

Vehicle routing problems for city logistics

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Abstract This paper surveys the vehicle routing problems met in cities for good distribution. It applies the following methodology. First, it gives an overview of the literature devoted to vehicle route optimization in cities. Then, it classifies and analyses urban logistic flows. As a result, it identifies the principal scientific challenges that need to be addressed: time-dependency, multi-level and multi-trip organization of the distribution, dynamic information. Finally, it focuses on each one of these challenges, analyses the main difficulties they imply and how they are treated in the literature.

Keywords City logistics · Time-dependent vehicle routing problem · Multi-level vehicle routing problem · Dynamic vehicle routing problem · Multi-trip vehicle routing probem

1 Introduction

Transportation has huge economic, social and environmental impacts. In 2009, 7 % of the gross domestic product (GDP) in the EU was due to the transport industry

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offered over 5 % of total employment. Public revenues benefit as well from transportation: 0.6 % of the GDP is collected from vehicle taxes and the biggest part of energy taxes (that counts 1.9 % of the GDP) comes from taxes on fuel (European Commission 2009c). Environmentally speaking, transportation has been the sector with the biggest growth rate of greenhouse gas (GHG) emissions compared to 1990 (European Commission 2009c). 60 % of the global oil consumption and 25 % of energy consumption are due to transportation (Rodrigue 2013). Moreover, road transport caused 39,000 deaths in EU in 2008 (European Commission 2009c).

On the other side, urbanization rate keeps growing. In 2007, 85 % of the EU's GDP was generated in urban areas where 72 % of the European population lived (European Commission 2009a). The urban population rate will keep growing and it is expected to reach 84 % in 2050 (European Commission 2009c).

Adding to these facts that nine out of ten Europeans believe that the traffic situation in their area should be improved (European Commission 2009a), that 69 % of road accidents occur in cities, that 25 % of the CO₂ emission of the whole transport sector comes from urban transport (European Commission 2011), and that more than half of the weight of goods in road transport are moved over distances below 50 km and more than three quarters over distances below 150 km (White paper—European Commission 2011), we can easily understand the importance of transportation in urban areas for private people, public authorities and enterprises.

Vehicle routing problems define a class of combinatorial optimization problems that allow optimizing itineraries of a fleet of vehicles, when these vehicles operate round trips (that is, have multiple stops along their itinerary). This situation represents a large part of the flow of vehicles for good distribution in cities. Previous research has demonstrated how vehicle routing optimization can lead to significant economic savings (estimated between 5–30 % by Hasle and Kloster 2007 or 5–20 % by Toth and Vigo 2002). However route optimization in cities presents some peculiarities that should foster the development of new models. The aim of this survey is to analyse these vehicle routing problems (VRP) and to discuss the directions in which future researches should be conducted in this field.

It is important to underline that our objective is not only to provide a synthesis of the existing literature on the subject. Indeed, we pursue two supplementary goals: give a clear overview of the organization of distribution in cities to help researchers to better understand the practical motivations for vehicle routing in cities; identify the most important challenges raised by vehicle routing for urban goods distribution. For these reasons, we address questions as:

- which types of city distribution schemes are organized with round-trips,
- with which volume,
- with which characteristics (for example, the number of stops, the vehicle capacity),
- with which specific constraints (for example time or size regulations).

Once these challenges are identified, we highlight the difficulties to tackle them and the solutions proposed in the literature. In view of these objectives, we split the paper in two parts and adopt the following organization:

First part (Sects. 2, 3) This part aims at identifying the main challenges, as explained above. Section 2 reviews the literature on vehicle routing for city logistics. Section 3 classifies and analyses logistic flows in cities, describes how vehicle routes are organized, and provides statistics. A discussion on the most important challenges concludes this part.

Second part (Sect. 4) In this part, each identified challenge is analysed in turn. Section 4.1 deals with VRP with time-dependent travel times. Section 4.2 considers multi-level VRP. Section 4.3 is about dynamic VRP. Section 4.4 reviews multi-trip VRP. In each case, we underline the main issues raised by the challenge in hand and present how they are addressed in literature.

Section 5 concludes the paper and opens perspectives for route optimization in the context of urban goods movement (UGM).

Before going to the core content of the paper, we have to define precisely what we mean by city logistics. The scientific community has recently adopted two main concepts. The one of *city logistics* was defined by Taniguchi et al. 2001 as “the process for totally optimizing the logistics and transport activities by private companies in urban areas while considering the traffic environment, the traffic congestion and energy consumption within the framework of a market economy”. A much larger concept is that of *urban logistics* (Ambrosini et al. 2004, Anderson et al. 2005), which includes all the organizational, behavioral, regulation and financing elements, as well as collaborative approaches, to study the logistics processes and the movements of goods and service flows in urban areas. Not only the retail distribution is concerned in this definition, but also shopping trips, civil works and city services’ maintenance, among others. In this sense UGM include all the existing flows of goods, from factories to wholesalers, from wholesalers to retail distribution, and also from shops to the households.

In this survey, we will retain the more general framework and we will consider all movements of goods related to urban logistics as defined above. However, we will use the term *city logistics* instead of *urban logistics* as it is more largely adopted in the operations research community.

2 Literature review on vehicle routing for city logistics

Two main objectives motivate vehicle route optimization in cities. The first, and the most common one, is reducing congestion and increasing mobility of freight transportation services in urban areas at minimum cost. The second is to contribute positively to the environment and to the sustainable development, mainly by contributing to reach the Kyoto objectives in terms of GHG emissions, by reducing pollution and noise or by improving living conditions of city inhabitants.

Since several stakeholders are seen in urban areas, the goals differ depending on the actors involved (Taniguchi and Van Der Heijden 2000). Public authorities’ stakes are mainly related to collective utility. Their objectives can be in conflict with the individual performance and the goals of private stakeholders, who seek mainly to increase their economic benefits by both reducing their costs and ensuring a good

quality of service. Furthermore, the leverage to attain these objectives strongly differ between these two stakeholders. While carriers control vehicle flows, local authorities can only influence them with adapted regulations. The combination of a different objective and a different leverage makes the vehicle routing models developed for these two stakeholders very different.

In the case of local authorities, models typically aim at evaluating the impact of new policies. Decisions are tactical in nature and data can only be estimated (using for example aggregation or simulation). These models are surveyed in Sect. 2.1.

In the case of private companies, the objective is generally to satisfy a daily demand at minimal cost. Problems are operational and the data fluctuates from day to day or can even evolve during the day. These models are surveyed in Sect. 2.2.

2.1 Local authorities

A first type of regulation, investigated by Muñozuri et al. (2012), is to limit the access to some special zones at some periods. The problem that arises is called Vehicle Routing Problem with Access Time Windows (VRPATW). Access time windows (access TW) differ from the TW considered in the VRP with time windows (VRPTW): they restrict the access to the overall concerned area (usually called restricted zone). Hence, they do not concern delivery times, but the time vehicles have the right to enter the zone. Also, they do not depend on the customer. Muñozuri et al. (2012) show how this type of regulations imposes extra costs to the carriers, forcing them to use more vehicles.

Limited access can be combined with the construction of a city distribution center (CDC) where goods are loaded in more environmental-friendly vehicles for final delivery. In this case, restricted zones are not constrained at some periods but for some types of vehicles. Crainic et al. (2004) discuss in details these types of architectures and show how it would reduce the number of truck-kilometers in city centers. Crainic et al. 2010 model this setting as a two-echelon VRP (2E-VRP, see Sect. 4.2) and evaluate how the use of CDC can reduce global costs comparing with VRP solution costs. More recently, variants of these models were explored in Grangier (2014), Masson et al. (2014), Nguyen et al. (2013) or Nguyen et al. (2014), where temporal decisions and synchronization issues between the different categories of vehicles are considered in more details.

Quak and de Koster (2009) also study the impact of TW and vehicle restrictions on good distribution in cities. They compute routes with the solution of a classical VRPTW, changing the data to simulate the different scenarios that they want to compare.

Boschetti and Maniezzo (2014) develop an application to help authorities to evaluate different organizational scenarios of a delivery system based on a single CDC located nearby a medium-sized city. The problem that arises is a rich variant of the Multi-Trip VRP with TW where both pickups and deliveries are considered, as well as a heterogeneous fleet of vehicles.

2.2 Companies

A first important aspect that planners should take into account is the strong relationship in urban areas between time of the day and travel times. With the development of information technologies, larger amount of data are available (see, e.g., Ehmke and Mattfeld 2010b and Ehmke et al. 2012) that can be exploited in the models. Several authors follow this line and include time-dependency in their VRP models: Taniguchi and Shimamoto (2004), Ando and Taniguchi (2006), Ehmke and Mattfeld (2010) and Kritzinger et al. (2012). Results show how it helps reducing CO₂ emissions (7 %, Maden et al. 2010) and time windows violations (solutions calculated without taking into account time-dependent travel times result in up to 60 % of missed time windows when evaluated in a time-dependent context, Donati et al. 2008).

Another characteristic of cities is their dynamics. Technical solutions now exist to handle unforeseen events by monitoring the fleet during the working time and react to these events with an intelligent re-routing of vehicles. Several authors investigate how route optimization can benefit from this information: Zeimpekis and Giaglis (2005), Novaes et al. (2011) and Qureshi et al. (2012). As an example, a courier company in Malmö, Sweden, performs a pick and delivery service. Tasks are made of up to three trips: they involve one trip when the vehicle goes to a fix destination, two trips when the vehicle moves to the pickup location and then to the delivery location, three trips when the return trip is considered. Communication allows vehicles to perform several task together, i.e., the vehicles are loaded with deliveries from several tasks. Results of the project outline how communication reduces the empty trips (from 17.3 to 15.2 %) and increases the deliveries per trip (from 1.97 to 2.28, project SMILE, 2009b).

