlling emissions. This suggests that backhauling could be initiated by companies to enhance energy consumption efficiency and reduce environmental impact. It appears that this paper is the first to incorporate minimizing GHG emissions in the model of *Vehicle Routing Problem with Backhauls*. Bektaş and Laporte (2011) proposed a *Pollution Routing Problem* with or without time windows and developed a comprehensive objective function that integrates the minimization of the cost of carbon emissions along with the operational costs of drivers and fuel consumption. However, their model assumed a free-flow speed of at least 40 km/h, which was contrary to the real world situation where congestion occurs. Following up this research, Demir, Bektaş, and Laporte (2012) proposed an extended Adaptive Large Neighborhood Search (ANLS) for *PRP* in order to enhance the computation efficiency for medium or large scale *PRP*. Faulin, Juan, Lera, and Grasman (2011) presented a *CVRP* with environmental criteria and considered more complex environmental impact. Apart from the traditional economic costs measurement and the environmental costs that are caused by polluting emissions, the environmental costs derived from noise, congestion and wear and tear on infrastructure were also considered.

6.2.2. Future research directions in PRP

Bektaş and Laporte (2011) highlighted several very inspiring conclusions based on the observation of their computational experiment results. They also provided the possibility of considering heterogeneous vehicles and time-dependent conditions in future research. We believe that the speed of vehicles and the traffic conditions especially in the congested urban areas are not negligible and the real-time transportation information is able to lay a solid foundation for continual research into the *PRP* by providing dynamic real-world data. With the support of real-time information about traffic conditions, vehicles can be directed to other roads which are less congested. This implies a more environmental-friendly case because less emission is generated when vehicles are traveling at the best speeds. In this context, the problem concerns whether those routes with good traffic conditions are preferable at the expense of choosing a longer path. Thus interesting future study may come up with exploring the trade-off between greater traveling distance (economic costs) and environmental impact (environmental costs).

One remarkable observation from Bektaş and Laporte (2011) is that an appropriate time window restriction makes the effect of energy reduction more significant. Based on this relation, future research may involve exploring the trade-off between the economic cost (including penalties) and the environmental cost in routing problems with soft time window constraints. Another interesting observation is that higher variation of customer demand can contribute to more room for energy consumption reduction. Chances are that inventory models can be incorporated into the *PDP* model to determine an optimal set of customer demands that yields the most environmental cost effectiveness, especially in VMI policy where the customer demand is flexible and can be distributed in different combinations. In that case, further study of *IRP* may extend its objectives with more environmental indicators, not merely the traditional economic cost like overall time or distance. The current studies on *PRP* are shown in Table 5.

6.3. VRP in Reverse Logistics (VRPRL)

Reverse logistics has received close attention in recent years. Dekker, Fleischmann, Inderfurth, and Van Wassenhove (2004) defined reverse logistics as "The process of planning, implementing and controlling backward flows of raw materials, in process inventory, packaging and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal". An overview of reverse logistics was provided by Carter and Ellram (1998).

Table 5
Recent studies of *PRP* during 2007–2012.

VRP variants	Papers (Total: 6)
Basic VRP or TSP	Bauer et al. (2010)
Capacitated VRP	Faulin et al. (2011);
VRP with Time Windows	Bektaş and Laporte (2011), Demir et al. (2012), Fagerholt et al. (2010), and Palmer (2007);
VRP with Clustered Backhauls	Ubeda et al. (2010)

VRP in Reverse Logistics (*VRPRL*) focuses on the distribution aspects of reverse logistics. There is a large amount of research on reverse logistics. However, we found only a small number of studies on reverse logistics from the perspective of vehicle routing. Actually, on the medium level of a reverse logistics system, the operator and the relationship between the forward and backward (reverse) flows make a difference on the operational level. In this context, Vehicle Routing Problems occur in different situations, which make *VRP* a direct and pertinent model for formulating the transportation issues in reverse logistics. Beullens, Wassenhove, and Oudheusden (2004) detected some gaps between vehicle routing models for reverse logistics and the availability of vehicle routing solution approaches in the literature. However, the coverage seems not exhaustive enough. Most *VRPRL* studies deal with recycling waste or end-of-life goods to one or more than one depot for further reprocessing. To facilitate the review of existing research of *VRPRL*, the problem is subdivided into four categories: Selective Pickups with Pricing, Waste Collection, End-of-life Goods Collection, and Simultaneous Distribution and Collection, which are summarized below. The future research directions in *VPRRL* are also suggested.

