Chapter 12

Software Tools and Emerging Technologies for Vehicle Routing and Intermodal Transportation

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12.1 ▪ Introduction

Vehicle routing is a central task in a large number of private and public corporations (see, e.g., Golden, Raghavan, and Wasil [30]). Tours have to be planned in very diverse sectors of the economy, not only in the logistics and transport business but in virtually all industrial sectors producing physical goods. Variants of the vehicle routing problem manifest in a remarkably wide range of commercial and non-commercial enterprises: from waste/refuse collection to retail distribution; from construction material delivery planning to postal and express delivery routing; from inbound manufacturing component transportation to finished car distribution; from in-home primary health care service to hospital operations; from transportation network optimization to *third Party Logistics* (3PL) operation scheduling; and from bulk collection and delivery planning to passenger transportation routing. Hence, vehicle routing is key to logistics efficiency in industry, the public sector, and society in general. The high complexity of the vehicle routing problem renders purely human planning inadequate for most applications. Typically, human-made plans have a large potential for improvement. Also, non-assisted planning occupies valuable human resources. Therefore, high-quality software tools for decision support in vehicle routing are crucial to effective and efficient planning in many sectors of society.

Vehicle Routing Problems (VRPs) in their many guises have been the subject of intensive study for more than half a century now (see Laporte [41]). These research efforts have led to the development of a variety of models and solution algorithms and the publication of thousands of scientific papers. Our ability to solve VRPs has increased tremendously over the past half century due to a combination of better VRP methods and the general performance improvement of computers. These results have, together with the progress of key enabling technologies, led to the emergence of numerous software companies worldwide, selling commercial vehicle routing software tools and accompanying services (see Hallamäki et al. [32], Drexl [13], and Partyka and Hall [50]). Among the most important enabling technologies are *Geographic Information Systems* (GIS), positioning, tracking, and tracing technologies, mobile communication, web services, and cloud computing.

Despite the large number of scientific studies, most of the models and algorithms we find in the research literature are not directly applicable to industrial routing problems. Real-life applications usually incorporate many aspects that are not adequately modeled in standard VRP definitions: additional variables, idiosyncratic side constraints, and more or less exotic and incommensurable objective components. To give a simplified picture, VRP research has been reductionistic in its nature. One precisely defines somewhat stylized models that are studied in detail to reveal its structure. Highly optimized, effective, and efficient solution methods are developed, but they are typically not robust; often they cannot solve problem instances that have additional side constraints or optimization criteria, or their performance is based on some assumption that is often violated in practical applications. Problem generalizations have traditionally emerged in a piecewise and systematic way in the research community. Hence, a classification of various VRP variants exists, and it is gradually being extended (see, e.g., Eksioglu, Vural, and Reisman [17]).

Although some variant of the VRP in the research literature may be the core of the application problem at hand, more often than not the real-life problem is somehow richer: with more detail for some operational aspects, with a wider scope along the supply chain, with more focus on dynamics and uncertainty, or all of the above. Industrial problems tend to combine many aspects of richness in a way that renders *Operations Research* (OR) models and their accompanying solution methods inadequate.

Having said this, the substantial research efforts over the past 50 years have not only given deep insights into stylized variants of the VRP. The models and algorithms developed have also to a large degree been industrialized in the form of commercial software tools. In the past decade or so, focus in the research community has moved to more industrially relevant problem definitions, models, and corresponding solution algorithms. Computational experiments in the scientific community are now to a larger degree performed on instances with size and complexity that are comparable to industrial requirements. There is a tendency towards more cooperation between researchers in industry and academia. Furthermore, there is no strict segregation between the developers of industrial VRP tools and researchers in academia; some have positions in both camps, and some companies are tightly connected to groups in academia. However, there is still a considerable way to go to coordinate the efforts in these communities.

The trend towards more industrial relevance has led to a new category of VRP research. The term "Rich VRP" (Hasle and Kloster [33] and Drexl [13]) has been coined to describe a more holistic approach where one defines a more generic model that adequately captures all of the most important aspects of a selected segment of industrial applications. A main goal is to develop solution algorithms that produce high quality solutions in reasonable time for any instance of the generic model. Often, one tries to achieve this "instance robustness" with a uniform algorithmic approach.