A third difficulty carriers often have to face when delivering goods in urban areas is the road-network structure, especially in old European cities: streets are narrow with no or few parking lots and are often one-way (Crainic et al. 2004; Muñuzuri et al. 2012b). Then, big trucks cannot easily enter city centers due to structural limitations (different than limitations introduced by authorities discussed in Sect. 2.1) and small vehicles must be used. Due to their limited capacity, these smaller vehicles perform several round trips during the day. Route optimization then differs from the traditional VRP where a single trip is allowed for each vehicle. Authors that investigated this situation (in the context of city logistics) are: Fleischmann (1990), Browne et al. (2011) and Delâtre and De Barbeyrac (2012). Fleischmann (1990) was the first to consider this issue, for the delivery of miscellaneous goods in Berlin, fresh food in Duisburg or beverages in Dortmund, and demonstrated how it helps better exploiting the time horizon and the vehicle capacity.

Consolidation and collaboration, already evoked in Sect. 2.1, are also subjects that raised a lot of interest for companies. Examples are Thompson and Hassall (2012), Qureshi and Hanaoka (2005), Quak (2012) and Browne et al. (2011) that all show how the use of intermediate facilities and collaborative systems can improve the quality of service, the routing cost, and eventually decrease CO₂ emissions.

Finally, Chang and Yen (2012) consider the case of a city-courier company in Taipei. Strict TW are taken into account due to the impossibility to park along most of the city streets. Moreover, waiting is not allowed on the whole network.

3 Urban goods movement

The purpose of Sect. 2 was to identify the types of vehicle routing problems that have been addressed in the context of city logistics. In this section, we give an overview of the flows involved in cities. The aim of this section is twofold: clarify which types of flows are found in cities, characterize these flows in terms of volume and complexity. Section 3.1 proposes a detailed classification of the UGM. Section 3.2 statistically analyses the UGM.

3.1 UGM classification

A detailed classification of the movements (following the definition of Segalou et al. 2004) is given in Fig. 1 to clearly understand what exactly are UGM. In this figure, the first column exhibits the different types of UGM. The second column illustrates these UGM with some examples. The third column describes the types of flows. The fourth column finally indicates the general modeling framework used for each type of UGM.

This classification is discussed below:

		Examples	Main types of flows	Modeling framework
Inter-establishment movements IEM	3rd party transportation	Hypermarket distribution Other grocery distribution Parcel deliveries Other retailer distribution Other flows	FTL LTL LTL LTL FTL/LTL	TP VRP LTL LTL FTL → TP LTL → VRP
	Sender's account	Craftsman, artisan and small producers Wholesalers and big producers	LTL LTL	TSP VRP
	Receiver's account	Retailers own collection	LTL	TSP
End consumer movements ECM	Shopping trips	Household shopping trips	Personal transport	-
	Home and proximity deliveries	Distance purchase home deliveries Shop-exit home deliveries Reception points	LTL LTL LTL	VRP TSP VRP
	Infrastructure management flows	Building and public works Network maintenance	FTL/LTL LTL	FTL → TP LTL → VRP VRP
Urban management movements UMM	Waste collection	Household waste collection Hazardous material collection	LTL LTL	ARP Hazardous VRP
	Document deliveries	Press and postal service	LTL	VRP
	Household logistics	Household moving	FTL	Fleet management

Fig. 1 UGM classification

- Inter-establishment movements (IEM): IEM are pickup and delivery trips related to the economic activities of the urban area (Gonzalez-Feliu et al. 2014). Three main organizational modes exist for these movements:
 - Third party transport: the transport is carried out by a third-party service provider and two main strategies are identified: full truckload (FTL) or less-than-truckload (LTL). FTL approaches mainly concern hypermarket distribution, urban industry and agriculture. LTL is related to retailing and tertiary activities distribution. Typical examples are parcel delivery services, express delivery services, supermarkets and medium stores distribution, as well as restaurants, hotels, food franchising, clothing retailers provision. Companies in charge of other activities, like non-hypermarket grocery, wholesalers and pallet distribution companies can also combine FTL and LTL transport schemes. FTL schemes are in general modeled by the well-known Transportation Problem (TP), introduced by Hitchcock (1941), and LTL schemes are in general modeled as VRP.
 - Sender's own account: this category refers to transport flows carried out directly by producers, artisans, craftsmen or distribution companies. A transport carrier is not involved. Routes are in general similar to small LTL circuits, although they are under-optimized with respect to third party transport services and have only one departure point (consolidation or multiple depot approaches are less deployed in own account transport). Note that craftsmen and small enterprises have often one single vehicle. In this case, transportation schemes can be modeled as Traveling Salesman Problems (TSP). For medium and large companies with several vehicles, VRP models apply.
 - Receiver's own account: the transport for this category is performed by the receiver. Examples are the distribution companies that collect goods at their suppliers, or the retailers that go to gross companies for their supply needs. Again, these flows are in general mono-vehicle. They are assimilated to pickup routes, easily identifiable as TSP routes. They additionally have the following common characteristic: purchased goods are selected at the supplier location, which implies important pickup times at each stop of the routes.
- End-consumer movements (ECM): ECM refer to the trips that (physically) connect the goods and the consumers. They consist of two main categories:
 - Shopping trips: traditionally, ECM flows were reduced to shopping trip chains made by private cars (Gonzalez-Feliu et al. 2012c). Individually, these flows are not formally optimized since they derive from behavioral patterns. Globally, they are modeled with classical four-steps models (Ortúzar and Willumsen 2011).
 - home and proximity deliveries: Home deliveries include business-to-customer flows from the parcel delivery sector (for example e-commerce shopping) and other types of deliveries like grocery home deliveries. For the former, LTL third-party transport is used. In both cases, VRP routes have to

be optimized. When goods are physically purchased at stores and delivered home, distribution rather takes the form of a TSP. Proximity delivery relies on proximity reception points where goods are delivered. Again, they are organized as VRP, with the trend that the number of delivery points is decreased thanks to the aggregation provoked by the reception point network.

- Urban management movements (UMM): UMM flows are related to the development of a city, public maintenance and other functional needs of the city. They are of various nature and characteristics, and can be grouped into four main sub-families:
 - Infrastructure management flows: these flows derive from building and public works. They are mainly non-periodic, non-systematic flows which take place in different parts of urban areas and depend strongly on the urban planning policies. Most of them are FTL flows when related to building and public works, although some LTL routes can be defined (remember that FTL flows are generally modeled as TP while LTL as VRP). Winter road maintenance (including snow plowing, snow disposal, deicing) can be added to this family. It involves predictive and reactive activities that are generally modeled with dedicated arc routing models (Perrier et al. 2007, 2007a, 2008). Network maintenance (phone, electricity, water, optic fiber, etc.) is another example, which is in general modeled as a VRP.
 - Waste collection flows: these flows concern garbage collection for individuals and professionals. Flows are organized differently depending on the type of waste (household, recyclable, hazardous, etc.). For household waste collection, arc routing models are generally used (Del Pia and Filippi 2006) so as to aggregate collection points located in a same street and that will be served successively. Garbage collection for professionals or for recyclable waste are organized as LTL routes. They can be sub-contracted to companies specialized in reverse logistics, that might be able to mutualize waste collection with deliveries. Models can then be complex pick-up and delivery VRP. Transportation of hazardous waste also gives raise to specific VRP, with risk minimization objectives (Tarantilis and Kiranoudis 2001).
 - Document deliveries: these flows include press and postal services. They can be modeled as VRP (or arc routing problems, ARP, for postal services) with a large number of customers. Routes are generally stable over relatively long periods of times (except that customers might possibly be skipped). However difficulties stem from the huge variability of the quantities to be delivered to customers, especially in the context of press distribution.
 - Household move logistics: these flows are provoked by individual moves. They are very heterogeneous and difficult to anticipate. They are mainly FTL routes or FTL shuttles (when for an intra-city move, a truck makes more than one trip to relocate all goods). The most important issues here are related to fleet management rather than vehicle dispatching.

3.2 Statistical analysis of UGM flows

In this section, we provide some statistics on UGM flows. The objective is to give insights on the relative importance of the different categories of flows in terms of volume in the city. Also, information is given on the size of the routes and, thus, the characteristics of the solutions that can be expected from vehicle route optimization.

Table 1 compares IEM, ECM and UMM on the basis of road occupancy. To obtain these statistics, we applied the data estimation method proposed in Gonzalez Feliu et al. (2014) to the urban area of Lyon (approximately 2 million of inhabitants). Note that the results are consistent with those obtained for other French cities (Segalou et al. 2004; Bonnafous 2001; Gonzalez-Feliu et al. 2014).

Traffic road occupancy reflects the occupancy of infrastructures by en route vehicles. It is expressed in km × equivalent vehicle (generally car-equivalent units, CEU). To compute this indicator, we used conventional equivalence rates (i.e., one private car or light vehicle equivalent to 1 CEU, one light goods vehicle to 1.5 CEU, one small single truck to 2 CEU, one big single truck to 2.5 CEU and one semi-articulated vehicle to 3 CEU). We found a total level of traffic road occupancy equal to 51,200,000 km × CEU. In the first column of Table 1 we indicate the distribution of traffic road occupancy among the different types of UGM flows. Impacts on road traffic of good movements are mainly shared between IEM and ECM, with almost equivalent rates. Durand and Gonzalez Feliu (2012) indicate that ECM traffic is essentially provoked by shopping trips, with private cars. Hence, this table demonstrates that IEM is the main contributor to truck traffic.