6.3.1. Selective Pickups with Pricing

The selective-pickup vehicle routing problem with pricing in reverse logistics is characterized by only choosing profitable pickup points to visit and by making the collection operation as profitable as possible. This problem incorporates *VRP with Profits* (Feillet et al., 2005) in the Pickup and Delivery Problem. A literature review of this problem was provided by Aras, Aksen, and Tekin (2011). Studies on this problem in the literature are limited. Privé et al. (2006) analyzed a vehicle-routing problem with the delivery of soft drinks to convenience stores and the pickup of empty bottles and aluminum cans. Each customer is visited exactly once. The deliveries were mandatory while the pickup process at each point was optional. Such collection was undertaken only when there was enough unused space and sufficient available loading capacity to load the collection at that moment. This problem was formulated as a *Vehicle Routing Problem with Pickups and Delivery*, with the setting of time window constraints, heterogeneous vehicles, and multiple types of products. The objective was the minimization of routing costs, minus the revenue yielded from the recycled bottles and cans. Gribkovskaia et al. (2008) examined a very similar problem but each customer was allowed to be visited twice. Aras et al. (2011) presented a selective multi-depot vehicle routing problem with pricing, in which the visit to each customer was selective, dependent on whether the visit was profitable and whether the remaining vehicle space could load all the recyclable products of that customer. Split collection was not allowed.

6.3.2. Waste Collection

Waste management, including waste avoidance, reuse and recycling, is a key process in protecting the environment and conserving resources. The transportation of waste materials is clearly part of the Green Logistics agenda (Sbihi & Eglese, 2007a). Vehicle routing models for waste collection issues date back to Beltrami and Bodin (1974). Recently they have been regarded as an important part of reverse logistics. Different variants of *VRP* are addressed in the literature to investigate the waste collection problem. Sculli et al. (1987) considered a *Site-dependent VRP* in refuse collection in Hong Kong. Mansini and Speranza (1998) developed a linear programming model for refuse collection services, which is a *Multi-compartment VRP*. *Multi-depot VRP* and *Location Routing Problem* for designing a waste recycling network were also discussed in Ramos and Oliveira (2011) and Mar-Ortiz, Adenso-Diaz, and González-Velarde (2011), respectively.

Table 6
Recent studies of *VRPRL*.

VRP variants	Papers (Total: 17)
Selective Pickups with Pricing (Total: 3)	
Capacitated VRP	Aras et al. (2011);
VRP with Time Windows	Privé et al. (2006);
VRP with Simultaneous Delivery and Pickup	Privé et al. (2006);
Multi-deopt VRP	Aras et al. (2011);
Mix Fleet VRP	Privé et al. (2006);
Generalized VRP	Gribkovskaia et al. (2008) and Aras et al. (2011)
Waste Collection (Total: 4)	
Multi-deopt VRP	Ramos and Oliveira (2011)
Mix Fleet VRP	Mar-Ortiz et al. (2011)
Location Routing Problem	Mar-Ortiz et al. (2011
Site-dependent VRP	Sculli et al. (1987)
Multi-compartment VRP	Mansini and Speranza (1998)
End-of-life Goods Collection (Total: 5)	
Capacitated VRP	Schultmann et al. (2006), Kim et al. (2009), and Kim et al. (2011)
Multi-depot VRP	le Blanc et al. (2006) and Kim et al. (2011)
Inventory Routing Problem	Krikke et al. (2008)
Simultaneous Distribution and Collection (Total: 5)	
VRP with Simultaneous Delivery and Pickup	Alshamrani et al. (2007), Çatay (2010), Dell'Amico, Monaci, et al. (2006), Dell'Amico, Righini, et al. (2006), Dethloff (2001), and Tasan and Gen (2012)