VRPs are, in essence, highly complex optimization problems. Because of this complexity, software for supporting human planners and decision makers has been widely used for years. Computerized vehicle routing helps businesses to improve the utilization of their transportation resources. It can help to reduce journey times, vehicle mileage, and costs, but also increase revenues and improve customer service. This is achieved by rapidly processing the information concerning customer locations and quantities and types of goods to be transported and matching these to available vehicle capacity in order to make best use of all resources. In addition, users obtain substantial customer service benefits through improved reliability and environmental benefits through reduced mileage. It also reduces risk of error and helps to reduce customer lead times. The typical reported savings in mileage, total time, or vehicle fleet are 10–30%. Moreover, vendors typically claim that planning time and use of human resources is often reduced by 80–90%. A routing software tool can also modify driver behavior and improve driver safety.

Vehicle routing software companies often have customers in a wide range of sectors, including industry (raw materials and (semi-) finished goods transportation), wholesale and retail trade (consumer goods distribution), *Less-than-TruckLoad* (LTL) and *Full-TruckLoad* (FTL) forwarders, parcel delivery and letter mail services, reverse logistics and waste collection, service technicians, and salesmen.

The purpose of this chapter is to give an overview of the existing vehicle routing software solutions and their key features, and to discuss relevant new and emerging technologies. We will interchangeably use the terms (vehicle) routing software and (vehicle) routing tool to denote software systems that provide optimization-based decision support for planning the routes of a fleet of vehicles. By (vehicle) routing technology we mean the somewhat broader concept of vehicle routing software and the related technologies. By and large, we limit our discussion to routing software for land-based transportation, as they are the most widespread and typical applications of VRP solvers.

The survey is based on several different sources of information. Apart from searching the literature and the web pages of VRP tool vendors, we refer the reader to the OPTLOG study conducted in 2007 by Hallamäki et al. [32]. We also conducted our own study in the form of questionnaires sent to 50 vendors worldwide (see Table 12.1 for a list of responding vendors). The personal experience of the authors on the development of several vehicle routing tools is another important source of information.

The rest of this chapter is structured as follows. In Section 12.2, we describe the basic functionalities of vehicle routing tools. Input and output are described in Section 12.3 and the various model properties in Section 12.4. The applied solution algorithms are discussed in Section 12.5, whereas Section 12.6 discusses implementation issues. Section 12.7 summarizes the results of our software survey. New and emerging technologies are discussed in Section 12.8. Section 12.9 contains a treatment of business aspects and prospects for the future. Conclusions are drawn in Section 12.10.

12.2 ▪ Basic Functionalities of Vehicle Routing Software

The main functionalities of vehicle routing software solutions include reading and displaying data on orders, vehicles, drivers, depots, as well as calculating distances and travel times between locations based on geocoded addresses. By calling a VRP algorithm, an optimized routing plan for the given data set (i.e., a problem instance) is generated automatically, possibly after entering a set of parameters to the solver. The resulting solution may be displayed several ways using the *Graphical User Interface* (GUI). After possible manipulations by the user, the solution may be exported to external systems.

The typical components of a tool are summarized in Figure 12.1 and in the following list:

- an interface to data files, database, or *Enterprise Resource Planning* (ERP) system,
- a GIS module for geocoding addresses, computing distance, cost, and travel time information, and visualizing data and solutions in digital maps,
- a planning module for automatic, manual, and interactive planning, which allows, e.g., to test the impact of various changes to costs and service levels,

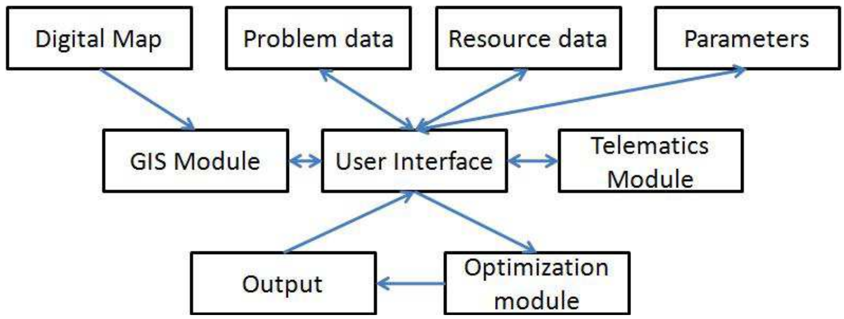

Figure 12.1. *Typical components of vehicle routing software.*

- a telematics module for data exchange between vehicles and the dispatching office, and for tracking and tracing of vehicles,
- a reporting module for presentation of plans, key performance indicators, and statistics in documents or via the GUI.

