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Integrated Vehicle Routing Problems: A Survey

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3.1 Introduction

The literature on vehicle routing problems is huge, due to the practical interest in this class of problems, the enormous number of interesting variants, and the related computational challenges [65]. In fact, while the Traveling Salesman Problem is considered a well-solved problem, vehicle routing problems are considered among the hardest combinatorial optimization problems. However, exact methods for problems of this class can solve larger and larger instances and many effective heuristics are available, especially for the most studied variants. This progress, combined with the technological advances, has encouraged researchers to study integrated problems, that is problems that jointly optimize two or more previously studied sub-problems.

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The solution of integrated problems, that are computationally harder to solve, offers substantial advantages with respect to the sequential solutions of the sub-problems. Examples of these benefits are presented in [4] for the Inventory Routing Problem and in [16] for the Two-Echelon Capacitated Vehicle Routing Problem. The primary purpose of this chapter is to provide an overview of the foremost classes of *integrated routing problems*, along with a synthesis of the most recent trends in the related literature. Quoting from [7], Integrated Vehicle Routing Problems (IVRP) can be defined as: "[...] problems where the VRP arises in combination with other optimization problems within the broader context of logistics and transportation." Based on the research interest that their study has arisen, as measured by the number of publications and citations, we have identified four main classes of IVRP: inventory routing problems, location routing problems, loading and routing problems, and two-echelon routing problems. In fact, other sub-problems have been considered jointly with routing problems, for instance, order batching and production scheduling. Given the limits in length of a book chapter, these integrated problems are not covered here.

Figure 3.1 provides a tree representation of the classes of IVRP surveyed in this chapter (the leaves), explicitly stating for each class the optimization problem arising in combination with the routing problem (the child of the root node).

The literature covering the above-mentioned classes of IVRP is extremely vast. It is out of the scope of the present survey to provide a thorough review of the research conducted on these classes of problems, also because dedicated surveys are already available. For each class of IVRP we provide

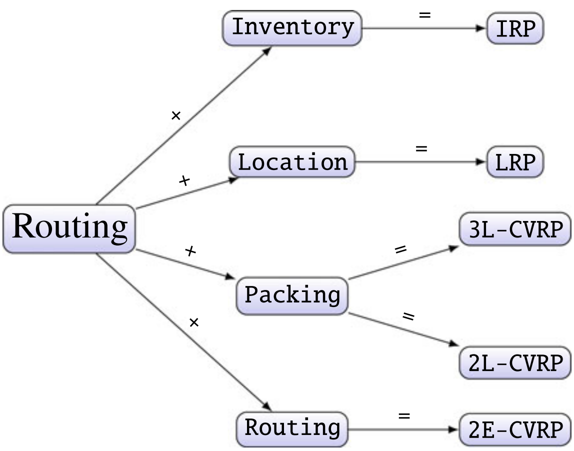

Fig. 3.1 A tree representation of the classes of IVRPs covered in this survey

a general description of the class, detail a prototypical basic problem, and review the most recent trends in the literature. References to previous surveys are provided, where the reader interested in the earlier literature is referred to. For some classes, namely the Inventory Routing Problem and Location Routing Problem, the surveys are very recent. In these cases, we do not provide a literature overview, but only refer the reader to the appropriate review papers.

Regarding the bibliographic search methodology, manuscripts have been searched by querying the Scopus database. The search was limited to articles published in top-tier international Operational Research (OR) journals (see Table 3.1). Papers that appeared in other journals were added, based on their research impact, as measured by the number of citations received. Figure 3.2 displays the distribution among the various OR journals, in percentage, of the papers mentioned in the present survey.

Table 3.1 Journals considered for the initial Scopus research

Journals (in alphabetical order)
4OR
Annals of Operations Research
Asia Pacific Journal of Operational Research
Central European Journal of Operations Research
Computers and Operations Research
Euro Journal on Computational Optimization
Euro Journal on Transportation And Logistics
European Journal of Operational Research
Expert Systems with Applications
Informs Journal on Computing
Interfaces
International Journal of Production Research
International Transactions in Operational Research
Journal of Heuristics
Journal of Scheduling
Journal of the Operational Research Society
Management Science
Networks
Omega United Kingdom
Operations Research
Operations Research Letters
OR Spectrum
TOP
Transportation Research Part B: Methodological
Transportation Science

Table 3.2 A summary of the main abbreviations used in the paper (in alphabetical order)

Problem		Algorithm	
Abbreviation	Description	Abbreviation	Description
2E-CVRP	Two-Echelon CVRP	ALNS	Adaptive LNS
2E-VRP	Two-Echelon VRP	B&C	Branch-and-Cut
2L-CVRP	CVRP with two-dimensional loading constraints	LNS	Large Neighborhood Search
3L-CVRP	CVRP with three-dimensional loading constraints	SA	Simulated Annealing
CVRP	Capacitated VRP	TS	Tabu Search
IRP	Inventory Routing Problem	VNS	Variable Neighborhood Search
IVRP	Integrated VRP		
LRP	Location Routing Problem		
TSP	Traveling Salesman Problem		
VRP	Vehicle Routing Problem		

Table 3.2 summarizes the main abbreviations used in the paper to identify optimization problems and solution algorithms.

The chapter is organized as follows. In Sect. 3.2, the class of Inventory Routing Problems is discussed, whereas Location Routing Problems are presented in Sect. 3.3. Section 3.4 reviews the class of routing problems combined with loading constraints. In particular, the issues related to loading two-dimensional items are discussed in Sect. 3.4.2, whereas the three-dimensional case is presented in Sect. 3.4.3. The combination of routing with routing, i.e., the class of Two-Echelon Routing Problems, is discussed in Sect. 3.5. Finally, conclusions are drawn in Sect. 3.6.

3.2 Inventory Routing Problems

The Inventory Routing Problems (IRP) have been studied for several decades, starting from the eighties, when the combination of routing optimization and inventory management was studied in some real settings. In [8], the first paper where the integrated problem is studied, an example is provided to show that, even when no inventory cost is considered and the transportation cost only is minimized, key decisions in distribution problems are when to

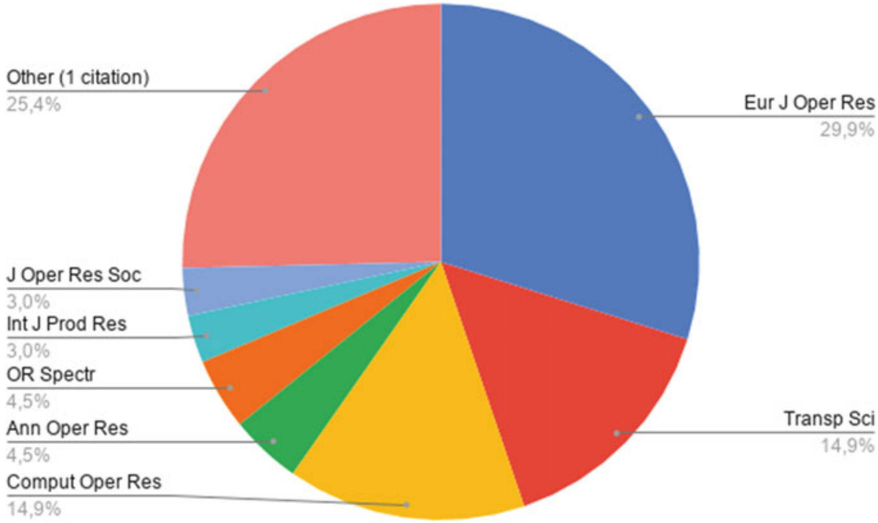

Fig. 3.2 The distribution among the various OR journals, in percentage, of the papers covered in this survey

serve customers and how much to deliver to them and that these decisions determine the routing cost.