6.3.3. End-of-life Goods Collection

The collection of some components of end-of-life products can benefit the original manufacturer because the recycled materials or components remain functional after further disposal or remanufacturing. Schultmann, Zumkeller, and Rentz (2006) investigated the reverse logistics of components of end-of-life vehicles in Germany. Tabu search is used to minimize the total distance of visiting up to 1,202 dismantlers scattered throughout Germany. le Blanc, van Krieken, Krikke, and Fleuren (2006) also presented a case study concerning recycling end-of-life vehicle components to optimize the logistics network for collecting containers that are used to deliver end-of-life materials from dismantlers in the Netherlands. They considered a vehicle routing model with settings of multiple depots and pickup and delivery. Krikke, le Blanc, van Krieken, and Fleuren (2008) considered the *Inventory Routing Problem* in the collection of materials that are disassembled from end-of-life vehicles. Using online inventory information, the inventory levels were observed and then used to construct collection plans including two types of collection orders: MUST and CAN orders. Kim, Yang, and Lee (2009) studied the backward flow of logistics for recycling end-of-life consumer electronic goods in South Korea. The model assumed that each regional recycling center (depot) had a fixed but sufficient number of identical vehicles and maximum traveling distance for each vehicle was constrained. Even though there were four regional recycling centers in the case study, they formulated models for each depot separately rather than a multi-depot vehicle routing model. Kim, Yang, and Lee (2011) extended a similar problem to a *Multi-depot VRP*. As shown above, some of the studies in this category considered the scenarios of multiple depots. Other constraints, such as time window settings, pickup and delivery, split visits, site-dependent visits, and periodic visits, are not addressed in the literature that deals with this problem.

6.3.4. Simultaneous Distribution and Collection

Studies of this problem use a *VRP with Simultaneous Delivery and Pickup* model to formulate the distribution process of reverse logistics. Dell'Amico, Righini, and Salani (2006) defined a 0–1 linear programming model and studied the application of the branch-and-price technique in solving this problem. Alshamrani, Mathur, and Ballou (2007) examined a real-world problem of blood distribution and collection of blood containers. Penalty cost was generated when the containers were not picked up. Additionally, stochastic demand and periodic visits were considered in the proposed model. Other studies include Dethloff (2001), Çatay (2010), and Tasan and Gen (2012).

6.3.5. Future research directions in VRPRL

In the light of the characteristics of the reverse logistics system and its operation, multi-depot setting and simultaneous pickup and delivery operations received relatively more attention in the studies of *VRPRL*, as shown in Table 6. However, time windows and periodic delivery imposed by the customer are seldom considered in the existing studies, even though such situations are frequently encountered in real-life waste collection issues. Additionally, most of papers we investigated above deal with the reverse flow from commercial locations, in which the issue was correspondingly modeled as a *Node Routing Problem*. Nevertheless, residential collection, which involves recycling household refuse door by door along a street, is a different problem and should be formulated as an *Arc Routing Problem*. To the best of our knowledge, research on the vehicle routing problem regarding the reverse logistics of residential collection (household refuse or end-of-life products) does not exist in the literature.

Reverse logistics in a multi-echelon distribution system also offer new research opportunities for *VRPRL*. Multi-echelon reverse logistics network design has drawn researchers' interest in the literature (Fleischmann et al., 1997). Recently, Min, Ko, and Ko (2006) developed a nonlinear mixed integer programming model and genetic algorithm to provide a minimum-cost solution for designing a multi-echelon reverse logistics network. Srivastava (2008) also formulated a cost effective and efficient multi-echelon reverse logistics network with multiple products and maximum profit. However, both of them tackled the network design problem from the perspectives of location-allocation rather than vehicle routing. Since multi-echelon reverse logistics networks play a significant role in Green Logistics, using vehicle routing models to optimize this network will make a significant impact on Greenness.

Overall, *GVRP* has grabbed researchers' attention during the last several years. Since its study is still at the beginning stage, there exist a variety of future research areas, as suggested in the next section.

7. Trends and future directions of Green Vehicle Routing Problems

Based on the review on the traditional *VRP* variants and *GVRP* presented above, we draw the following conclusions about the trends of *GVRP*, through the analysis of how the *GVRP* can interact with the traditional *VRP* variants.

7.1. Interdisciplinary research and systematic approaches

Although the number of the publication on *GVRP* is growing, the studies are still limited. The reason for this may be the fact that solving such problems calls for an interdisciplinary approach incorporating energy use and environmental impact, public policy, engineering, transportation system management, and even urban planning. The wide scope of the research content requires an interdisciplinary and systematic approach provided by researchers and engineers from different backgrounds. Besides, the experimental problem instances in existing research mainly come from previous research or are generated randomly. More realistic experimental data and real-world cases that support the research still need to be provided by government or other official organizations.

7.2. VRP with uncertainty

Stochastic service time, stochastic traveling time as well as stochastic customer demand are largely neglected in the literature, though these parameters are frequently used to describe the dynamic environment. Queuing models and inventory models might be involved in this problem to make the studies more convincing. The time windows and the customer demand in place will make more room for the reduction of energy consumption. In most cases, the time windows and customer demand are set by ambiguous linguistic statements and are closely related to the customer satisfaction level. Using the fuzzy theory, future studies may explore the trade-off between customer satisfaction, environmental cost and economic cost.