The GIS and automatic planning modules are the most crucial components. The differences between GIS modules lie in the algorithms, the accuracy, and types of supported maps. The map can directly affect the quality of the produced solutions and causes significant differences between systems. Most VRP tools calculate distances and times by running shortest path calculation (often with Dijkstra's algorithm [12]) on the electronic road network. Often, different types of vehicles may have different speed profiles. Here the term profile refers not only to varying vehicle dependent speeds, but to the fact that a set of different speeds must be defined for each vehicle type, depending on road categories and/or signed speed limits. The most sophisticated tools also consider speed profiles that account for rush hours. Another option supported by most systems is the use of Euclidean distances. Examples of accuracy issues include street level details, address geocoding, driving costs (e.g., uphill), and driving restrictions.

There are often significant differences between tools, depending on used data and modeling properties of the software. From the algorithmic viewpoint, the systems vary from the use of external software for distance and travel time calculation via simple Dijkstra implementations to very sophisticated and fast route and contraction hierarchies, filters, goal directed approaches, distance oracles, etc. (see, e.g., Geisberger et al. [20] and Puranen and Brigatti [53]). In the more sophisticated versions, the criterion for the shortest path may also vary and be based, e.g., on distance, time, cost, and safety. The input and output functionalities are discussed in more detail in Section 12.3 and the properties of automatic planning or optimization in Sections 12.4 and 12.5.

Vehicle routing software is usually used on three main planning levels. The first is operational planning, including both static and dynamic short-term planning in a period less than a week. In the operational context, software can also be used to validate manually planned routes and to test various what-if scenarios. Interactive planning is also supported in most cases. At the tactical level the key issue is typically the determination of resource use, such as vehicle fleet or drivers. One may also analyze different service policies and service networks as well as service areas and user-defined entities. For strategic purposes, the software can be used to plan the network, all resource requirements, sizing and locations, seasonal variations, and budget business based on forecasts and to evaluate alternative options, often in the form of scenarios. One can also use the software, e.g., on longer term service level studies or 3PL evaluations.

In addition to the above-mentioned planning entities, vehicle routing software can be used to

- review the distribution strategy regularly with changes in the business;
- consider larger entities by combining different elements of distribution, such as FTL routing and multi-depot operations;
- integrate with production planning, order processing, and warehouse activity;
- monitor key parts of the logistics chain using key cost drivers (such as visit density and volume);
- facilitate innovative changes within the business, for example, service level differentiation;
- adjust and design sales, service, delivery districts, and vehicle depots;
- to define fixed routes (geographic clustering);
- dispatch for police, fire, and emergency vehicles;
- optimize fuel purchase operations;
- automatically use real-time data in optimization; and
- optimize terminal and depot usage.

12.3 ▪ Input and Output

The input and output capabilities of vehicle routing software solutions are considerable. Often one has specific import and export wizard tools. The supported input data formats include text file, Excel, Access, ODBC, web services, SAP IDoc, and direct ERP integration and are variably available, depending on the software. The applied map data formats include Google maps, Navteq, TomTom, Microsoft, ShapeFile, MapInfo, and MID/MIF.

Often the imported data must be in a given format, though many systems allow adjusting the import format. Several software tools also include different error-correction mechanisms, such as an address matching and correction tool to automatically correct small errors in the input data using imported electronic address and map data. The data itself can vary from basic static single day data to dynamic, stochastic, or long-period data, and it can be based on single orders, or average or aggregate data.

In addition to actual data that includes order, terminal, vehicle fleet, and driver information, the user must specify a number of parameters. We distinguish between *operational parameters* and *planning parameters*.

Typical operational parameters include cost factors (e.g., used cost unit, vehicle and driver costs, revenue of order), units (e.g., distance and time unit, load unit), regulations (e.g., working regulations, turning costs, rules), and operational factors (e.g., vehicle speeds, loading rate). Correspondingly, the typical planning parameters include, for example, cost basis (time, cost, distance), length of planning period, use of depots (open, defined, to optimize), number of trips per vehicle, fleet type (fixed, defined by optimization), allowed maximum route length, and route departure times.

In addition one must define the actual optimization parameters used by the algorithms/optimization process. Often this process is facilitated by one or several alternative default settings or by automatic parameter setting.