In general, in IRPs the decisions to be taken are about when to serve customers, how much to deliver to them, which is the sequence of visits for each of the used vehicles. Formally, the main elements of the basic IRP are as follows. Let $G = (V, A)$ be a complete weighted graph. Set $V = \{0, 1, 2, \ldots, n\}$ is the set of vertices, where 0 represents the depot, and set $V \setminus \{0\}$ is the set of customers. In IRPs, often the depot represents the supplier and customers represent the retailers. Set A is the set of arcs (i, j), each being associated with a non-negative traveling cost c_{ij}. A planning horizon $T = 1, \ldots, |T|$ is defined. The depot and the customers have an initial inventory level, with customers also being characterized by a maximum inventory capacity. At each period $t \in T$, the quantity r_{0t} is made available at the supplier and the quantity r_{it} is consumed at retailer i. A unit inventory holding cost is defined for both the supplier and the retailers. A fleet of K homogeneous vehicles is available at the depot to serve all the customers. Each vehicle has a maximum capacity Q.

The minimization of the total inventory and routing costs is sought, subject to the following constraints. From a routing perspective, any feasible solution must satisfy the following conditions: in each period,

(RC1) each route starts and ends at the depot;

(RC2) each customer served in that period must be visited by exactly one vehicle;
(RC3) no more than K vehicles are used;
(RC4) the quantity assigned to a vehicle does not exceed its maximum capacity Q.

Any feasible inventory management pattern must not violate the following additional constraints: in each period,

(IM1) inventory definition for the depot (customers): the inventory must be consistent with the inventory at the previous period, the quantity made available (received) and the quantity distributed (consumed);
(IM2) stockout definition at the depot (customers): the quantity in inventory must be not lower than the quantity delivered.

A formulation of the basic IRP is defined in [5] for the case with a single vehicle. This class of integrated routing problems has been recently covered in [46], where a survey dedicated to routing problems that have a timing component is provided. A classification of the problems in the class is presented [15] and tutorials on the IRPs can be found in [9] and [10].

3.3 Location Routing Problems

Classical facility location problems (see [51]) aim at finding the best possible locations for facilities, that is, the locations that minimize the sum of the fixed cost for the chosen facilities and the transportation cost for a direct visit from facilities to customers. The cost for direct shipments from the facilities to the customers may be seen as an approximation of the real transportation cost in a tactical/strategic facility planning phase where detailed information about the demands of customers is unknown. However, in general, the assumption of direct shipments may lead to an overestimation of the real transportation cost. This is the reason for studying the Location Routing Problems (LRP), that is, problems where the location decision is taken jointly with the decisions about from which facilities to serve customers and the sequence of visits of the vehicles used for the service.

Formally, the LRP is defined as follows. Let $G = (V, A)$ be a complete weighted graph. Set $V = D \cup C$ is the set of vertices, where D is the set of potential facilities and C is the set of customers to be served. Set A is the set of arcs (i, j), each being associated with a non-negative traveling cost

c_{ij}. Each facility is characterized by an opening cost and a capacity. Each customer is characterized by a demand. A set K of vehicles is available, each with capacity Q.

The minimization of the total facility opening cost and routing cost is sought, subject to the following constraints. From a routing perspective, any feasible solution must satisfy the following conditions:

(RC1) each route starts and ends at an open facility;
(RC2) each customer must be served by exactly one vehicle;
(RC3) no more than K vehicles are used;
(RC4) the quantity assigned to a vehicle does not exceed its maximum capacity Q.

From a facility location perspective, the following constraint must hold:

(FL1) the demand of each customer must be satisfied;
(FL2) customers are supplied only from open facilities;
(FL3) the demand served from an open facility does not exceed its capacity.

We refer the interested reader to the following recent surveys on the LRP. [54] survey the literature on the LRP presented since the survey of [48]. Drexl and Schneider [25] present a survey of variants and extensions of the LRP whereas a survey on the standard LRP is presented in [60]. Finally, the most recent classification of the literature on the LRP is presented in [43].

3.4 Routing in Combination with Packing: Routing with Loading Constraints

The present section is structured as follows. We first provide a general introduction to the class of VRPs integrated with packing problems, often called Routing Problems with Loading Constraints or Routing and Packing Problems. Then, we define the Capacitated Vehicle Routing Problem with Two-dimensional Loading constraints (hereafter referred to as the *2L-CVRP*) and the Capacitated Vehicle Routing Problem with Three-dimensional Loading constraints (henceforth called the *3L-CVRP*), which are two prototypical members of this class of problems. Finally, we review the recent trends in the literature on VRPs combined with packing problems.

3.4.1 Introduction to the Class of Problems

Until recently, the typical approach in Capacitated VRPs, such as the CVRP, has been to assume that the demand of each customer is expressed by a single value, which usually represents the total weight (or volume) of the items requested. Thereby, the capacity of each vehicle measures the maximum weight (or volume) it can carry. Thus, assuming that all the other constraints are satisfied, a solution is feasible if the total weight (or volume) assigned to each vehicle does not exceed its capacity. Nevertheless, in several application contexts, the former assumptions are too restrictive, as it cannot be neglected that the demand of a customer consists of one or multiple items, which are characterized not only by weight (or volume) but also by shape. In these situations, a solution that is feasible to the CVRP may turn out to be infeasible in practice, as it is not possible to determine a feasible loading pattern that allocates all the items within the loading area of each vehicle. Further complications arise when special equipment is required for carrying out loading and unloading operations, or when the items transported are fragile or heavy. In the latter case, unloading must be carried out without reshuffling the loaded items. This is also true whenever the items transported cannot be moved inside the load compartment (or it is preferable not to do so) once they have been loaded. In these situations, the loading plan imposes a strict constraint on the sequence of visits to the customers. As an example, if the items requested by a customer are positioned in the deepest section of the load compartment, that customer has to be visited at the end of the route, as otherwise unloading the items requested is blocked by those demanded by other customers visited later in the route. On the other hand, the sequence of visits of a vehicle constrains the loading plan. All the previous observations highlight that loading and routing are two strictly inter-twinned problems that, if solved sequentially, may lead to sub-optimal solutions.