7.3. More operational constraints in waste collection

Most existing research assumed that the vehicles were identical. The studies incorporating heterogeneous vehicles are still limited. When dealing with using *Site-dependent VRP* to solve the waste collection problem, the different vehicle types are a key factor to determine the optimal routes. Other cases include considering multi-compartment vehicles and two-dimensional or three-dimensional loading constraints in recycling classified garbage. The problem of reverse logistics of residential collection, which is frequently encountered in real-life issues and should be formulated as *Arc Routing Problem*, is worthy of study.

7.4. Multi-echelon distribution system

All the problems presented focus on the traditional one-level distribution system rather than the multi-echelon distribution network. As the multi-echelon distribution system has drawn attention for academic research or for practical application, it is well worth exploring whether a multi-echelon vehicle dispatching system has a significant impact on reducing overall energy consumption and emissions. As part of green supply chain management, a multi-echelon reverse logistics network opens new possibilities for determining a more cost effective solution of dispatching vehicles for recycling refuse or end-of-life products.

8. Conclusion

Concern about Green Logistics has been constantly increasing both in industry and in academic research. In line with this "green" trend, *GVRP* has received scientific attention from researchers in the OR/MS field. To bring order into the research literature on *GVRP*, we reviewed the articles about *GVRP*, together with analyzing how the traditional *VRP* variants could be involved in or interact with *GVRP* and contribute to further study on *GVRP*. Notably, we suggest the trends and future directions for *GVRP* which offer insights and inspiration for interested researchers.

Even though the current literature of *GVRP* is still limited to idealized models and the gaps between the theoretical achievements and applicable agenda, we see a large number of potential, fruitful and practical research outcomes in this area. There is still a long way to go on the path to connect *VRP* with sustainable issues. We hope and trust that this literature survey will stimulate researchers' and logistics practitioners' interests in *GVRP* and lead to new research and application opportunities for a sustainable industry.

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Appendix A. Mathematical models for CVRP and VRPTW

A.1. The formulation of CVRP (Fisher & Jaikumar, 1981)

Constants

K	The number of vehicles
n	The number of all customer nodes. All customers are indexed from 1 to n and the central depot is denoted as index 0
b_k	The capacity of vehicle k
a_i	The weight or volume of the shipment to customer i
c_{ij}	The cost of direct travel from customer i to customer j

Decision variables

y_{ik}	y_{ik} equals 1 if the order from customer i is delivered by vehicle k. Otherwise, y_{ik} equals 0
x_{ijk}	x_{ijk} equals 1 if vehicle k travels directly from customer i to customer j. Otherwise, x_{ijk} equals 0

The mathematical model

$$\min \sum_{ijk} c_{ij} x_{ijk} \tag{1}$$

s.t.

$$\sum_i a_i y_{ik} \leqslant b_k, \quad k = 1, \ldots, K \tag{2}$$

$$\sum_k y_{ik} = \begin{cases} K, & i = 0 \\ 1, & i = 1, \ldots, n \end{cases} \tag{3}$$

$$y_{ik} \in \{0, 1\}, \quad i = 0, \ldots, n;\ k = 1, \ldots, K \tag{4}$$

$$\sum_i x_{ijk} = y_{jk}, \quad j = 0, \ldots, n;\ k = 1, \ldots, K \tag{5}$$

$$\sum_j x_{ijk} = y_{ik}, \quad i = 0, \ldots, n;\ k = 1, \ldots, K \tag{6}$$

$$\sum_{ij \in S \times S} x_{ijk} \leqslant |S| - 1, \quad S \subseteq \{1, \ldots, n\};\ 2 \leqslant |S| \leqslant n - 1;\ k = 1, \ldots, K \tag{7}$$

$$x_{ijk} \in \{0, 1\}, \quad i = 0, \ldots, n;\ j = 0, \ldots, n;\ k = 1, \ldots, K \tag{8}$$

The objective function (1) aims at minimizing the total cost of transportation. Constraints (2)–(4) are the constraints of a generalized assignment problem, ensuring that the load assigned to a vehicle does not exceed the vehicle capacity, that each vehicle starts and ends at the depot, and that each customer is visited by some vehicle. Constraint (5)–(8) define a traveling salesman problem over the customers that have been assigned to a given vehicle *k*.