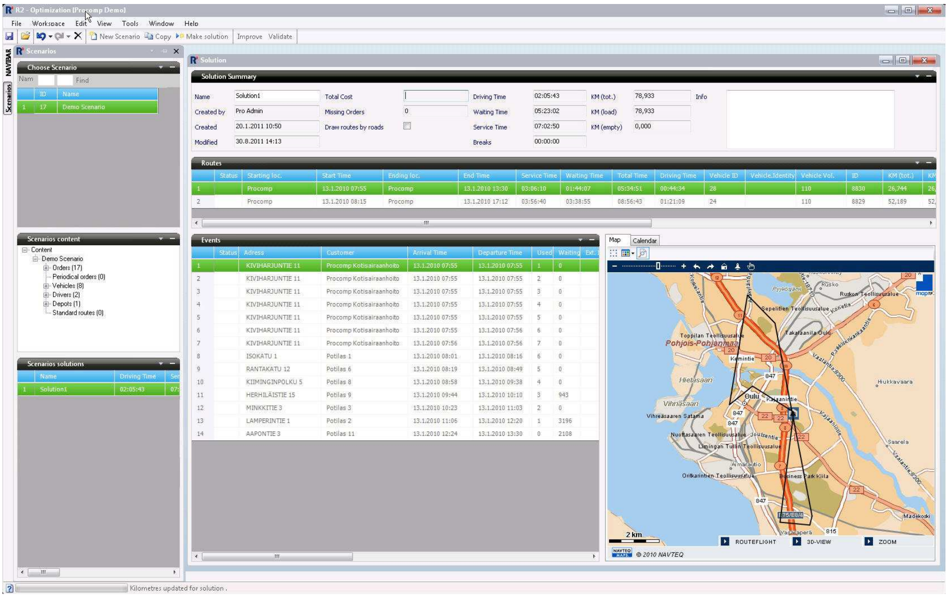

Figure 12.2. *An example of a vehicle routing software GUI. Software: R2, Procomp Solutions Oy (*www.procomp.fi*).*

Practically all systems allow manual adjusting of the routes, often with automatic suggestions. Apart from basic changes such as inserting or deleting orders, re-sequencing orders, exchanging depot, modifying used resources, or adding rest periods, most current systems include drag and drop functionality that also displays the effects of each change on feasibility and operating cost. An example of a GUI of the R^2 software with different types of plan visualization is given in Figure 12.2.

The available reports typically include printed color maps and tree view of data, resources, and results as well as route summaries (distance, time, points to visit, quantities, costs). Other reports include time utilization summaries showing the proportion of time spent on different activities and load manifests or daily traffic sheets showing the allocation of drivers and vehicles to routes. Often, a multi-language support, i.e., possibility to choose the language of the interface, is also provided. In addition, many systems have Gantt-charts (e.g., on time usage), performance monitoring reports (comparing actual results with planned), and status info on the execution of the plan and displaying of active resources. Some software solutions also include profit and loss reports (e.g., order or route basis), invoicing, interfacing to financial accounts, and a web interface.

A few vendors have recently also included carbon footprint display for each route, cost per order delivered, and automatic download of stops to a driver's handset. Other more rarely encountered features include management of diaries of driver shift patterns and holiday fleet maintenance diaries, storing and reporting of actual hours used and per formance monitoring, as well as historical travel times and stop times. In some systems one may also utilize weather forecast information, display warnings for violating service levels and qualifications, and show animated load diagrams. Advanced vehicle tracking and monitoring, including GPS locations, vehicle maintenance information, and vehicle motion details is becoming more and more common. The same applies to integration with vehicle navigation and support for smartphone and tablet apps, SMS text alerts, email alerts, web portals, *Interactive Voice Response* (IVR), voice-assisted drive mode, and telematics platforms such as GTS, CSB-System, TomTom, Fleetboard, AVL/MDT systems, and RFID Scanner. Features of increasing importance also include multi-user or multi-site usage and a posteriori calculation of complex objective functions.

Normally, one may configure customized reports using external software applications; see, for instance, Goel [27] for details. Some software applications will display reasons for orders left unplanned (such as insufficient capacity, errors, or conflicts in data), allowing the user to quickly make adjustments to particular routes and display any constraints that would be broken as a result of the manual alterations. Reports can obviously be exported, for instance, to ERP systems, spreadsheets, and databases.

12.4 ▪ Model Properties

Solving any VRP requires at first determining the problem type and setting up key input data values. This definition is often done through parameter adjustment, but it is also possible via automatic analysis of the problem data. We discuss this setup phase in Section 12.4.1. In addition, one must always define the objective and the constraints for the problem at hand. In VRP software, the objective evaluations can be sophisticated, including numerous factors and even true multi-objective planning. This is discussed in Section 12.4.2. In Section 12.4.3, we have divided the constraints in three parts, depending on whether they are related to order, available resources, or the plan itself.