Park road occupancy is an indicator that reflects the occupancy of infrastructures by vehicles when they stop. It is expressed in hours × equivalent vehicle. It includes and does not differentiate among the different types of parking (on delivery areas, on the street network, etc.). We obtained a total quantity of 703,000 h × CEU for the whole urban area (101,000 h × CEU for the inner city). The distribution among the different types of UGM is reported in Table 1. The issue of park road occupancy is essentially related to ECM (shopping trips) in the whole urban area. However, when focusing on city centers, the question of parking for IEM becomes prominent. This observation explains the interest for synchronization or waiting times observed in the literature (Sect. 2).

Tables 2, 3 and 4 focus on IEM flows. As stated before, these flows represent the most important part of the UGM once shopping trips (that cannot be addressed with route optimization strategies) are removed. The data shown in these tables are new statistics retrieved from the French Surveys on Urban Goods Movement database

Table 1 Road occupancy rates

	Traffic road occupancy (%)	Park road occupancy	
		Whole urban area (%)	Inner city (%)
IEM	46	28	47
ECM	46	64	34
UMM	8	8	19

(Patier and Routhier 2009). The database compiles three surveys made in late 90s in France, respectively for the urban areas of Bordeaux, Marseille and Dijon. These surveys contain three nested questionnaires: one at the establishment level, one at the operation level and one at the vehicle level. We exploit here this last set of data, which was less explored so far. This set however suffers from certain lacks: from about 2100 collected routes, about two thirds of them cannot be exploited because of missing details or because they concern marginal types of goods (e.g., cattle transportation). The size of the sample is thus not sufficient to be too affirmative on the results. For this reason, we limit our analyses to the main trends that can be observed.

From the selected route dataset, four categories of transport have been defined, according to French practice. Categories of routes are defined according to their number of deliveries, with five categories: 1 delivery, from 2 to 10 deliveries, from 11 to 20, from 21 to 30 and more than 31 deliveries. Tables 2, 3 and 4 display information on the percentages involved with each category of transport and route size with regard to the number of deliveries, the number of routes and the weight delivered, respectively. In these tables “–” indicates that no route included in the dataset fits the category.

A first conclusion that can be drawn from Tables 2, 3 and 4 is that third-party transport manages about 75 % of IEM in terms of number of deliveries, and around 60 % in terms of number of routes and weight transported. The other part of IEM is mostly due to sender own account, while receiver own account plays a marginal role.

It can be observed that classical and small parcel delivery services are almost equivalent in terms of routes generated, but they are unbalanced with respect to the number of deliveries and weight. This is explained by the fact that parcels delivered by small parcel delivery system weigh less than those transported by classical service. Also, small parcel delivery involves routes with much more stops in average than classical delivery services. Hence, more than 50 % of the weight that is delivered in cities originates from classical third-party logistics with less-than-20-deliveries routes, representing less than 20 % of the routes and 10 % of the deliveries. Conversely, more than 50 % of the deliveries comes from small parcel

Table 2 Percentage of deliveries with respect to the total number of deliveries

Route size category (in number of deliveries)	Third-party transport		Own account		Total (%)
	Classical delivery service (%)	Small parcel delivery service (%)	Sender (%)	Receiver (%)	
1 delivery (FTL routes)	0.21	–	0.34	0.07	0.62
2–10 deliveries	2.78	0.63	5.77	0.11	9.29
11–20 deliveries	4.35	3.92	9.24	0.29	17.80
21–30 deliveries	4.92	6.40	6.40	–	17.72
31 deliveries and more	5.79	47.30	1.48	–	54.57
Total (%)	18.05	58.25	23.23	0.47	100.00
	76.30		23.70		

Table 3 Percentage of routes with respect to the total number of routes

Route size category (in number of deliveries)	Third-party transport		Own account		Total (%)
	Classical delivery service (%)	Small parcel delivery service (%)	Sender (%)	Receiver (%)	
1 delivery (FTL routes)	4.01	–	4.66	1.29	9.96
2 to 10 deliveries	9.18	1.55	18.50	0.65	29.88
11 to 20 deliveries	5.43	4.79	11.13	0.50	21.85
21 to 30 deliveries	3.75	4.79	4.79	–	13.33
31 deliveries and more	2.98	21.22	0.78	–	24.98
Total (%)	25.35	32.35	39.86	2.44	100.00
	57.70		42.30		

Table 4 Percentage of weight delivered with respect to the total delivered weight

Route size category (in number of deliveries)	Third-party transport		Own account		Total (%)
	Classical delivery service (%)	Small parcel delivery service (%)	Sender (%)	Receiver (%)	
1 delivery (FTL routes)	6.70	–	6.86	2.15	15.71
2–10 deliveries	31.21	0.13	16.58	0.85	48.77
11–20 deliveries	16.91	0.52	7.76	0.13	25.32
21–30 deliveries	2.45	0.58	1.52	–	4.55
31 deliveries and more	2.42	3.18	0.05	–	5.65
Total (%)	59.69	4.41	32.77	3.13	100.00
	64.10		35.90		

delivery with more-than-20-deliveries routes, while representing less than 5 % of the total weight.

Receiver's own account represents only a very small percentage of the goods transported in the city. Routes involve a limited number of stops, with a single customer visit in more than 50 % of the cases.

Regarding sender's own account, as already mentioned, it represents about 40 % of the routes. The structure of these routes approximately matches the one of classical third-party: most routes imply between 2 and 20 deliveries. However, contrary to third-party, the chances that these routes are finely optimized are limited. One can suspect that place for a lot of optimization is left here.

Papers surveyed in Sect. 2 mostly refer to third party transportation. The analysis conducted justifies researcher's behavior to focus on that specific transportation segment.

3.3 Discussion

From the above sections, one can note the high importance, the huge variety and the originality of vehicle routing in cities. Vehicle routing is faced for a large part of UGM. Different products, organizations and time-scales are concerned. The literature on the subject strongly reflects this variety. Case-study papers address a set of very different topics, with different organizational or technological prerequisites. From the analysis of the schemes that have been described and the papers that have been cited in the previous sections, we however retain different attributes for vehicle routing problems. We consider these attributes fundamental for city logistics and relevant from an academic point of view. They are listed in the following.

A first noticeable characteristic is the time-dependency. Efficient transportation in urban areas should consider traffic congestion and rush hours, even if many cities reflect on how UGM could be transferred to more quiet hours (e.g., at night).

A second important topic is multi-level distribution. Many papers highlight how new distribution schemes based on distribution centers in the outskirts of the city and satellites inside the city could limit nuisances and costs of UGM.

A third subject is related to the transition from large trucks to small environmentally-friendly vehicles. A direct consequence of using small vehicles is the reduction of route sizes, which implies both quick access to the customers from the depots (which relates to the use of multi-level distribution or the move of distribution centers towards city centers) and multiple returns of the vehicles to their depots during the day. In terms of vehicle routing, the latter refers to the class of multi-trip VRP.

Finally, the dynamics of the cities and the development of new communicating technologies motivate the study of dynamic VRP, where vehicle routes can be re-optimized according to different types of information (actual travel times, new requests, unexpected events).

The inclusion of these attributes in vehicle routing models raises important scientific challenges, even taken separately. In the second part of this paper, we will separately consider each one of these four categories of attributes and review them. In each case, we will enlarge the scope and also consider papers not directly connected to city logistics. We will describe which additional difficulties are implied and how they are handled in the literature. We start in Sect. 4.1 with time-dependency in travel times. Section 4.2 continues with the consideration of multiple levels in city distribution. Section 4.3 is about the way the city dynamics can be addressed. Section 4.4 completes the review considering the fact that vehicles might be reused for multiple trips.

4 Main challenges in the optimization of vehicle routes for urban goods movements

The four challenges surveyed in this section strongly differ in nature. Multi-level distribution assumes a different design of the distribution scheme, with additional

facilities and transshipments. Allowing multiple trips rather implies a different organization of the routing. No facilities are introduced; instead, the daily management of the fleet is modified. Regarding time-dependent travel times, the novelty concerns the modeling. The physical organization is the same as in standard VRP but models better capture the variability of travel times. Finally, taking into account the dynamics, the optimization setting changes as data are revealed in the course of time.

A first consequence of these differences is that the four challenges are not exclusive. Actually, all combinations are possible. Hence, one has to keep in mind while reading this section that the issues are treated separately, but might be faced simultaneously. Also, the literature devoted to the different challenges sometimes intersects and it is possible that some papers appear twice or more.

A second consequence is that the topics that are worth being underlined are not the same for the different attributes. For this reason, the structure of the four subsections will vary.

4.1 Time-dependent travel times

4.1.1 Motivation

Traditionally, vehicle routing problems consider fixed travel times on roadways. In practice, and especially in an urban setting, travel times continuously vary during the day. It is thus important to clarify whether ignoring this time-dependency has negative impacts on the quality of the solutions. Several authors addressed this issue (Ehmke et al. 2012b; Maden et al. 2010; Kuo et al. 2009; Kuo 2010).

The methodology used by these authors is the following. They compute two series of solutions: a series of solutions obtained with a classic VRP formulation and their counterparts where time-dependent travel times are taken into account. Then, they evaluate both types of solutions *a posteriori*, using time-dependent data, and compare the results.

They all conclude that significant benefits can be obtained when considering time-dependent travel times in the solution framework. However, the above papers consider different contexts (not necessarily related to city logistics). As a consequence, it is difficult to evaluate the average improvements that can be reached, but gains between 5 and 10 % are reported, both in terms of total duration of routes and CO₂ emissions.