Based on the shape of the items requested, two major classes of integrated routing and packing problems can be identified. In some transportation applications, the customers request two-dimensional (also called rectangular-shaped) items that, because of their fragility or weight, cannot be stacked on top of each other. Examples of such applications are the transportation of large or heavy items—such as furniture, household appliances, and some mechanical components—or fragile items—such as pieces of catering equipment like food trolleys (e.g., see [53]). In all these cases, the routing problem must incorporate additional constraints to guarantee a feasible packing of the two-dimensional items requested.

In other transportation applications, the customers request three-dimensional items that can be superposed (possibly, with some limitations). Examples of such applications are the transportation of soft drinks and staple goods (e.g., see [59]). In these cases, additional constraints must be added to the routing problem to impose a feasible packing of the three-dimensional items requested by the customers.

The two packing problems mentioned above are multi-dimensional packing problems, which arise as extensions of the classical (one-dimensional) bin packing problem. In their basic forms, they are known as the Two-dimensional Bin Packing Problem (2BPP) and the Three-dimensional Bin Packing Problem (3BPP), respectively (see [32] and the references cited therein). In integrated routing and packing problems, additional restrictions are added to the 2BPP and the 3BPP to capture several loading issues, as detailed below.

In the following, we describe two prototypical problems integrating routing and packing. First, we illustrate the 2L-CVRP and, then, the 3L-CVRP, which can be seen as an extension of the former (e.g., see [32]).

It is worth highlighting that, given the scope of this survey, we focus on the two former problems. Nevertheless, the area of combined routing and packing problems is wider, including the VRPs with multiple compartments, the Traveling Salesman Problems (TSP) with pickups and deliveries and specific unloading restrictions, the double TSPs with multiple stacks. For more general overviews that include also the latter problems, we refer the interested reader to the surveys by [32, 33], and, more recently [53].

3.4.2 The Capacitated Vehicle Routing Problem with Two-Dimensional Loading Constraints

In the 2L-CVRP the customers request rectangular-shaped items (i.e., each item is characterized by width and length). For each vehicle, the loading surface available is also expressed in two dimensions (width and length). The 2L-CVRP models transportation applications where the items are heavy or fragile, such as refrigerators, or pieces of catering equipment, such as food trolleys, or when customer requests are loaded onto pallets which cannot be stacked on top of each other (e.g., see [16]).

Formally, the 2L-CVRP can be defined as follows. Let $G = (V, E)$ be a complete undirected and weighted graph. Set $V = \{0, 1, 2, \ldots, n\}$ is the set of vertices, where 0 represents the depot, and set $V \setminus \{0\}$ is the set of customers. Set E is the set of edges (i, j), each being associated with a non-negative traveling cost c_{ij}.

A fleet of K homogeneous vehicles is available at the depot to serve all the customers. Each vehicle has a maximum capacity Q, and a rectangular loading surface that is accessible from the rear for loading/unloading operations. The loading surface of each vehicle has a given width and length denoted by W and L, respectively.

Each customer $j \in V \setminus \{0\}$ has a known and deterministic demand comprising m_j items, each one having a specific width and length, denoted as w_j^p and l_j^p (with $p = 1, \ldots, m_j$), respectively. Let q_j denote the total weight of the items demanded by customer j.

The 2L-CVRP calls for the determination of a minimum-cost set of routes traveled by the fleet of vehicles available to serve all the customers, subject to the following set of constraints. From a routing perspective, any feasible solution must satisfy the following conditions:

(RC1) each route starts and ends at the depot;
(RC2) each customer must be served by exactly one vehicle;
(RC3) no more than K vehicles are used;
(RC4) for each vehicle, the total weight of the items assigned does not exceed its maximum capacity Q.

Any feasible loading pattern must not violate the following two additional constraints:

(LC1) each item must be loaded with its edges parallel to those of the vehicle (*orthogonality constraints*);
(LC2) there must exist a non-overlapping loading pattern of all the items assigned to a vehicle into its loading surface (*bin packing constraints*).

Additional constraints that define the feasibility of a loading pattern depend on the variant studied. It is worth now recalling the classification proposed in [27] for the 2L-CVRP. This classification is based on the possible loading configurations, and is as follows:

(i) *Sequential Loading* (SL) or rear loading or Last-In First-Out (LIFO) policy, when items must be loaded in reverse order with respect to the customers visits, as they cannot be reshuffled inside the load compartment;
(ii) *Unrestricted Loading* (UL), when items are allowed to be rearranged while visiting a customer;

and,

(I) *Oriented Loading* (OL), when items have a fixed orientation and cannot be rotated;
(II) *Non-oriented Loading* (NL) or rotated loading, when items are allowed to be rotated by 90°.

The possible combinations of the latter four constraints lead to four *basic 2L-CVRP variants*: (a) Two-dimensional Sequential and Oriented Loading (2|*SL*|*OL*); (b) Two-dimensional Sequential and Non-oriented Loading (2|*SL*|*NL*); (c) Two-dimensional Unrestricted and Oriented Loading (2|*UL*|*OL*); (d) Two-dimensional Unrestricted and Non-oriented Loading (2|*UL*|*NL*).

The majority of the problems studied in the literature assume the presence of SL constraints. Such restrictions impose that when customer *j* is visited, the requested items must be freely available for unloading through a sequence of straight movements (one per item) parallel to the length edge of the loading compartment. In other words, there must not be any item requested by another customer, that will be visited later in the route, blocking the unloading, i.e., between the items requested by customer *j* and the doors of the vehicle.

Figure 3.3 shows an example of a feasible solution to a 2|*SL*|*OL*.

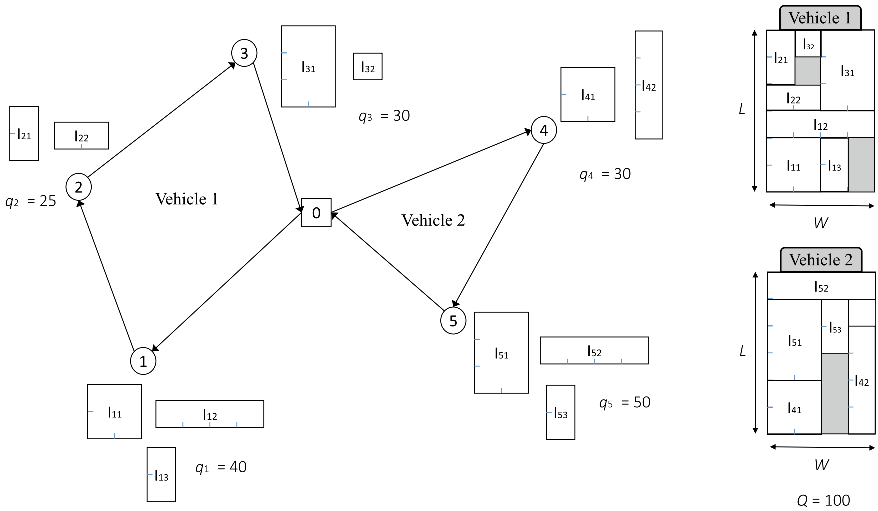

Fig. 3.3 An example of a feasible solution to a 2|*SL*|*OL* variant

Iori et al. [34] show that the 2L-CVRP reduces to the classical CVRP by assigning to each customer a single item having both width and length equal to 1, and setting the dimension of the loading surface of each vehicle equal to the total number of customers.