12.4.1 ▪ Basic Setup

The problem definition setup step includes defining the service/operation type, planning horizon, demand type and size, available resource set, start and end locations for the route, and service times at locations. These are discussed in detail below.

Order Type. One must distinguish between pickup, delivery, separate and simultaneous pickup and delivery, service, and node and arc routing–type operations (see, e.g., Gendreau et al. [23]). The problem may also consist of any combination of these. The supported order type has a strong impact on how to model and solve the problem, e.g., through precedence constraints, same tour constraints, and different location definitions. Some solutions support alternative pickup and delivery locations, referring to a combined problem where in addition to defining the pickup-and-delivery sequences, one must choose the most efficient pickup and/or delivery location from several alternatives.

A further complicating aspect is due to alternative ways of performing a request. In addition to the above listed basic order types, some tools also support more complex transshipment orders, linked orders, and optional orders (see, e.g., Drexl [14]). Transshipment of load as a term can refer not only to exchanging the complete load in a swap-body platform, but to partial exchange or one-way transfer of load from one vehicle to another, for example in multi-modal transportation. As an example, a load from A to B may be performed by a direct transportation, via a meet and turn operation, or via one or several hubs. All possibilities must be considered. According to Drexl [13] only a few systems can handle this. Optional requests refer to orders that need not be assigned to a route, but whose execution brings a bonus.

Demand Size. A key part of most practical VRPs is a vehicle capacity constraint. To deal with that, in the beginning one must define the actual demand size for each order and product type. Demand size can be measured, e.g., by weight, volume, loading meters, number of pallets, or a combination of these. Often, demand size is given directly in the data. However, there are several real-life complicating factors, such as time-dependent order size that may refer to production capacity at load site or consumption rate at delivery location. In such applications of inventory routing, demand size depends on the timing of the visit, initial stock, and storage capacity (see, e.g., Andersson et al. [3]). The goal is to ensure that no customer runs out of stock within the planning period and to minimize transportation costs. Another issue is to determine realistic capacity usage. A practical example is school bus routing where pupils with wheelchair require more space. Such aspects are supported by some tools. In case order size exceeds vehicle capacity, one must split the order among several vehicles, potentially leading to a complex optimization problem, especially if the number of splitting options is large. Here, one may need to consider a minimum delivery amount.

Service Time. In order to deal with time-related constraints such as customer time windows, maximum duration of routes, or drivers' working regulations, one must define the stop time at each visited location. In the basic case, this is simply given as a single service time value, but in real-life applications and software solutions this is rarely good enough. Possibly, a comprehensive model for service times may give the required accuracy. More often than not, stop times depend on several factors, such as the number of products to load/unload, the presence and type of loading dock, and the vehicle type. The use of a loading dock can reduce stop time considerably. On the other hand, if the loading docks are all in use, one must wait. A few tools have functionality to schedule visit times at locations according to loading dock availability. Moreover, service times often depend heavily also on the vehicle type and the need for rearranging the current load. To illustrate, if the vehicle is too small to use the loading docks, or if it does not have necessary (un)loading equipment, the stop time often increases considerably.

To our knowledge, these properties are not fully supported by any tool on the market. One important issue is also vehicle maneuvering at the customer location. It must be considered separately to actual service time. Otherwise, it would be hard to deal with cases where multiple orders are serviced at same location. Some products have service time models that accommodate this aspect. Another practical problem is that, without setting a cost for parking a vehicle, optimization algorithms cannot avoid visiting centrally located customers (along multiple routes) several times. In addition to customer locations, one may also need to define stop times for the start and end locations for routes, for example due to servicing the vehicle or preparing it for the next day. Finally, the product type and used transport units may impact the stop time.

Route Start and End. Many systems allow route start and end positions to be set freely. This means, e.g., that one may define different start and end positions for the route, optimize the start and end depots, or generate open routes (Repoussis et al. [55]) without specifying the start and/or end depot.