In addition, they show that neglecting time-dependency of travel times results in routes of which duration is very badly evaluated: with errors in the range of $\pm 20\%$, depending on the time of the day, according to Ehmke et al. 2012b. As a consequence, it may happen that many routes do not respect time constraints. For example, in the case investigated by Maden et al. 2010, around half of the routes do not respect the maximum working time, even with conservative values for travel times.

From these different studies, one can conclude that considering time-dependent travel times is essential when solving VRP in cities, especially when time-

constraints are tight (for example, short TW). This should certainly become a must-have attribute in the future. The difficulties implied are developed below.

4.1.2 Data collection and management

Until the 90s, time-dependent travel times were not addressed for two main reasons: data collection and data storage (Hill and Benton 1992).

Data collection is still a very hard task despite the development of new measurement devices (e.g., cell phone or probe vehicle tracking). These new sources of information however provide data that remains very incomplete and difficult to consolidate. As underlined by Fleischmann et al. (2004), arcs of the network are furthermore affected very differently by the traffic. This complicates the data completion and limits the use of historical information.

The storage of the data also raises important difficulties. Ehmke et al. (2012b) discuss how storage and access to data can be improved by clustering network segments into homogeneous groups according to their relative variation of daily speeds. Van Woensel et al. (2008) propose a queueing approach to get time-dependent travel speeds from traffic flow data. Ehmke (2012d) explains how including the time dimension in the input data affects the computation of the distance-matrix that supports time-dependent VRP models.

4.1.3 Modeling of travel times

Because rough data cannot directly be used to represent travel times, the planning horizon is generally discretized for modeling purpose. Every time slot is then given either a constant speed (Ichoua et al. 2003; Donati et al. 2008) or a constant travel time (Fleischmann et al. 2004).

An important property that should be respected when defining the model is the First In First Out (FIFO) property (called as well non-passing property). FIFO property, firstly defined in Ahn and Shin (1991), can be stated as follows. Let $\tau_{ij}(t)$ be the travel time between i and j when service starts at time t at node i . The FIFO property holds if $t_1 + \tau_{ij}(t_1) > t_2 + \tau_{ij}(t_2)$ is verified when $t_1 > t_2$. Roughly speaking, identical vehicles traversing arc (ij) must reach location j in the order they leave location i .

It seems natural to expect from a modeling that the FIFO property holds. However, one should be conscious that it is not necessarily true when data are dynamic (which is usually not the case: travel times are varying but are assumed to be known). Indeed, arcs represent shortest paths in the street network and it is possible that two vehicles following the same arc do not travel through the same streets. Thus, a vehicle leaving earlier from node i might sometimes be stuck in an unexpected congestion while a vehicle departing later will be able to avoid it.

Several early models, based on stepwise functions for speed (Hill and Benton 1992) or travel times (Malandraki and Daskin 1992) do not respect the FIFO property. Figure 2a depicts a situation where it does not hold (see for example times $t_2 = 9.55$ and $t_1 = 10.00$).

Different modelings have more recently been proposed to ensure this property. Fleischmann et al. (2004) explain how stepwise travel time functions can be smoothed to satisfy the FIFO property (see in Fig. 2b its application on the model from Fig. 2a). Ichoua et al. (2003) consider stepwise speed functions and explain how they can be adjusted between consecutive time periods to ensure the FIFO property. Other interesting references on the subject are Kuo et al. (2009) or Figliozi (2012).

4.1.4 Impact on solution methods

Algorithms designed for the VRP cannot straightforwardly be adapted to the time-dependent VRP (TDVRP): local changes on a route have complex consequences on the whole schedule of the route. Ahn and Shinm (1991) however explain how the FIFO property can help. Assuming this property, the arrival time function is monotonic and can thus be inverted. Then, given a feasible route, the latest starting time of service for the customers in the route, can be computed in linear time using backward relations. Checking feasibility when inserting non-routed nodes, combining distinct routes and exchanging nodes can thus be quickly done.

Another difficulty arises from the fact that the TDVRP is typically strongly asymmetric (Kok et al. 2009). Local search moves as $k - opt$ that modify the sense in which some links are traversed have to be carefully designed in this context (Malandraki and Daskin 1992).

Finally, differently than for the classical VRP, leaving the depot as early as possible is not optimal. Waiting at the depot can then be beneficial. 2008 call *optimal start time problem* the problem of determining the optimal starting time. It needs to be recomputed each time a route changes. Depending on the side-constraints, it is possible to solve it in polynomial time (Hashimoto et al. 2008) or not (Kok et al. 2010).

Based on the previous ingredients, different heuristics and meta-heuristics have been proposed to solve the TDVRP: a modified Clarke and Wright and 2-opt

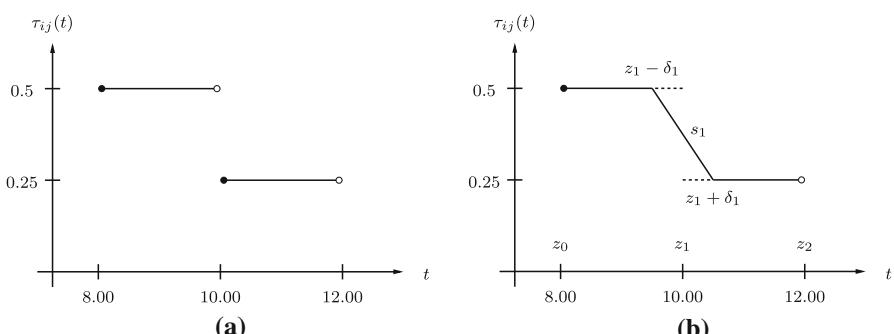


Fig. 2 Time-dependent travel time $\tau_{ij}(t)$ for an arc (i,j) . Time and traveling time in hours (a) FIFO property does not hold. (b) Traveling times smoothed as proposed by Fleischmann et al. 2004: FIFO property holds

heuristic (Hill and Benton 1992), nearest-neighbor heuristic and a cutting plane heuristic (Malandraki and Daskin 1992), iterated LS (Hashimoto et al. 2008), simulated annealing (Kuo 2010), multi ant colony system (Donati et al. 2008), tabu search (Maden et al. 2010; Kuo et al. 2009), parallel tabu search (Ichoua et al. 2003). Moreover, in Ehmke et al. (2012b) classical heuristics for the TSP are adapted to the time-dependent TSP. Another direction explored by Soler et al. (2009) is to adapt the graph structure and transform the TDVRP with TW into an Asymmetric Capacitated VRP. Table 5 lists the papers cited in this section.

4.2 Multi-level distribution

4.2.1 Motivation

In the VRP, distribution is assumed to be organized from a central depot, from which vehicles leave and operate deliveries directly to a set of customers. Recently, in the context of city logistics, more complex distribution systems have been studied where goods are dispatched to intermediate depots before reaching the final destinations. In this case, two types of vehicles are typically used. Large trucks supply the intermediate facilities; environmentally friendly vehicles perform the final deliveries from these facilities. Depending on their characteristics, intermediate facilities are called CDC or satellites. Following Rushton et al. (2006), a CDC can be warehouse, a transshipment site or a cross-docking facility (no storage offered). The term satellite is normally used to indicate a small CDC where freight can be stored only for a very limited period and vehicle-waiting is not offered. It is often installed on existing facilities. For example, a satellite can be located on a public parking or a municipal bus garage (Crainic 2008).

Reasons to investigate these complex distribution schemes are numerous, both for local authorities and carriers. Firstly, CDC are installed to achieve a high degree of consolidation in the good flows, aiming at the reduction of traffic congestion, pollution and cost (BESTUFS 2002). Additionally, their proximity to final customers permits more reactivity, flexibility and eventually improvements in terms of quality of service.

Secondly, many cities impose using small/green vehicles in city centers or are likely to impose it in a near future. Because of the limited autonomy and capacity of these vehicles, intermediate facilities (satellites) are needed. Carriers then have to adapt to this new environment or to anticipate possible future restrictions.

Table 5 Articles cited that concern TDVRP

References

Ahn and Shim (1991)	Hashimoto et al. (2008)	Kuo (2010)
Hill and Benton (1992)	Van Woensel et al. (2008)	Maden et al. (2010)
Malandraki and Daskin (1992)	Kok et al. (2009)	Ehmke (2012d)
Ichoua et al. (2003)	Kuo et al. (2009)	Ehmke et al. (2012b)
Fleischmann et al. (2004)	Soler et al. (2009)	Figliozzi (2012)
Donati et al. (2008)	Kok et al. (2010)	

For all these reasons, new VRP models including transfers within intermediate facilities are absolutely needed to provide operational tools for these new distribution schemes or to anticipate their development. In the subsequent subsections we explain how vehicle routing problems have been adapted to this context and how algorithms are impacted.

4.2.2 Academic models

In what follows the generic term *logistic platform* (LP) is used for facilities. 1-LP are the sources of merchandise. 2-LP are the intermediate facilities. 1-level vehicles are the large trucks used from the 1-LP. 2-level vehicles are the green vehicles used for final deliveries, from the 2-LP.

A difficulty met by academics when addressing routing optimization for these multi-level distribution systems is the variety of possible systems. Numerous parameters can characterize each LP as storage capacity, storage period limit, vehicle accessibility, number of vehicles that can access it at the same time, possibility of vehicle-waiting and so on. Many distribution policies can also be implemented, allowing or not, for example, direct-trips from 1-LP to final customers, multiple trips or trips between different 2-LP for 2-level vehicles, split delivery to 2-LP. Other possibilities can even be considered as interconnection with the public transportation system for the first level (Masson et al. 2014) for example. A general situation of multi-level distribution is depicted in Fig. 3.

An important issue in these systems is the complexity of synchronization constraints at the 2-LPs. Depending on the emphasis put on these constraints, very different models have been proposed.