Côté et al. [16] quantify the potential benefits produced by tackling directly the 2L-CVRP with a unified solution approach, with respect to solving separately the individual routing and packing problems, by means of three non-integrated approaches. As a proof of concept, the authors consider a 2|*SL*|*OL* variant and show, by using worst-case analysis, that the cost of a solution obtained with one of the considered non-integrated approaches may be as large as twice the cost of the solution produced by an integrated exact approach. Furthermore, the authors provide empirical results to show the cost increase when a non-integrated approach is adopted with respect to an integrated approach.

3.4.2.1 Recent Trends in the Literature on the 2L-CVRP

Since its introduction by [34], the 2L-CVRP has received an ever-increasing academic attention. As mentioned above, surveys on routing problems that incorporate loading constraints, which obviously cover also the 2L-CVRP, are available in [32, 33], and [53]. Hence, in the following, we limit the overview to the recent trends on the 2L-CVRP, and refer the reader to the above-mentioned surveys for the earlier literature.

Basic 2L-CVRP variants are studied in [16, 31, 67], and [68], where the authors propose heuristic or exact solution methods for their solution. The exact solution approaches are proposed for the solution of a 2|*SL*|*OL* variant, whereas the heuristic algorithms are applied to the solution of the latter and some other basic variants. More particularly, [31] develop for the 2|*SL*|*OL* variant a Branch-and-Cut (B&C) algorithm, which incorporates several packing routines based on branch-and-bound, constraint programming, and metaheuristic approaches. For the same variant, [16] implement a B&C, derived from the approach proposed [17] for its stochastic counterpart. As mentioned above, to gauge the benefits of addressing the problem by using a unified solution approach, the authors compare the solutions obtained by such approach with those produced by three non-integrated approaches that consider separately the routing and the loading sub-problems. [67] design a heuristic for the solution of the 2|*SL*|*OL* and 2|*UL*|*OL* variants. The general idea is to employ a Variable Neighborhood Search (VNS) to address the routing sub-problem, and a skyline heuristic (i.e., a sort of sequence-based Tabu Search - TS) to check the loading feasibility of the routes produced by the VNS. All four basic variants (i.e., 2|*SL*|*OL*, 2|*SL*|*NL*, 2|*UL*|*OL*, 2|*UL*|*NL*) are solved by the Simulated Annealing (SA) algorithm proposed in [68]. This algorithm is based on four neighborhood structures, which are employed probabilistically, and on an open space local search heuristic to check the loading feasibility.

Extensions of the basic variants are studied in the following articles, where the solution approach proposed is, in the majority of the cases, heuristic. [23] and [69] investigate extensions where both collection and distribution of items may occur in the same route. More specifically, [23] analyze 2|*SL*|*OL* and 2|*SL*|*NL* problems with backhaul customers, where a precedence constraint imposes that on each route the backhaul customers, if any, are visited after all linehaul customers (see [65], Chap. 9). For the solution of this problem, the authors develop a hybrid algorithm that combines a Large Neighborhood Search (LNS) heuristic with biased-randomized versions of classical routing and packing heuristics. Based on applications arising in reverse logistics, [69] extend each of the four basic 2L-CVRP variants to problems where customers require simultaneous pickup and delivery services. The heuristic framework developed consists of a local search method for optimizing the routing sub-problem and a packing heuristic to produce feasible loading plans.

The time dimension is considered in the extensions investigated by [2] and [62]. In the former article, the authors study a time-dependent 2|*UL*|*OL*, where the travel time between a given pair of nodes is a function of the departure time from the origin node. The problem is formulated as a bi-objective optimization model, where the two objective functions are the minimization of the total travel time, on one hand, and the balance of the weight distribution among the vehicles achieved by using a minimax approach, on the other hand. A method called elitist non-dominated sorting local search is developed to solve this problem. Inspired by an application encountered in the food services industry, [62] study a multi-product 2L-CVRP with time windows constraints. In addition, the authors consider a modified SL constraint (called Adapted LIFO) where straight movements parallel to both the length edge and the width edge of the loading compartment are allowed. A generalized VNS algorithm is designed for the solution of this problem.

Dominguez et al. [24] extend the two UL basic variants (i.e., 2|*UL*|*OL* and 2|*UL*|*NL*) to consider a heterogeneous fleet of vehicles, where each vehicle type has a different weight capacity, width, length, as well as fixed and variable costs. The objective function considered aims at minimizing the total cost, which includes the driving distances and the fixed and variable costs associated with the vehicles routed. To solve this problem, the authors develop a multi-start algorithm based on biased-randomized versions of routing and packing heuristics previously proposed in the literature. Based on an application arising in the grocery distribution, [50] investigate a multi-compartment 2L-CVRP where the size of the compartments is flexible and has to be determined as part of the optimization. The objective function proposed aims at minimizing the sum of routing, loading, and unloading costs. For its solution, the authors implement both an exact (B&C) and a heuristic (LNS) algorithm. To the best of our knowledge, [17] are the only authors that study a stochastic 2L-CVRP. In particular, they address a $2|SL|OL$ variant where item sizes and weights are not known with certainty when vehicle routes are planned, but are stochastic and, hence, associated with discrete probability distributions. The authors model this problem as a two-stage stochastic program and solve it by means of an exact integer L-shaped method.

3.4.3 The Capacitated Vehicle Routing Problem with Three-Dimensional Loading Constraints

The 3L-CVRP is a natural extension to three dimensions of the 2L-CVRP presented above. In the 3L-CVRP customers request rectangular boxes, that is, besides width and length, the shape of each item is also characterized by height. Similarly, the loading surface available in a vehicle is three-dimensional and defined by width, length, and height. This problem is often encountered in the distribution of soft drinks, staple goods, and certain types of furniture and household appliances (e.g., see [53]) where some items can be superposed on top of each other. Introducing the height dimension implies that some additional loading issues might have to be taken into consideration. Of particular relevance are the issues concerning the fragility of the items, which limits the items that are stackable, and those concerning the stability of the items, when items are superposed on top of others.

Compared to the formal definition provided above for the 2L-CVRP, in the 3L-CVRP the loading surface of each vehicle is further characterized by its height, denoted as H. Similarly, each item demanded by a given customer $j \in V\setminus\{0\}$ has a specific height, denoted as h_j^p (with $p = 1, \ldots, m_j$). Furthermore, each item is also associated with a fragility flag f_j^p that takes value 1 if item p demanded by customer j is fragile, and 0 otherwise.