Planning Horizon. One of the most important problem definition issues is the planning horizon. In basic delivery planning, the assumption is that the planning horizon is a single day and all data is known at the start of the day. This basic case is supported by all systems. In practice there are several variants. The most obvious one is a multi-day planning horizon, which again has several subvariants. It may consist of multiple single day plans such that the delivery day is fixed or such that the delivery day is determined by the optimization. A further complication includes 24-hour planning horizons so that the routes do not have actual start or end positions or times but run in a continuous loop. This as well as overnight routes (considering, e.g., overnight cost, maximum overnights per journey) is supported by only a few tools. On the other hand, periodic, multi-period, or rolling horizon planning is supported by several systems. In periodic planning (Chao, Golden, and Wasil [9]) one typically has a longer planning horizon of several weeks or even months and given visit frequencies at each customer site, such as once a week. The goal is to define the optimal visit days for the whole period, given the allowed visit patterns. In rolling horizon planning (Rakke et al. [54]) the key idea is to repeatedly determine an optimized plan for a defined short-term planning horizon within a longer planning horizon. One may also distinguish important variants within the single day planning horizon, such as dynamic or real-time routing that is nowadays supported by most systems. The key idea in real-time routing (Psaraftis [52]) is allowing changes onto previously optimized routes and to reoptimize the routes quickly. The changes may include, e.g., new requests, cancelled requests, changed request size, delays, changed traffic conditions, or vehicle breakdowns.

Uncertainty. As most real-life route planning situations are full of uncertainties, stochastic planning (Gendreau, Laporte, and Séguin [22] and Flatberg et al. [19]) is an important issue. Given enough relevant information, parts of the input data should be given as probability distributions instead of crisp numbers. Of course, stochastic problems need more sophisticated algorithms that consume more computational resources. Only very few companies state that their algorithms are capable of handling stochastic customers or stochastic demand/supply. A few companies deal with the issue by using simulation to study the behavior (expected distance, arrival times, time window violations, and the robustness of solutions) of routing plans over a longer time horizon.

Resources. Apart from the constraints and objectives, there are a few resource-related issues that need to be set up in the beginning. Despite the very fast recent shortest path calculation engines, most of the systems are still based on the usage of distance and time matrices that are calculated in the beginning and stored before the actual route optimization can start. Here one must consider the used vehicle fleet. Even though practically all systems support multiple vehicle types, only a few practically allow calculating a separate distance and time matrix for each vehicle type, considering speeds, restrictions, impacts of different turns, etc. It is even rarer to find support for using bicycles and pedestrian routes and travel times, which are important in many applications (e.g., mail and newspaper delivery and school bus routing). Some systems provide support for multiple transport modes such as rail, barge, ship, and air, in addition to standard road-based transportation.

Another important aspect supported by some tools is the usage of trailers or semi-trailers (see, e.g., Villegas et al. [64]). This often requires defining separate tours for the tractor/vehicle and the vehicle-trailer combination and determining the optimal parking positions for trailers as well as trailer assignments. The vehicle fleet may be given, or it may be a part of the optimization objective, resulting in a fleet size and mix optimization problem (see, e.g., Bräysy et al. [7] and Hoff et al. [34]). Even in the case of a given vehicle fleet, assigning vehicles to routes is a complex optimization task if the fleet is heterogeneous. Unless this issue is not specifically supported, most heuristics fail to find the optimal vehicle allocation for practical problems. One may also need to consider the vehicle and driver rotations in planning the resource usage. This is, however, only rarely supported.

12.4.2 ▪ Objective Function

A large variety of objective functions is available in all or most systems. It is possible to minimize the number of vehicles used, the overall distance covered by all vehicles, and the total time or cost of all vehicles. The most common extensions include route balancing and penalty costs for violating soft constraints such as time windows, route total time, preferred vehicles, overnight charges, number of reloads or overloading (see, e.g., Jozefowiez, Semet, and Talbi [39] and Figliozzi [18]). There are a number of metrics used to balance the routes: duration, number of stops per week, stops per day, stops per driver, time on site per driver, driving distance per driver, and sales volume. A related issue is the goal of generating varying routes, e.g., in the context of transporting valuables or planning security patrol routes. Penalty costs are often used to consider undesired but not strictly infeasible properties of solutions or to allow infeasible solutions during the solution process. One may, e.g., penalize the waiting time of the route, which may also require the definition of optimal route start times. In the multi-depot context, the goal may also include defining the optimal depot. The most accurate cost models include even the daily allowances for drivers. Recently, some software vendors have added support to calculate CO_2 emissions.

Some systems allow the user to specify transport revenue details with order data, enabling a more realistic revenue maximization objective. Often this can be described in a variety of ways (e.g., per order, per pallet, or per kg). Similarly, some systems allow considering the inventory costs at depots, terminals, or hubs. Transportation tariffs are also supported by some tools. The tariffs are typically dependent on good type, order size, and distance and are still commonly used in several countries. The key idea here is that the cost is not dependent on the exact route but on the tariff. The goal is typically to design the optimal transportation network, given the tariffs.