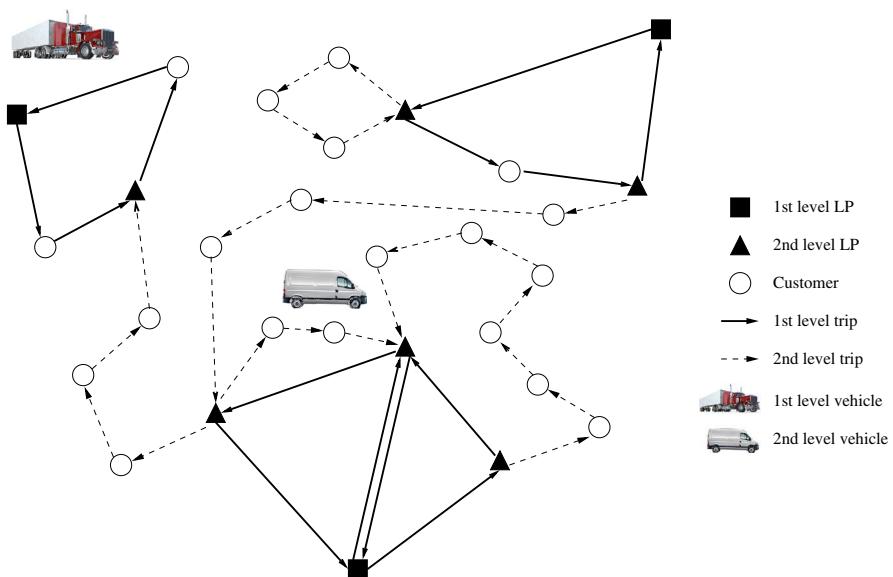


Fig. 3 General two-level distribution system

The most studied problem is the Two-Echelon VRP (2E-VRP) where synchronization is limited to the balance of product flows at the 2-LP (Gonzalez-Feliu 2008; Crainic et al. 2012b; Perboli et al. 2011; Crainic et al. 2011; Hemmelmayr et al. 2012). This simplification is justified by the fact that the model is defined for tactical purposes. Common assumptions in the 2E-VRP are the following. Distribution starts from a unique 1-LP (the central depot). 1-level vehicle routes supply the set of 2-LP, under capacity constraints that represent the storage capacity of the 2-LP. At this level, split delivery is possible. Customers are served by 2-level vehicles with a standard VRP framework (one single round-trip around a 2-LP for each vehicle, without split delivery). This situation is depicted in Fig. 4a.

When the 2-LPs that are used need to be chosen among a set of possible 2-LPs, the Two-Echelon Location Routing problem (2E-LRP) arises (Nguyen et al. 2012; Jepsen et al. 2013)—see Fig. 4b. A cost associated with the usage of a certain 2-LP (opening cost) is given and the objective is to minimize opening and routing costs. It is noteworthy that when all the opening costs are zero, 2E-VRP and 2E-LRP coincide.

Several authors started developing more complex models based on the same framework, where temporal constraints are added. Crainic et al. (2009) propose a model that generalizes the 2E-VRP with time-dependent travel times and TW associated with customers. Grangier (2014) introduce temporal synchronization between vehicles of the two levels. They also allow a more complex routing at the second level.

Another type of distribution scheme is investigated in Lee et al. (2006) and Wen et al. (2009). A single fleet of vehicles is considered, located at a CDC. Merchandise needs to be picked-up at supplier locations and delivered to retailer via the CDC where consolidation takes place. Lee et al. (2006) force all the vehicles to arrive at the CDC simultaneously. Wen et al. (2009) authorize temporary storage at the CDC.

4.2.3 Impact on solution methods

One observation that should be mentioned about the solution algorithms developed for multi-level VRPs is the possibility to exploit the natural decomposition between the different levels.

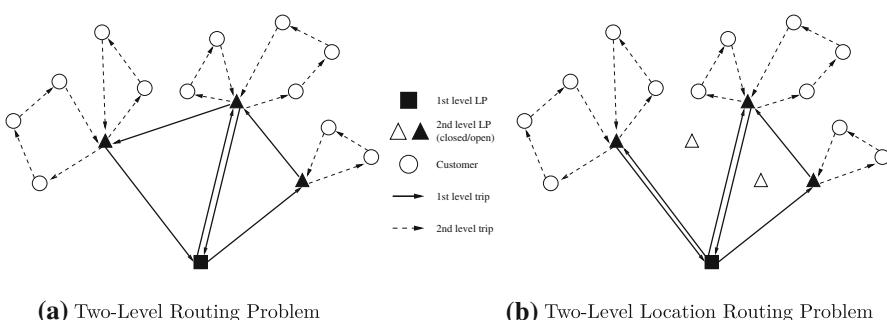


Fig. 4 Two-Level Problems **a** two-level routing problem. **b** Two-level location routing problem

In the 2E-VRP, coupling between the two-levels is ensured by decisions of assigning each product (customer) to a 2-LP. Assuming that these decisions are taken, the second level optimization reduces to the solution of as many VRP as the number of 2-LP, and the first level optimization reduces to a VRP with split delivery. Following this observation, several two-phase heuristics have been proposed for this problem (Crainic et al. 2011, 2012b; Perboli et al. 2011) with different ways of managing the assignment of customers to the 2-LP (clustering, information given by the linear relaxation of a integer programming formulation ...).

If time variables are considered, decomposition is still possible but implies to fix deadlines at which goods should be available at the 2-LP. The VRP met at the second level then become VRP with release dates, introduced by Cattaruzza et al. (2014). TW need to be added to the VRP at the first level. We are however not aware of any paper exploiting this possibility. Actually, the stronger the synchronization constraints, the harder the development of a method based on decomposition. Then, inspiration can rather be taken from the literature on synchronized VRP (see the recent survey by Drexel 2012).

Table 6 presents the paper cited in this section. We refer to Gonzalez Feliu (2013) and Cuda et al. (2014) for complete surveys on two-level distribution systems.

4.3 Dynamics of the city

4.3.1 Motivation

First, it is important to clarify the scope of this section. Following Psaraftis (1995), we consider that “*a vehicle routing problem is dynamic if information (input) on the problem is made known to the decision maker or is updated concurrently with the determination of the set of routes. By contrast, if all inputs are received before the determination of the routes and do not change thereafter, the problem is termed static*”. Note that with this definition the TDVRP is static, while it is considered dynamic for some authors (e.g., Ghiani et al. 2003) because the input data explicitly depends on time. Note also that in the literature the word dynamic is often replaced by *real time* or *on-line*.

In vehicle routing optimization, the dynamics are mainly involved by changes in travel times, service times and/or arrival of new requests (Potvin et al. 2006, Fleischmann et al. 2004b). For the largest part of the product flows described in Sect. 3, the requests are known in advance and logistic organization do not allow (for the time being) considering new requests in real-time. However, one can anticipate the development of more reactive systems. A clear example is pickup routes in third party logistics, due to the competitive advantage that shorter delays can provide. Another example is given by Makhlofi et al. (2014), that prospectively consider real-time optimization of delivery routes, in the context of distribution from a CDC with dynamic arrival of delivery requests. On the contrary, congestion, unavailability of parking places, unexpected events and in general unpredictability of travel and service times is the daily reality of UGM.

Table 6 Articles cited that concern multi-level distribution

References		
Lee et al. (2006)	Crainic et al. (2011)	Gonzalez Feliu (2013)
Crainic (2008)	Perboli et al. (2011)	Jepsen et al. (2013)
Crainic et al. (2012b)	Hemmelmayr et al. (2012)	Cuda et al. (2014)
Gonzalez Feliu (2008)	Nguyen et al. (2012)	Grangier (2014)
Crainic et al. (2009)	Cattaruzza et al. (2014)	Masson et al. (2014)
Wen et al. (2009)		

The interest in Dynamic VRP (DVRP) has rapidly grown with the concurrent development of communication technologies (GPS, mobile phones), geographic information systems and computing power. Indeed, vehicle activity can now be constantly monitored, allowing quick re-optimization of route planning. Kim et al. (2005) show how using real-time information on congestion can produce cost savings up to 3.65 % and reduction of vehicle usage up to 6.88 % compared to routing plans computed using travel times based on historical data. Grzybowska and Barceló (2012) show that the exploitation of traffic information can improve the cost of routing plans up to 25 % (this result however compares a static VRP with average travel-time values to a DVRP with time-dependent travel times).

From these elements, one can easily conclude that DVRPs should raise the interest of researchers when optimizing routes in cities. In the next subsections we highlight the main challenges implied for vehicle routing. The interested reader is referred to Ichoua et al. 2007, Larsen et al. 2008, Berbaglia et al. 2010 and Pillac et al. 2013 for recent surveys on DVRPs.

4.3.2 Optimization framework

Very different solution frameworks are possible depending on whether reactive modifications of the routing plans are possible or not. When real-time modifications are not possible, robust routing plans are sought. Different paradigms as robust optimization, chance constrained programming or stochastic programming with recourse can be used. Robust optimization prevents against worst-case events. Chance constrained programming limits the probability of failure. The disadvantage of the latter against the former is to require stochastic information. Conversely, robust optimization can lead to more conservative solutions. In stochastic programming with recourse, an expected cost is minimized, composed of the static routing plan cost plus the expected cost of so-called recourse actions. Recourse actions can simply represent penalties (because of late delivery for example) or proactive actions, that is, actions defined in advance for reacting to failures (e.g., inclusion of a return to the depot in a route when it happens that the vehicle is full). As in chance constrained programming, stochastic information is needed.