Appendix B. The formulation of VRPTW (Ioannou, Kritikos, & Prastacos, 2001)

Constants

V	The set of available identical vehicles
C	The capacity of vehicle
L	The set of customers including the depot. Index $i = 1$ refers to the depot while indices i, j and u valued between 2 and n denote the customers
q_i	The demand of customer i
$[e_i, l_i]$	The time window requested by customer i, where e_i represents the earliest service starting time and l_i refers to the latest service starting time
s_i	The service time of customer i
t_{ij}	The travel time directly from customer i to customer j
c_{ij}	The cost of direct travel from customer i to customer j
w_k	The fixed cost of activating vehicle k

Variables

a_i	The arrival time to customer i
p_i	The departure time from customer i

Decision variables

x_{ij}^k	x_{ij}^k equals 1 if customer i follows customer j in the sequence of customers visited by vehicle k. Otherwise, x_{ij}^k equals 0
z_k	z_k equals 1 if vehicle k is activated. Otherwise, z_k equals 0

The mathematical model

$$\min \sum_{k=1}^{|V|}\sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}x_{ij}^k + \sum_{k=1}^{|V|} w_k z_k \tag{9}$$

s.t.

$$\sum_{i=1}^{n}\sum_{k=1}^{|V|} x_{ij}^k = 1, \quad \forall j = 2,3,\ldots,n \tag{10}$$

$$\sum_{j=1}^{n}\sum_{k=1}^{|V|} x_{ij}^k = 1, \quad \forall i = 2,3,\ldots,n \tag{11}$$

$$x_{ij}^k \leqslant z_k, \quad \forall i,j = 1,2,\ldots,n \tag{12}$$

$$\sum_{j=2}^{n} x_{1j}^k \leqslant 1, \quad \forall k = 1,2,\ldots,|V| \tag{13}$$

$$\sum_{i=2}^{n} x_{i1}^k \leqslant 1, \quad \forall k = 1,2,\ldots,|V| \tag{14}$$

$$\sum_{i=2}^{n} x_{iu}^k - \sum_{j=2}^{n} x_{uj}^k = 0, \quad \forall k = 1,\ldots,|V|;\ \forall u = 1,\ldots,n \tag{15}$$

$$\sum_{i\in F}\sum_{j\in F} x_{ij}^k \leqslant \sum_{i\in F}\sum_{j\in L} x_{ij}^k - 1, \quad \forall F \subseteq L;\ 2 \leqslant |F| \leqslant \sum_{i\in L}\sum_{j\in L} x_{ij}^k,\ \forall k \in V \tag{16}$$

$$\sum_{i=1}^{n} q_i \left(\sum_{j=1}^{n} x_{ij}^k\right) \leqslant C, \quad \forall k = 1,2,\ldots,|V| \tag{17}$$

$$a_j \geqslant (p_i + t_{ij}) - (1 - x_{ij}^k)M, \quad \forall i,j = 1,2,\ldots,n;\ \forall k = 1,2,\ldots,|V| \tag{18}$$

$$a_j \leqslant (p_i + t_{ij}) + (1 - x_{ij}^k)M, \quad \forall i,j = 1,2,\ldots,n;\ \forall k = 1,2,\ldots,|V| \tag{19}$$

$$a_i \leqslant p_i - s_i, \quad \forall i = 1,\ldots,n \tag{20}$$

$$e_i \leqslant p_i \leqslant l_i, \quad \forall i = 1,\ldots,n \tag{21}$$

$$a_1 = 0 \tag{22}$$

$$x_{ij}^k \in \{0,1\}, \quad \forall i,j = 1,\ldots,n;\ \forall k = 1,2,\ldots,|V| \tag{23}$$

$$z_k \in \{0,1\}, \quad \forall k = 1,2,\ldots,|V| \tag{24}$$

The objective function (9) formulates the trade-off between transportation and vehicle activation cost. Constraint (10) and (11) guarantee that every customer is serviced by exactly one vehicle. Constraint (12) ensures that no customers can be serviced by inactive vehicles. Constraint (13) and (14) bound the number of arcs, related to each vehicle directly leaving from and returning to the depot, to less than one, respectively. Constraint (15) accounts for the flow conservation equation that ensures the continuity of each vehicle route. Constraint (16) eliminates sub-tours. Constraint (17) limits the total load of each vehicle not larger than the vehicle capacity. Constraint (18) and (19) make sure that if customers j follows customer i in the route, the arrival time at customer j is equal to the departure time from customer i, plus the travel time between these two customers. Constraint (20) and (21) relate arrival time, departure time, and service time and guarantee that their relationships are compatible to the time window. Constraint (22) means the departure time from the depot is zero. Constraint (23) and (24) enforce x_{ij}^k and z_k as binary variables.

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