The 3L-CVRP calls for the determination of a minimum-cost set of routes to be traveled by the given fleet of vehicles to serve all the customers, subject to the above-mentioned routing constraints (RC1)–(RC3), and the loading constraints (LC1)–(LC2) plus the following additional loading constraints:

(LC3) no non-fragile item is stacked on top of a fragile one, whereas a fragile item can be superposed on fragile as well as non-fragile items (*fragility constraints*)

(LC4) when an item is stacked on top of others, its base must be supported by a minimum supporting area to guarantee the vertical stability of the cargo (*stability constraints*).

Regarding the latter constraints, it is worth highlighting that the supporting area of a given item is determined by the area touched by the base of that item. The packing is feasible only if such an area is not smaller than a given percentage of the base of the item itself.

The classification proposed by [27] for the 2L-CVRP (see Sect. 3.4.2) can be extended to the 3L-CVRP with the following specifications:

(I') SL constraints: when a customer j is visited, there must not be any item requested by another customer, that will be visited later in the route, placed over any item requested by j or between these items and the doors of the vehicle;

(II') NL constraints: items are allowed to be rotated by 90° on the horizontal plane, but have a fixed vertical orientation (i.e., they cannot be rotated upside-down).

The basic 3L-CVRP variants can then be identified by using a labeling notation analogous to the one introduced for the 2L-CVRP: 3|*SL*|*OL*, 3|*SL*|*NL*, 3|*UL*|*OL*, and 3|*UL*|*NL*.

Figure 3.4 shows an example of a feasible solution for a 3|*SL*|*OL* where items I_{12}, I_{22}, and I_{32} are assumed to be non-fragile. A feasible loading plan for vehicle 1 is shown in Fig. 3.5.

3.4.3.1 Recent Trends in the Literature on the 3L-CVRP

The introduction of the 3L-CVRP by [28] has inspired a large stream of research. As mentioned above for the 2L-CVRP, in the following we concentrate on the latest advances found in the literature on the 3L-CVRP, and refer the interested reader to the above-mentioned surveys for the earlier literature.

Basic 3L-CVRP variants are studied in [40, 64], and [31]. The first two papers propose heuristics for the basic 3|*SL*|*NL* variant. In more details, [64] design a TS, which iteratively invokes two greedy packing heuristics for the loading sub-problem, whereas [40] propose a column generation-based

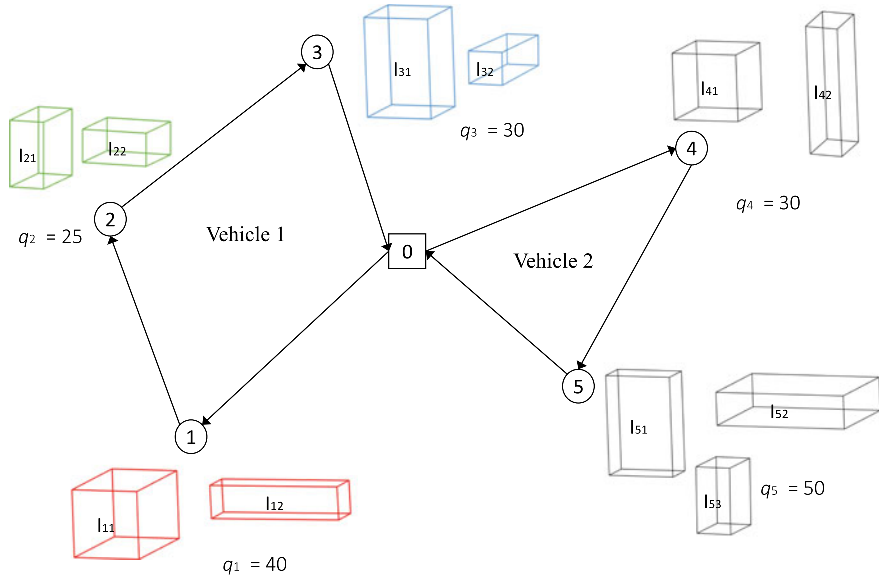

Fig. 3.4 An example of a feasible solution to a 3L-CVRP

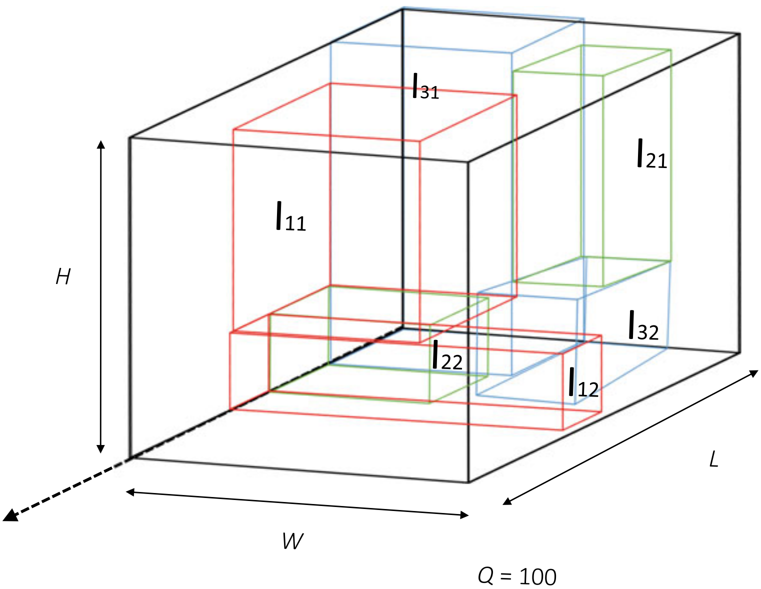

Fig. 3.5 A feasible loading plan for vehicle 1 from Fig. 3.4

heuristic. Hokama et al. [31] extend the exact approach mentioned above for the 2L-CVRP to a basic 3L-CVRP variant.