When real-time reoptimization is possible, a different solution framework can be adopted. Usually, it starts with a first routing plan computed using available (static) data and a static algorithm. Then, re-optimization can take place each time a new event occurs, or at pre-fixed *decision epochs* (Chen and Xu 2006). Practically, since

the routes can often change, drivers generally only know their next location. Of course, stochastic information or robustness objectives can also be integrated within this framework.

While in the VRP the classical objective function is the minimization of the travel distance and/or time, in the dynamic case different objectives can be more adequate. Indeed, one has to evaluate the possible infeasibilities provoked by non-anticipated events. For example, Barkaoui and Gendreau (2013) minimize customer service denial and total lateness at customer location in addition to total traveled distance. Other important issues for real-time reoptimization are the definition of waiting, relocation and diversion strategies.

A *waiting strategy* is an assignment of waiting times to the customers of a tour (including the depot) compatible with time constraints (Branke et al. 2005). Several papers demonstrate the importance of this strategy to deal effectively with dynamic data (Branke et al. 2005; Mitrović-Minić ; Laporte 2004), especially if stochastic information is available (Ichoua et al. 2006). Examples of proposed strategies in these papers are: earliest possible departure, latest possible departure, waiting proportional to the total slack time, waiting at farthest locations from the depot.

A *relocation strategy* is a waiting strategy where vehicles are allowed to move to arbitrary locations. Bent and Van Hentenryck (2007) show that it can improve the quality of the solution when stochastic information is available, since it permits to relocate vehicles in a place convenient for future events.

The *diversion strategy* indicates whether a vehicle can be redirected or not during its journey to the next location. In most papers, diversion towards another customer is not accepted for practical reasons (difficulty to inform the driver, reluctance of the driver, etc.). Ichoua et al. (2000) however show that it can be beneficial.

4.3.3 Dynamic travel and service times

The Dynamic VRP with dynamic travel or service times has received little attention in the literature. According to Pillac et al. (2013), no paper explicitly consider dynamic service times while dynamic travel times has only been considered recently. Probably, the main reasons are the technical difficulties described in Sect. 4.1 for data collection, data management and travel-time modeling, which are still enhanced in a real-time context. A short list of references can however be found in Pillac et al. (2013).

A richer literature exists based on a stochastic modeling. However, obtaining meaningful distributions is a very difficult task, especially in cities where, as pointed out by Güner et al. (2012), over 50 % of travel time delays are due to non-recurrent (and then unpredictable) events.

4.3.4 Dynamic arrival of new requests

Another important strategy that need to be defined in the context of dynamic arrival of requests is the *acceptance strategy*.

In some cases requests must be accepted (e.g., Fleischmann et al. 2004b or Chen and Xu 2006). Otherwise, if it can be refused (e.g., Barkaoui and Gendreau 2013;

Yang et al. 2004), one has to decide when requests are rejected. A first possibility is to reject only requests that cannot be feasibly inserted in the planning. A second possibility is to reject requests that are not convenient based on the balance between generated revenue and cost. In all cases a quick decision is needed to avoid long waiting times for customers when booking.

Table 7 summarizes the articles cited in this section.

4.4 Routes with multiple trips

4.4.1 Motivation

As largely documented in Sects. 3 and 4.2, both carriers and cities have strong incentives for generalizing the use of small environmentally friendly vehicles in city centers. A direct consequence is the limited capacity of these vehicles, and, if electric engines are used, their limited autonomy.

Combined to other factors (development of the e-commerce, new customer expectations), this evolution entails a tendency to bring back facilities inside cities or to introduce new intermediate facilities. The immediate effect of these two developments is the interest for vehicle route optimization where multiple trips are allowed.

One can observe that most recent papers interested in multi-level distribution at an operational level allow multiple trips for the second level vehicles (Crainic et al. 2012; Nguyen et al. 2013; Cattaruzza et al. 2014; Grangier et al. 2014).

We describe below the main difficulties involved by multiple trips in solution methods.

4.4.2 Impact on solution methods

The multi-trip VRP (MTVRP) combines three types of decisions: assignment of customers to routes, sequencing of the customers in the routes and assignment of the routes to vehicles. Compared to the VRP, the third type of decisions is new: in the VRP each route is identified to a vehicle.

A natural heuristic approach to solve the MTVRP is then a two-phase approach where the first phase determines the routes by means of a VRP algorithm, and the second phase assigns the routes to vehicles using a bin packing heuristic. Several authors design heuristics following this scheme (Fleischmann 1990; Taillard et al. 1996; Petch and Salhi 2004; Olivera and Viera 2007). In most cases, a pool of routes is maintained in the first phase, from which routes are selected in the second phase.

Cattaruzza et al. (2013) propose a new tailored local search operator. It detects deteriorating moves (among those usually considered in the VRP context) that together with a swap of trips assigned to different vehicles, yields to a global improvement.

When TW are introduced, two-phase algorithms are not as suited, because of the difficulty caused by TW to the packing (second phase). Several papers then exploit the limited size of the routes (Azi et al. 2010; Macedo et al. 2011; Hernandez

Table 7 Articles cited that concern DVRP

References		
Psaraftis (1995)	Kim et al. (2005)	Berbeglia et al. (2010)
Ichoua et al. (2000)	Chen and Xu (2006)	Grzybowska and Barceló (2012)
Ghiani et al. (2003)	Ichoua et al. (2006)	Güner et al. (2012)
Fleischmann et al. (2004b)	Potvin et al. (2006)	Barkaoui and Gendreau (2013)
Mitrovic and Laporte (2004)	Bent and Van Hentenryck (2007)	Pillac et al. (2013)
Yang et al. (2004)	Ichoua et al. (2007)	Makhlofi et al. (2014)
Branke et al. (2005)	Larsen et al. (2008)	

et al. 2013): as explained above, MTVRP are typically considered for small vehicles, thus inducing a limited number of customers in routes; introducing time windows, this number becomes even smaller. Then, it can be possible to enumerate the set of all possible routes. In the three aforementioned papers, this set is first enumerated and a feasible (actually optimal) solution is constructed by solving different integer programming formulations, where routes are selected, time-stamped and assigned to vehicles. The interested reader is referred to Cattaruzza et al. (2014) for a recent survey on multi-trip problems.

Table 8 lists the papers cited in this section.

5 Conclusion

Urban areas are growing faster and becoming the cornerstone of our society. Transportation of people and merchandise impacts the quality of inhabitants' life producing pollution and congestion. In this paper, we give a picture of how vehicle routing problems can help limiting these externalities in such a way that both the quality of the transportation services and the livability of inhabitants can be improved at an acceptable cost. We applied the following methodology.

First, we surveyed the literature on vehicle routing applied to city logistics to determine which issues have been identified by researchers (Sect. 2). Secondly, we classified the UGM, describing the main categories of product flows and providing statistics on their characteristics (Sect. 3). From these figures, we underlined the situations in which vehicle route optimization is the most needed. Another expected contribution of this section was to give a complete view of vehicle routing for UGM.

From the aforementioned literature review, classification and statistics, we identified what we believe are the most important challenges for vehicle route optimization in city logistics: time-dependency of travel times, organization of the distribution in multi-levels, dynamics of the cities, organization of the routes with multiple trips (Sect. 3.3). Then, for each one of these challenges, we analyzed the difficulties that they raise and how these difficulties have been addressed in the literature (Sect. 4).

A first clear conclusion that can be drawn from these analyses is that vehicle routing optimization can indeed play a key role in the improvement of UGM. A

Table 8 Articles cited that concern MTVRP

References		
Fleischmann (1990)	Hernandez et al. (2013)	Cattaruzza et al. (2014)
Taillard et al. (1996)	Macedo et al. (2011)	Nguyen et al. (2013)
Petch and Salhi (2004)	Crainic et al. (2012)	Cattaruzza et al. (2014)
Olivera and Viera (2007)	Cattaruzza et al. (2013)	Grangier (2014)
Azi et al. (2010)		

second equally clear conclusion is that an important amount of work is still needed from the academics to produce new relevant models and solution methods. In more details, the following points can be emphasized.

Models combining multi-level distribution and multiple trips recently started being investigated. Though room is still left for research on topics like synchronization, it was the core subject of works on vehicle routing for city logistics in the last ten years. However, the inclusion of time-dependent travel times in these models, especially in a real-time setting, still seems a big challenge. Reasons are probably not only related to algorithmic design difficulties: the data management is a hard task and VRP models only give an abstracted view on actual road networks. Another point scarcely explored in these models is mutualization at the second-level facilities (fleet sharing, product transfers). It implies dealing with vehicles starting and ending their trips at different facilities, considering balancing strategies or managing transfers.

Another avenue of research that might be followed in the future is multiobjective optimization. We outlined the numerous stakes that arise in the urban distribution context as reducing pollution or increasing mobility. There is a need of developing models and criteria that better consider and represent the different stakes in play.

Last but not least, researchers should recognize the continuous and dynamic development of the cities and capture these changes into their approaches. Examples are: access time windows, parking spots booking systems, interconnections with public transportation, home delivery, and stronger interaction with customers through mobile devices.