The avoidance of toll roads and bridges is a quite common feature, but, for example, congestion charges, impact of vehicle weight along the route, or altitude related truck routing costs (e.g., trip routing to reduce hill climbing) are rarely supported.

Multi-objective optimization (Bãnos et al. [4]) is becoming more and more important. From this viewpoint, about half of all optimization tools support a weighted sum of one-dimensional objective functions that is a simple way to deal with multiple objectives. Real multi-criteria optimization (Steuer [61]) is supported by only very few systems, and even in these cases only for limited properties such as priorities, open orders, and total cost based on, e.g., rate, distance, time, and other input variables.

12.4.3 ▪ Constraints

In addition to the objective, a key issue is to specify a number of hard or soft constraints. We divide the constraints into three classes depending on their relation to order data, resource data, or plan generation. Some constraint types may also exist in several classes.

12.4.3.1 ▪ Order Specific Constraints

Time Windows. Some customers want to receive their deliveries within one or several alternative time windows. Note that the time windows can also be defined flexible or soft, meaning that violation is allowed against a penalty cost that is considered in the objective function (Figliozzi [18]). Time windows are supported by practically all routing tools, and soft and multiple time windows are also commonly available. A related, very rarely supported feature is determining multiple visits within a single time window to the same location. One may, for example, define that three visits are required within a working day within an 8–16 time window. One obviously cannot do the visits in a row—there must be approximately equal split between the visit times. An easy and often used solution is to generate additional orders with tighter non-overlapping time windows, but it does not work well in many practical cases. For proper solutions, an additional constraint on minimum time between visits is required. The time windows may also depend on the used vehicle type (for example, large delivery vehicles having more restrictive access to customers in inner-city zones than small ones). Again, this is only rarely supported (Drexl [13]).

Delivery Day. In some multi-day optimization cases a specific delivery day is defined for some customers. This can be used to force an order delivery on a specified day each week. In case the day is not specified, the systems will attempt to allocate the delivery in the most economic way. A related issue is the determination of visit patterns in the periodic optimization cases. One may, for instance, set the frequencies of visits per week or per month, or directly give allowed visit days or visit day combinations.

Priorities. Priorities can refer to two different issues. The most typical is to allocate priority sequences for orders so that higher-priority orders are visited first in time or they are preferred in case all orders cannot be served. Alternatively one may also define given delivery sequences for orders. The other possibility is to define for each order a priority order for vehicles and drivers servicing a customer so that the given worker, driver, or vehicle is preferred to serve that particular order or location.

Precedence Constraints. A precedence constraint is typically enforced by a routing tool to make sure that a pickup is performed before the corresponding delivery in pickup-and-delivery problems. In some tools, more general precedences may be defined among orders to model business aspects that are not directly supported.

Same Tour Constraint. To support pickup-and-delivery problems, tools will enforce same tour constraints to make sure that pickup-and-delivery tasks are performed on the same route. Again, this constraint can also be used to enforce user-defined combinations of requests on the same route, e.g., in case of pre-planned routes.

Time Limits. One may need to limit the maximum time that an order resides on a vehicle, e.g., in school bus routing, dial-a-ride operations, or distribution of perishable goods (Vidal et al. [63]). Related to this, some tools have support for real-time temperature control. In some applications one must consider the total time of multiple routes or even the whole supply chain.

Other Constraints. More rarely encountered constraints include interdependent requests where the key idea is to force two or more vehicles or workers to serve an order at the same location at the same time. In the literature this is often called synchronization constraint (Ioachim et al. [37] and Drexl [15]). Examples of applications include home care and street maintenance operations. Another restriction is time-based consistency, referring, for instance, to loading dock restrictions at the customer location. Sometimes one may also need to limit the maximum number of terminals per order.

12.4.3.2 ▪ Resource-Related Constraints

In this section we focus on constraints related to the common resources such as vehicles, drivers, depots, and terminals. Other important resources include vehicle equipment and trailers.