Extensions of the basic 3L-CVRP variants are studied by the following authors, where the solution approach developed is always heuristic. Significant attention has been devoted to extensions of the 3|*SL*|*NL* basic variant where both collection and distribution of items may occur in the same route. In more details, [12] study a 3|*SL*|*NL* variant with backhauls and propose two hybrid heuristics for its solution. Both solution approaches employ a tree search heuristic to solve the loading sub-problem, and they differ in terms of the procedure applied for the routing sub-problem (an Adaptive LNS-ALNS - versus a VNS). Koch et al. [37] study a 3|*SL*|*NL* variant with mixed backhauls, where the precedence constraint present in classical VRPs with backhauls is relaxed (see [65], Chap. 9) so that linehaul and backhaul customers can be visited in any arbitrary sequence. As in such extension items associated with linehaul and backhaul customers might be simultaneously carried on the same vehicle, the loading sub-problem becomes particularly challenging. For its solution, the authors implement a hybrid heuristic consisting of a reactive TSfor the routing sub-problem and different packing heuristics for the loading sub-problem. Koch et al. [36] address a 3|*SL*|*NL* variant with simultaneous pickup and delivery, where each customer demands the delivery of a set of items and the pickup of another set of items (see [65], Chap. 6). Additionally, time windows are associated with each customer, as well as the depot. This problem is solved by means of a hybrid algorithm that consists of an ALNS for solving the routing sub-problem, and several construction and local search heuristics for the loading sub-problem. Time windows are also considered in the extensions addressed by [57], along with some elements tackled in the previous three papers. More particularly, [57] study four extensions, namely a 3L-CVRP with backhauls, with mixed backhauls, with simultaneous pickup and delivery, and with divisible deliveries and pickups (i.e., where delivery and pickup at a customer location may be performed in a single visit or in two separate visits, see [65], Chap. 1). The authors develop a solution approach based on invoking, first, a TSto solve the packing sub-problem, and then solving the resulting VRPwith time windows instance by means of an algorithm that combines a multi-start evolutionary strategy with a TS. Männel and Bortfeldt [41] introduce pickup and deliveries into a 3|*SL*|*NL* variant. The authors show that in this case the standard SL constraint is not sufficient to avoid any reloading, i.e. any temporary or permanent repositioning and rotating of boxes after loading and before unloading, but some additional restrictions are needed. Hence, they present five variants that differ in terms of the reloading efforts involved.

Three of these five variants are solved in [41] by using a heuristic combining an LNS for the routing sub-problem, and a packing heuristic taken from the literature for the loading sub-problem. The remaining two variants are tackled in [42] by using a heuristic that works along the same general lines of the solution procedure developed in [41].

Zhang et al. [70] address a $3|SL|NL$ variant where the objective function aims at minimizing the total fuel consumption, which is assumed to be a function of both the total weight of the vehicle and the distance traveled. This problem is solved by means of an evolutionary local search, which employs an open space heuristic to verify the feasibility of the loading plans. Bortfeldt and Yi [11] introduce the possibility of split deliveries into a $3|SL|NL$ variant, i.e. a customer can be visited in two or more tours (see [65], Chap. 9). The authors consider two splitting policies: (i) a delivery is split only if the demand of a customer cannot be transported by a single vehicle because it exceeds its volume or weight capacity; (ii) a delivery can be split any number of times. For the solution of both cases, the authors develop a hybrid heuristic consisting of a genetic algorithm and several construction heuristics for the packing sub-problem, and a local search algorithm for the routing sub-problem.

3.5 Routing in Combination with Routing: Two-Echelon Routing Problems

This section is organized as follows. We first provide a general description of the class of two-echelon VRPs. Then, we define the Two-Echelon Capacitated Vehicle Routing Problem (henceforth referred to as the *2E-CVRP*), which is a prototypical member of this class of problems. Finally, we provide an overview of the recent trends in the literature on two-echelon VRPs.

3.5.1 Introduction to the Class of Problems

Modern distribution networks are often structured in multiple *echelons*, where an echelon (sometimes called level of the network) represents a pair of stages (e.g., producer-wholesaler, or retailer-customer) between which the transportation of freight occurs. The number of echelons depends on several factors, including the structure of the supply chain and the characteristics of the freight transported.

In the last two decades, a holistic approach to supply chain management has stimulated scholars working in different research areas to study problems characterized by the presence of more than one echelon; that is problems where freight, from its origin, is hauled to some intermediate facilities (e.g., distribution centers or cross-docks) before being delivered to its final destination. Nevertheless, implementing such an approach raises several issues, the most relevant being how to coordinate the flows of freight moving in one echelon with the flow moving in the following one and, more particularly, how to handle the dependency of the second level from the first one. Although in several cases coordinating the flows of freight moving in two adjacent echelons is too complex, in other cases this has proven to be highly beneficial.

We now recall the labeling notation introduced by [38], and later integrated by [19], to classify multi-echelon location routing problems. The notation is as follows: $\lambda/M_1/\dots/M_{\lambda-1}$, where λ denotes the number of stages, and M_i the type of distribution mode between stages i and $i+1$. The distribution mode can be $M_i = R$ if between i and $i+1$ only return trips (i.e., trips to and from a given vertex) are allowed. On the other hand, if trips leaving from i can be routes visiting a sequence of vertices, then $M_i = T$. Finally, if location decisions are considered at stage i, the corresponding distribution mode identifier is marked with an overline (i.e., $\overline{R}$ or $\overline{T}$).

In the present survey, we focus on Two-Echelon VRPs (from now on, *2E-VRPs*), that is, given the above-mentioned labeling notation, on $3/T/T$ problems. In general terms, a 2E-VRP can be described as follows. The distribution network comprises three disjoint sets of vertices, corresponding to the locations of the origins of the freight (hereafter called *depots*), the locations of the intermediate facilities (from now on called *satellites*), and the locations of the destinations of the freight (henceforth called *customers*). Hence, the distribution network consists of two echelons. Direct deliveries from a depot to a customer are usually not allowed, that is, freight must generally transit through a satellite before being delivered to a customer. Freight is transported by two different fleets of vehicles, one fleet per echelon. Vehicles moving through the first echelon are called *primary vehicles*, whereas those moving across the second echelon are named *secondary vehicles*. Routes are possible at both echelons. Note that in the literature several authors call 2E-VRPa problem where routes are possible at only one echelon, and only return trips are allowed at the other echelon. These papers are out of the scope of this survey and therefore are not covered. Despite we concentrate on distribution networks consisting of two echelons, it is worth noticing that our bibliographic search did not return any recent result concerning networks comprising more than two echelons and where routes are possible at each level. Furthermore, the decisions involved in the 2E-VRP sketched above are mainly at a tactical planning level: the routing of freight through each echelon and the allocation of customers to the satellites. Note that strategic planning decisions, e.g., location decisions, are not considered, as we assume that the set of depots and satellites is given. The bibliographic search returned very few papers where location decisions are considered at any stage of the network. The reader interested in the latter area is referred to [56] and [45], and the references cited therein. Finally, truck and trailer routing problems can also be classified as two-echelon routing problems. The latter class is not covered in this survey. The interested reader is referred to the survey by [20], and the more recent articles by [58] and [1].

Real-life applications that can be modeled as two- or multi-echelon distribution systems can be encountered in city logistics, multi-modal transportation, postal and parcel delivery, and grocery distribution (e.g., see [20]). Among those, the most frequently cited application is city logistics. In fact, the paper by [18], who study a two-echelon distribution network in a city logistics context, is usually regarded as the one that inspired the stream of research on 2E-VRPs, despite the latter expression appeared only later in the literature. The following arguments explain the ever-growing interest in 2E-VRPs applied to urban areas. In this context, freight transportation is one of the major causes of congestion, pollution, noise, and chaos. An effective implementation of a two-echelon distribution system may substantially reduce those externalities. In such systems, the freight demanded by a set of customers, located within the city boundaries, is carried by large trucks (called urban vehicles) from the freight origin to the satellites. The latter are located on the outskirt of the city. At the satellites, the freight is unloaded from the large trucks, sorted, consolidated, and finally loaded onto small and eco-friendly vehicles (named city freighters) that are allowed to travel within the city and can deliver the freight to the customers.