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References

- Ahn BH, Shinm JY (1991) Vehicle-routing with time windows and time-varying congestion. *J Oper Res Soc* 42(5):393–400
- Ambrosini C, Routhier JL (2004) Objectives, methods and results of surveys carried out in the field of urban freight transport: an international comparison. *Transp Rev* 24(1):57–77
- Anderson S, Allen J, Browne M (2005) Urban logistics—how can it meet policy makers' sustainability objectives? *J Transp Geogr* 13(1):71–81
- Ando N, Taniguchi E (2006) Travel time reliability in vehicle routing and scheduling with time windows. *Netw Spat Econ* 6(3):293–311

- Azi N, Gendreau M, Potvin J-Y (2010) An exact algorithm for a vehicle routing problem with time windows and multiple routes. *Eur J Oper Res* 202(3):756–763
- Barkaoui M, Gendreau M (2013) An adaptive evolutionary approach for the real-time vehicle routing and dispatching. *Comput Oper Res* 40(7):1766–1776
- Bent R, Van Hentenryck P (2007) Waiting and relocation strategies in online stochastic vehicle routing. In: Proceedings of the 20th international joint conference on Artificial intelligence. pp 3041–3050
- Berbeglia G, Cordeau JF, Laporte G (2010) Dynamic pickup and delivery problems. *Eur J Oper Res* 202(1):8–15
- Bonnafous A (2001) Les marchandises en ville: le problème méthodologique de l'appréhension statistique. L'intégration des marchandises dans le système des déplacements urbains., Etudes & Recherches-Laboratoire d'économie des transports. Lyon, France, pp 86–91
- Boschetti M, Maniezzo V (2014) A set covering based matheuristic for a real-world city logistics problem. In: *Trans Oper Res.* doi:[10.1111/itor.12110](https://doi.org/10.1111/itor.12110)
- Branke J, Middendorf M, Noeth G, Dessouky M (2005) Waiting strategies for dynamic vehicle routing. *Transp Sci* 39(3):298–312
- Browne M, Allen J, Leonardi J (2011) Evaluating the use of an urban consolidation centre and electric vehicles in central london. *IATSS Res* 35(1):1–6
- Cattaruzza D, Absi N, Feillet D (2014) The multi-trip vehicle routing problem: a survey. Technical Report 2014–03, Ecole des Mines de Saint-Etienne
- Cattaruzza D, Absi N, Feillet D (2014) The multi-trip vehicle routing problem with time windows and release dates. Technical Report 2014–01, Ecole des Mines de Saint-Etienne
- Cattaruzza D, Absi N, Feillet D, Vidal T (2014) A memetic algorithm for the multi trip vehicle routing problem. *Eur J Oper Res* 236(6):833–848
- Chang TS, Yen HM (2012) City-courier routing and scheduling problems. *Eur J Oper Res* 223(2):489–498
- Chen Z-L, Xu H (2006) Dynamic column generation for dynamic vehicle routing with time windows. *Transp Sci* 40(1):74–88
- Crainic TG (2008) City Logistics, pages 181–212. Tutorials in Operations Research 2008—state-of-the-Art Decision Making Tools in the Information-Intensive Age. INFORMS
- Crainic TG, Gajapati Y, Gendreau M (2012) Multi-zone multi-trip vehicle routing problem with time windows. Technical Report 2012–36, Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport, Université de Montréal, Montréal, QC, Canada
- Crainic TG, Mancini S, Perboli G, Tadei R (2008) Clustering-based heuristic for the two-echelon vehicle routing problem. Technical Report 2008–46, Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport, Université de Montréal, Montréal, QC, Canada
- Crainic TG, Mancini S, Perboli G, Tadei R (2011) Heuristics for the two-echelon vehicle routing problem: A multi-start approach. Technical Report 2011–16, Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport, Université de Montréal, Montréal, QC, Canada
- Crainic TG, Perboli G, Mancini S, Tadei R (2010) Two-echelon vehicle routing problem: a satellite location analysis. *Procedia Soc Behav Sci* 2(3):5944–5955
- Crainic TG, Ricciardi N, Storchi G (2004) Advanced freight transportation systems for congested urban areas. *Transp Res Part C* 12(2):119–137
- Crainic TG, Ricciardi N, Storchi G (2009) Models for evaluating and planning city logistics systems. *Transp Sci* 43(4):432–454
- Cuda R, Guastaroba G, Speranza MG (2014) A survey on two-echelon routing problems. *Comput Oper Res.* doi:[10.1016/j.cor.2014.06.008](https://doi.org/10.1016/j.cor.2014.06.008)
- Del Pia A, Filippi C (2006) A variable neighborhood descent algorithm for a real waste collection problem with mobile depots. *Int Trans Oper Res* 13(2):125–141
- Delâitre L, De Barbeyrac C (2012) Improving an urban distribution centre, the french case of samada monoprix. *Procedia Soc Behav Sci* 39:753–769
- Donati AV, Montemanni R, Casagrande N, Rizzoli AE, Gambardella LM (2008) Time dependent vehicle routing problem with a multi ant colony system. *Eur J Oper Res* 185(3):1174–1191
- Drexel M (2012) Synchronization in vehicle routing—a survey of vrps with multiple synchronization constraints. *Transp Sci* 46(3):297–316
- Durand B, Gonzalez-Feliu J (2012) Urban logistics and e-grocery: have proximity delivery services a positive impact on shopping trips? *Procedia Soc Behav Sci* 39:510–520

- Egger D, Ruesch M (2002) Best practice handbook year 3—road pricing and urban freight transport urban freight platforms. Technical report, BESTUFS
- Ehmke JF (2012) Provision of distance matrices. In: Integration of Information and Optimization Models for Routing in City Logistics, International Series in Operations Research & Management Science. Springer, pp 83–104
- Ehmke JF, Mattfeld DC (2010) Data allocation and application for time-dependent vehicle routing in city logistics. *Eur Transp* 46:24–35
- Ehmke JF, Mattfeld DC (2011) Integration of information and optimization models for vehicle routing in urban areas. *Procedia Soc Behav Sci* 20:110–119
- Ehmke JF, Meisel S, Mattfeld DC (2012) Floating car based travel times for city logistics. *Transp Res Part C* 21(1):338–352
- Ehmke JF, Steinert A, Mattfeld DC (2012) Advanced routing for city logistics service providers based on time-dependent travel times. *J Comput Sci* 3(4):193–205
- Figliozi MA (2012) The time dependent vehicle routing problem with time windows: Benchmark problems, an efficient solution algorithm, and solution characteristics. *Transp Res Part E* 48(3):616–636
- Fleischmann B (1990) The vehicle routing problem with multiple use of vehicles. Technical report, Fachbereich Wirtschaftswissenschaften, Universität Hamburg
- Fleischmann B, Gietz M, Gnutzmann S (2004) Time-varying travel times in vehicle routing. *Transp Sci* 38(2):160–173
- Fleischmann B, Gnutzmann S, Sandvoß E (2004) Dynamic vehicle routing based on online traffic information. *Transp Sci* 38(4):420–433
- Ghiani G, Guerriero F, Laporte G, Musmanno R (2003) Real-time vehicle routing: Solutions concepts, algorithms and parallel computing strategies. *Eur J Oper Res* 151(1):1–11
- Gonzalez-Feliu J (2008) Models and methods for the City Logistic. The Two-Echelon Capacitated Vehicle Routing Problem. Ph.D. thesis, Politecnico di Torino
- Gonzalez-Feliu J (2013) Vehicle routing in multi-echelon distribution systems with cross-docking: a systematic lexical-metanarrative analysis. *Comput Inf Sci* 6(3):28–47
- Gonzalez-Feliu J, Ambrosini C, Pluvinet P, Toilier F, Routhier JL (2012) A simulation framework for evaluating the impacts of urban goods transport in terms of road occupancy. *J Comput Sci* 6(4):206–215
- Gonzalez-Feliu J, Toilier F, Ambrosini C, Routhier JL (2014) Estimated data production for urban goods transport diagnosis. The freturb methodology. Sustainable urban logistics: concepts., methods and information systems. Springer, Berlin, pp 113–143
- Grangier P, Gendreau M, Lehuédé F, Rousseau L-M (2014) An adaptive large neighborhood search for the two-echelon multiple-trip vehicle routing problem with satellite synchronization. Technical Report 2014–33, Centre interuniversitaire de recherche sur les réseaux d’entreprise, la logistique et le transport, Université de Montréal, Montréal, QC, Canada
- Grzybowska H, Barceló J (2012) Decision support system for real-time urban freight management. *Procedia Soc Behav Sci* 39:712–725
- Güner AR, Murat A, Chinnam RB (2012) Dynamic routing under recurrent and non-recurrent congestion using real-time its information. *Comput Oper Res* 39(2):358–373
- Hashimoto H, Yagiura M, Ibaraki T (2008) An iterated local search algorithm for time-dependent vehicle routing problem with time windows. *Discrete Optim* 5(2):434–456
- Hasle G, Kloster O (2007) Geometric modelling, numerical simulation, and optimization. In: Operations Research Computer Science Interfaces. Springer, pp 397–436
- Hemmelmayr VC, Cordeau JF, Crainic TG (2012) An adaptive large neighbourhood search heuristic for two-echelon vehicle routing problems arising in city logistics. *Comput Oper Res* 39(12):3215–3228
- Hernandez F, Feillet D, Giroudeau R, Naud O (2013) A new exact algorithm to solve the multi-trip vehicle routing problem with time windows and limited duration. *4OR*. doi:10.1007/s10288-013-0238-z
- Hill AV, Benton WC (1992) Modelling intra-city time-dependent travel speeds for vehicle scheduling problems. *J Oper Res Soc* 43(4):343–351
- Hitchcock FL (1941) The distribution of a product from several sources to numerous facilities. *J Math Phys* 20(2):224–230
- Ichoua S, Gendreau M, Potvin J-Y (2000) Diversion issues in real-time vehicle dispatching. *Transp Sci* 34(4):426–438

- Ichoua S, Gendreau M, Potvin J-Y (2003) Vehicle dispatching with time-dependent travel times. *Eur J Oper Res* 144(2):379–396
- Ichoua S, Gendreau M, Potvin J-Y (2006) Exploiting knowledge about future demands for real-time vehicle dispatching. *Transp Sci* 40(2):211–225
- Ichoua S, Gendreau M, Potvin J-Y (2007) Planned Route Optimization for Real-Time Vehicle Routing. Springer, pp 1–18
- Jepsen M, Spoorendonk S, Ropke S (2013) A branch-and-cut algorithm for the symmetric two-echelon capacitated vehicle routing problem. *Transp Sci* 4(1):23–37
- Kim S, Lewis M, White C (2005) Optimal vehicle routing with real-time traffic information. *Intell Transp Syst IEEE Trans* 6(2):178–188
- Kok AL, Hans EW, Shuttten JMJ (2009) Vehicle routing under time-dependent travel times: the impact of congestion avoidance. In: Technical Report 267, Beta Research School for Operations Management and Logistics, University of Twente
- Kok AL, Hans EW, Shuttten JMJ, Zijm WHM (2010) A dynamic programming heuristic for a vehicle routing with time-dependent travel times and required breaks. *Flex Serv Manuf J* 22(1–2):83–108
- Kritzinger S, Doerner KF, Hartl RF, Kiechle G, Stadler H, Manohar SS (2011) Using traffic information for time-dependent vehicle routing. *Procedia Soc Behav Sci* 39:217–229
- Kuo Y (2010) Using simulated annealing to minimize fuel consumption for the time-dependent vehicle routing problem. *Comput Ind Eng* 59(1):157–165
- Kuo Y, Wang CC, Chuang PY (2009) Optimizing goods assignment and the vehicle routing problem with time-dependent travel speeds. *Comput Ind Eng* 57(4):1385–1392
- Larsen A, Madsen OBG, Solomon MM (2008) Recent Developments in Dynamic Vehicle Routing Systems. In: The vehicle routing problem—latest advances and new challenges, number 43 in Operations Research Computer Science Interface. Springer, pp 199–218
- Lee Y, Jung J, Lee K (2006) Vehicle routing scheduling for cross-docking in the supply chain. *Comput Ind Eng* 51(2):247–256
- Macedo R, Alves C, Valério deCarvalho JM, Clautiaux F, Hanafi S (2011) Solving the vehicle routing problem with time windows and multiple routes exactly using a pseudo-polynomial model. *Eur J Oper Res* 214(3):536–545
- Maden W, Eglese R, Black D (2010) Vehicle routing and scheduling with time-varying data: a case study. *J Oper Res Soc* 61:515–522
- Makhoulfi R, Cattaruzza D, Meunier F, Absi N, Feillet D (2014) Simulation of a mutualized urban logistics system with real-time management, International Symposium of Transport Simulation
- Malandraki C, Daskin MS (1992) Time dependent vehicle routing problems: formulations, properties and heuristic algorithms. *Transp Sci* 26(3):185–200
- Masson R, Trentini A, Lehuédé F, Malhéné N, Péton O, Tlahig H (2013) Optimization of a city logistics transportation system with mixed passenger and goods. Technical Report ENM Working Paper 13/1/AUTO, Ecole des Mines de Nantes
- Mitrović-Minić S, Laporte G (2004) Waiting strategies for the dynamic pickup and delivery problem with time windows. *Transp Res Part B* 38(7):635–655
- Muñozuri J, Cortés P, Guadix J, Onieva L (2012) City logistics in spain: Why it might never work. *Cities* 29(2):133–141
- Muñozuri J, Grosso R, Cortés P, Guadix J (2013) Estimating the extra costs imposed on delivery vehicles using access time windows in a city. *Comput Environ Urban Syst* 41:262–275
- Nguyen PK, Crainic TG, Toulouse M (2013) A tabu search for time-dependent multi-zone multi-trip vehicle routing problem with time windows. *Eur J Oper Res* 231(1):43–56
- Nguyen PK, Crainic TG, Toulouse M (2014) Multi-zone multi-trip pickup and delivery problem with time windows and synchronization. Technical Report 2014-18, Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport, Université de Montréal, Montréal, QC, Canada
- Nguyen V-P, Prins C, Prodhon C (2012) Solving the two-echelon location routing problem by a grasp reinforced by a learning process and path relinking. *Eur J Oper Res* 216(1):113–126
- Noveas AGN, Frazzon EM, Burin PJ (2011) Dynamic vehicle routing in over congested areas. *Dyn Logist Second Int Conf LDIC* 2009:49–58
- Commission of the European Communities (2009) Action plan on urban mobility. Technical Report COM (2009) 490. <http://ec.europa.eu>
- Commission of the European Communities (2009) Full evaluation report - satellite based traffic management for smes. Technical report. http://www.civitas.eu/index.php?id=79&sel_menu=23&measure_id=250

- Commission of the European Communities (2009) A sustainable future for transport: Towards an integrated, technology-led and user friendly system. Technical Report COM, pp 279. <http://ec.europa.eu>
- Commission of the European Communities (2011) Roadmap to a single european transport area - towards a competitive and resource efficient transport system. Technical Report COM (2011) 144. <http://ec.europa.eu>
- Olivera A, Viera O (2007) Adaptive memory programming for the vehicle routing problem with multiple trips. *Comput Oper Res* 34(1):28–47
- Ortúzar JD, Willumsen LG (2011) Modelling transport, 4th edn. Wiley
- Patier D, Routhier JL (2009) How to Improve the Capture of Urban Goods Movement Data. In: Transport survey methods. Keeping up with a changing world. Emerald, Bingley, pp 251–287
- Perboli G, Tadei R, Vigo D (2011) The two-echelon capacitated vehicle routing problem: models and math-based heuristic. *Transp Sci* 45(3):364–380
- Perrier Nathalie, Langevin André, Amaya Ciro-Alberto (2008) Vehicle routing for urban snow plowing operations. *Transp Sci* 42(1):44–56
- Perrier N, Langevin A, Campbell JF (2007) A survey of models and algorithms for winter road maintenance. part III: vehicle routing and depot location for spreading. *Comput OR* 34(1):211–257
- Perrier N, Langevin A, Campbell JF (2007) A survey of models and algorithms for winter road maintenance. part IV: vehicle routing and fleet sizing for plowing and snow disposal. *Comput OR* 34(1):258–294
- Petch RJ, Salhi S (2004) A multi-phase constructive heuristic for the vehicle routing problem with multi trips. *Discrete Appl Math* 133(1–3):69–92
- Pillac V, Gendreau M, Guéret C, Medaglia AL (2013) A review of dynamic vehicle routing problems. *European Journal of Operational Research* 225(1):1–11
- Potvin J-Y, Xu Y, Benyahia I (2006) Vehicle routing and scheduling with dynamic travel times. *Comput Oper Res* 33(4):1129–1137
- Psaraftis HN (1995) Dynamic vehicle routing: status and prospects. *Ann Oper Res* 61(1):143–164
- Quak HJ (2012) Improving urban freight transport sustainability by carriers—best practices from the netherlands and the eu project citylog. *Procedia Soc Behav Sci* 39:158–171
- Quak HJ, de Koster MBM (2009) Delivering goods in urban areas: how to deal with urban policy restrictions and the environment. *Transp Sci* 43(2):211–227
- Qureshi AG, Hanaoka S (2005) Analysis of the effects of a cooperative delivery system in bangkok. In: Recent adavances in city logistics. Langkawi
- Qureshi AG, Taniguchi E, Yamada T (2011) A microsimulation based analysis of exact solution of dynamic vehicle routing with soft time windows. *Procedia Soc Behav Sci* 39:205–216
- Rodrigue JP (2013) The geography of transportation systems. Routledge, Taylor & Francis Group. <http://people.hofstra.edu/geotrans/index.html>
- Rushton A, Croucher P, Baker P (2006) The handbook of Logistic and Distribution Management, 3rd edn. Kogan Page
- Segalou E, Ambrosini C, Routhier JL (2004) The environmental assessment of urban goods movement. In: Logistics systems for sustainable cities—proceedings of the 3rd International Conference on City Logistics. Elsevier, pp 207–220
- Soler D, Albiach J, Martínez E (2009) A way to optimally solve a time-dependent vehicle routing problem with time windows. *Oper Res Lett* 37(1):37–42
- Taillard ÉD, Laporte G, Gendreau M (1996) Vehicle routeing with multiple use of vehicles. *J Oper Res Soc* 47(8):1065–1070
- Taniguchi E, Shimamoto H (2004) Intelligent transportation sistem based dynamic vehicle routing and scheduling with variable travel times. *Transp Res Part C* 12(3–4):235–250
- Taniguchi E, Thompson RG, Yamada T, van Duin R (2001) City logistic—network modelling and intelligent transport systems. Pergamon, Amsterdam
- Taniguchi E, Van Der Heijden RECM (2000) An evaluation methodology for the city logistics. *Transp Rev* 20(1):65–90
- Tarantilis CD, Kiranoudis CT (2001) Using the vehicle routing problem for the transportation of hazardous materials. *Oper Res* 1(1):67–78
- Thompson RG, Hassall KP (2012) A collaborative urban distribution network. *Procedia Soc Behav Sci* 39:230–240
- Toth P, Vigo D (2002) The vehicle routing problem. Monographs on discrete mathematics and applications, Siam

- Van Woensel T, Kerbache L, Peremans H, Vandaele N (2008) Vehicle routing with dynamic travel times: a queueing approach. *Eur J Oper Res* 186(3):990–1007
- Wen M, Larsen J, Clausen J, Cordeau J-F, Laporte G (2009) Vehicle routing with cross-docking. *J Oper Res Soc* 60:1708–1718
- Yang J, Jaillet P, Mahmassani H (2004) Real-time multivehicle truckload pickup and delivery problems. *Transp Sci* 38(2):135–148
- Zeimpekis V, Giaglis GM (2005) A dynamic real-time management system for incident handling in city logistics. In: *Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st*, vol. 5. pp 2900–2904