In the following, we describe one prototypical problem where routes are possible at two levels of the distribution network, the 2E-CVRP.

3.5.2 The Two-Echelon Capacitated Vehicle Routing Problem

In the 2E-CVRP one uncapacitated depot and a set of capacitated satellites are available at given locations. Each customer demands a given amount of freight. Two limited fleets of capacitated vehicles are available to carry out the deliveries, one fleet per echelon. The primary vehicles are based at the depot, and are allowed to transport freight from the latter to the satellites.

Each satellite can be served by more than one vehicle, i.e., split deliveries on the first echelon are allowed. The secondary vehicles are shared by the satellites. These vehicles are allowed to transport freight from the satellites to the customers. In other words, in the standard 2E-CVRP direct deliveries from the depot to the customers are not allowed. Each satellite is associated with a capacity expressed as the maximum number of secondary vehicles that can start their route from it. Furthermore, each satellite is associated with a handling cost for loading/unloading operations. Finally, each customer must be served by exactly one vehicle.

Formally, the 2E-CVRP can be defined as follows. Let $G = (V, E)$ be an undirected and weighted graph. Set $V = \{0\} \cup S \cup C$ is the set of vertices, where 0 represents the (uncapacitated) depot, $S = \{1, \ldots, |S|\}$ is the set of satellites, and $C = \{|S| + 1, \ldots, |S| + |C|\}$ is the set of customers. Set $E = E^1 \cup E^2$ is the set of edges (i, j), which are partitioned as follows. Set $E^1 = \{(i, j) : i < j; i, j \in \{0\} \cup S\}$ includes those edges connecting the depot with each satellite, as well as those connecting each pair of satellites. Set $E^2 = \{(i, j) : i < j; i, j \in S \cup C; (i, j) \notin S \times S\}$ comprises the edges connecting each satellite with each customer, as well as those connecting each pair of customers. Each edge $(i, j) \in E^1$ (resp. E^2) is associated with a non-negative traveling cost $c^1_{ij} (c^2_{ij})$.

A fleet of K^1 homogeneous primary vehicles is available at the depot. Each primary vehicle has a maximum capacity Q^1, starts its route from depot 0, serves one or more satellites in S, and then returns to the depot (i.e., each primary vehicle traverses only edges in set E^1). A fleet of K^2 homogeneous secondary vehicles is shared by the satellites. Each secondary vehicle has a maximum capacity Q^2 (usually, $Q^2 < Q^1$), starts its route from a given satellite $s \in S$, visits one or more customers in C, and then returns to s (i.e., each secondary vehicle traverses only edges in set E^2). From each satellite $s \in S$ at most K^2_s secondary vehicles can be routed. Furthermore, a handling cost h_s is paid for each unit of freight shipped through satellite $s \in S$. Note that, if cost-effective, some satellites may be left unused. Finally, each customer $j \in C$ demands a known and deterministic amount q_j of freight. The 2E-CVRP calls for the determination of a minimum-cost set of routes at both echelons such that the demand of all customers is satisfied and that the capacity restrictions of the vehicles and satellites are not violated. Notice that in the 2E-CVRP the cost of a solution is given by two components: on one hand, the cost of routing primary and secondary vehicles and, on the other hand, the handling cost at the satellites. Regarding the routes at the first echelon, any feasible solution must satisfy the following conditions:

(F-RC1) each route starts and ends at the depot, and visits one or more satellites;
(F-RC2) each satellite is visited by one or more primary vehicles;
(F-RC3) no more than K^1 primary vehicles are used;
(F-RC4) for each primary vehicle, the total amount of freight assigned does not exceed its maximum capacity Q^1.

On the other hand, regarding the routes at the second echelon any feasible solution must satisfy:

(S-RC1) each route starts and ends at a given satellite, and visits one or more customers;
(S-RC2) each customer must be served by exactly one secondary vehicle;
(S-RC3) no more than K^2 secondary vehicles are used;
(S-RC4) for each satellite $s \in S$, no more than K_s^2 secondary vehicles are used;
(S-RC5) for each secondary vehicle, the total amount of freight assigned does not exceed its maximum capacity Q^2.

Figure 3.6 depicts an example of a feasible solution to a standard 2E-CVRP.

Guastaroba et al. [30] propose to classify freight transportation planning problems with intermediate facilities according to the type of network (pure or hybrid), the number of intermediate facilities (single facility or

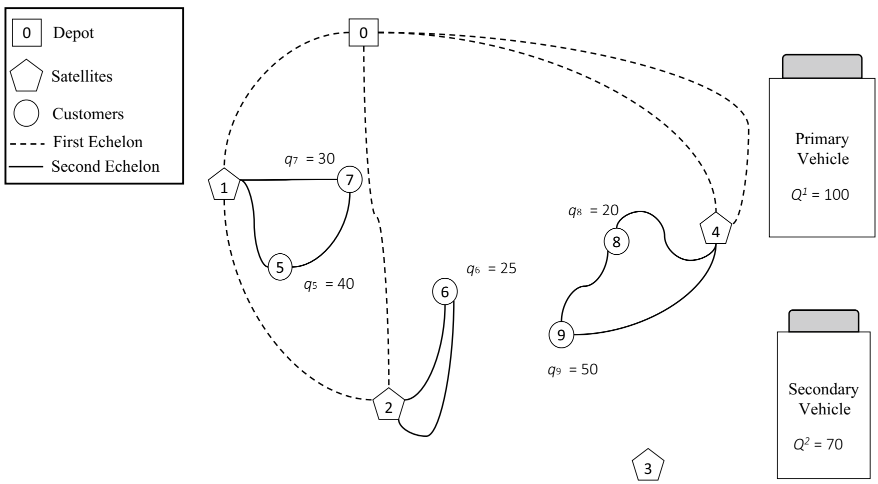

Fig. 3.6 An example of a feasible solution to a standard 2E-CVRP

multi-facility), the origin-destination structure (one-to-one, one-to-many or many-to-many), and the number of commodities (single commodity or multi-commodity). According to such classification, the above 2E-CVRP is a multi-facility problem defined on a pure network, with a one-to-many origin-destination structure, and a single commodity.

3.5.3 Recent Trends in the Literature on 2E-VRPs

The origin of the research on 2E-VRPs is usually associated with the paper by [18], although the first formal definition of the class of 2E-VRPs and of the 2E-CVRP, as described above, can be found in [52]. Surveys on routing problems that cover 2E-VRPs, as well as related problems, are provided in [20] and [30]. Hence, in the following, we concentrate on the recent trends in the literature on 2E-VRPs, and refer the reader to the above-mentioned surveys for the earlier literature.

Most of the recent research efforts are concentrated on the study of variants of the standard 2E-CVRP defined above. The latter basic problem is tackled in [13] by means of a hybrid heuristic that combines local and large neighborhood search with destroy-and-repair principles, and in [44] with a Branch-Cut-and-Price exact algorithm.

We have already highlighted the importance in 2E-VRPs of capturing the dependence of the second level from the first one. The standard 2E-VRP captures a space dependency, that is freight that a secondary vehicle delivers to its customers must be provided to the associated satellite by a primary vehicle. Introducing in such a simple scheme the time dimension makes the problem more realistic but requires capturing the dependency in time between the two levels. Grangier et al. [29] study a 2E-CVRP with time windows constraints associated with customers. As satellites are assumed to have no storage capacity, the arrival of primary and secondary vehicles is explicitly considered by introducing a set of synchronization constraints. Secondary vehicles are allowed to perform multiple trips, which may start at different satellites. The authors present an ALNS to solve this problem. Nolz et al. [49] address a 2E-CVRP with one single satellite, that has a limited capacity, and time windows constraints for the customers. Furthermore, primary vehicles can serve directly a customer, and both primary and secondary vehicles can perform multiple trips. Also in this problem, the synchronization in time between vehicles belonging to the two echelons plays a crucial role. The authors design a three-phase heuristic that combines a genetic algorithm, local search, and integer programming for the solution of this problem. Scheduling synchronized meetings at satellites between vehicles of the two echelons is fundamental also in the 2E-CVRP investigated in [3]. In this problem, customers are grouped into three subsets: a set of customers visited by primary vehicles, a set visited by secondary vehicles, and a set of so-called "grey zone" customers that must be assigned to primary or secondary vehicles. The authors cast this problem as a multi-objective optimization program, by incorporating an economic, an environmental, and a social objective. For its solution, an LNS is integrated into a multi-objective method to find solutions along the Pareto front. Finally, time windows constraints associated with customers are also considered in [21] and [22]. In the former paper, the authors study a 2E-CVRP having a many-to-many origin-destination structure (i.e., there are multiple depots), and where the usage of each vehicle incurs the payment of a fixed cost. The objective function considered aims at minimizing the sum of the total transportation costs and the total fixed cost paid for using vehicles. The authors propose Branch-and-Price algorithms for solving this problem. Dellaert et al. [22] study a 2E-CVRP with time windows, and customer-specific origin-destination, non-substitutable demands. As in [21], the origin-destination structure is many-to-many, and a fixed cost is paid for using a vehicle. The problem is solved by extending the Branch-and-Price approach introduced in [21].

Besides [21] and [22], multi-depot variants are considered also in [61] and [71]. In addition, in the 2E-CVRP addressed by [61] customers can be served by primary vehicles. Based on the method proposed by [6], the authors derive a lower bound, which is then used to obtain an upper bound to the problem at hand. Motivated by applications arising in performing last mile deliveries, [71] tackle a 2E-CVRP where customers can be selected among different delivery options (e.g., direct delivery to home, or pickup at a given location, such as parcel lockers). For the solution of this problem, the authors propose a hybrid multi-population genetic algorithm.

The usage of electric vehicles or, more generally, the consideration of environmental issues is studied in the following papers. Breunig et al. [14] consider a 2E-CVRP where secondary vehicles are electric, so that detours for battery recharging may be necessary because of the limited driving range. The cost of a solution, to be minimized, includes a fixed cost for each vehicle used, and driving costs proportional to the distance traveled. For its solution, the authors extend the approaches developed in [13] and [6] for the standard 2E-CVRP, resulting in a LNS heuristic and an exact algorithm, respectively. In the problem addressed by [35] electric vehicles are present at both levels, which should visit a swapping station to swap their batteries before their battery power runs out. The vehicles are homogeneous within each echelon, in terms of capacity, battery driving ranges, power consumption rate, and battery swapping cost. The objective function aims at minimizing the sum of travel, battery swapping, and handling costs at satellites. For its solution, the authors propose a hybrid algorithm that combines column generation principles with an ALNS algorithm. Environmental considerations connected to the vehicle fuel consumptions and the related emissions characterize the 2E-CVRP tackled by [63]. Furthermore, to account for traffic congestion, in this problem travel times are time-dependent. Soysal et al. [63] cast this problem as a mixed integer linear program, which is solved by means of CPLEX on a small real-world instance inspired by the activities carried out by a supermarket chain operating in the Netherlands. Based on the problem introduced in [63, 66] develop a matheuristic combining VNS and integer programming, where integer programming is employed as a post-optimization technique or to produce minimum-cost routes for primary vehicles.

Liu et al. [39] address a 2E-CVRP where the set of customers is divided upfront in a set of disjoint groups, and a set of additional constraints (called grouping constraints) are added to the problem to ensure that customers from the same group are served by vehicles based at the same satellite. A B&C is developed for the solution of this problem. Similar to [71], in the 2E-CVRP studied by [26] customers can choose among different delivery options (called covering locations) where they can pick up goods themselves. In this variant, there is only one depot available and covering locations can be visited solely by primary vehicles. This problem is solved by means of an ALNS algorithm. Mühlbauer and Fontaine [47] tackle a 2E-CVRP where vans are used as primary vehicles, whereas cargo-bicycles are used as secondary vehicles to perform the final deliveries. As for cargo-bicycles travel distances and times can be significantly asymmetric, the problem is defined on a directed graph. Furthermore, to simplify the cargo transfer at satellites, swap containers are used. These containers are loaded beforehand at the depot according to the second-level routes so that, at a satellite, only the containers are moved from vans to cargo-bicycles. The authors present a parallelized LNS for the solution of this problem. Qiu et al. [55] investigate a 2E-CVRP where production decisions are further integrated into the optimization problem. Because of the production sub-problem, the nature of this variant is multi-period and aims at determining for each day whether and how much to produce; the quantity to deliver from the depot to the satellites, as well as from every satellite to each customer; and the routes of the primary and secondary vehicles at the minimum total cost over the whole planning horizon. For the solution of this problem, the authors present a B&Calgorithm coupled with a matheuristic, where the latter is used to provide feasible initial solutions.

3.6 Conclusions

In this chapter, the most relevant classes of integrated problems with a routing component have been surveyed. Pointers to recent related surveys have been provided and the recent trends in the literature have been discussed.

The research on integrated routing problems is attracting, and we expect it will continue to attract, considerable research efforts, motivated by the clear benefits that integration can bring over more traditional approaches tackling each sub-problem individually. New modeling and algorithmic advancements, together with contributions from other fields such as statistics and computer science, will play an important role in shaping the impact of this topic.

The study of integrated problems contributes to bridge the gap between academic research and real-life applications. Many research directions remain open, from not yet studied integrated routing problems to exact and heuristic methods for the problems that have been already introduced in the literature. Moreover, the majority of papers does not consider dynamic and stochastic aspects that play a relevant role in real-life problems. Considering such characteristics and assessing the benefit of such a consideration is one of the most promising and enticing research directions.

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