Capacity. The most obvious and common resource-related constraint is capacity. Capacity is typically defined for vehicles, but in some software systems, terminal capacity can be considered as well. In the basic case there is only a single capacity constraint per vehicle, but often one needs to consider several dimensions simultaneously, such as volume, weight, and pallet places. Many systems support different capacities for trailers and for multiple vehicle compartments, with compatibility constraints between products and compartments. In multiple compartment cases there are often numerous alternative allocation options that should be optimized. In some cases one must also consider vehicle balance in the allocation, which further complicates the problem. In a few cases one can find support for special handling of container-type orders and for exact vehicle loading optimization, including vehicle loading patterns and loading restrictions, referring to 2D or 3D bin packing problems (see, e.g., Alvarez-Valdes, Parreno, and Tamarit [2]). A special case is 2.5D packing, where one has layers and towers based on can-stack-on rules, can-be-stacked-on rules, and product dimensions. Another very rarely supported real-life complication is nested containers, for example, packing of actual items in one container, platform or equivalent, and then the packing of these containers or platforms within the vehicle. In a few cases one can define the minimum load size for the vehicle and the impact of tail-lifts, side or rear loading.

Temporal Availability. The temporal availability is similar to the time window defined above for order and can be set to all resource types. The availability can be used to schedule vehicle maintenance operations, drivers' working calendar and shifts, or terminal opening hours. These are supported by most systems, often via specific resource calendars.

Compatibility. Compatibility is a very commonly encountered constraint supported by practically all tools. Compatibility comes in many forms and can refer to several resource or order combinations (Goel and Gruhn [29]). The most typical compatibility check is the vehicle-order check, i.e., can a given vehicle serve a given order? Other common examples are order-order (can the two orders be on the same tour?), driver-order (can a worker/driver serve the order?), driver-vehicle (does the driver have the necessary licenses?), and equipment-order (forces a special equipment to serve an order). From a driver compatibility viewpoint, in many cases in practice, drivers are assigned manually to vehicles or vehicle routes after the latter have been planned. A hard real-life example of equipment compatibility restrictions involves key management. More precisely, to access a customer location one often needs keys, and there may be only a single key per location available, resulting in complex key management and swapping issues, especially in real-time applications such as security services. Often one may also constrain the vehicle type servicing a location or driving a road, possibly due to height, length, weight, equipment, or emission restrictions. A common example of equipment constraint is snow plowing where the required plow type depends on the road type. According to Drexl [13] these are supported by about half of the systems that he surveyed. Related to this, a few systems support even axle weight restrictions and trailer kingpin settings. Another, more rarely supported check is sequential incompatibility, where the key idea is not to transport request B on a route that has transported request A before, at least unless a cleaning operation is performed in between. A related issue is a spatial loading constraint where, e.g., two reactive chemicals cannot be transported in neighboring compartments.

Driving Regulations. Another matter of utmost importance in real-world transportation is driver rules. In the European Union (EU) and in other parts of the world, there is extensive safety legislation on driving, working, and break and rest times for drivers; see Goel [28] for an overview. From the viewpoint of vehicle routing software, several systems include some basic capabilities, such as driver compatibility or setting a maximum tour length, corresponding to a work day or shift length. Setting up the breaks is also supported by many tools, but rarely in an accurate way. For example, the tool often does not consider break locations (they can be anywhere), or it adjusts the break timings after changes to the solution have been made. It is also rare to find support for night and weekend rests and detailed shift planning. Moreover, only a few systems contain the rules for double-manned vehicles.

Zoning. Geographical limitations to planning are often encountered in practice (Ouyang [49]). The most obvious limitation is defining zones or areas for delivery. Some tools can define area preferences for vehicles or drivers, driver home terminals, zones where traffic is prohibited, and time-dependent regional driving bans for drivers. Another type of geographical limitation is allocation of orders to terminals and thus allowing service of a given order from a given terminal only.

12.4.3.3 ▪ Plan Related Constraints

The available systems also allow one to constrain the actual optimization or planning in multiple ways. The most common strategies supported by several tools include balanced routes, locked orders, and various maximum limits. As mentioned above, balancing refers to the soft constraint of having all tours be similar with respect to covered distance, duration, number of requests, or cost (Jozefowiez, Semet, and Talbi [39]). Often, in case of real-time routing or pre-planned routes, one has a given route allocation or already executed orders that cannot be changed. Some tools also allow one to create new separate routes for previously unscheduled tasks. This allows the planner to determine the use of additional (short-term) hired vehicles to handle a given volume of goods. Examples of maximum limits include maximum and minimum number of hours, stops, capacity, dump trips, and distance desired for each vehicle. These may differ from the values given in the actual data to analyze different scenarios. One may also set the maximum number of trips for each vehicle, maximum waiting time, or separately the maximum limit for additional distribution kilometers caused by a single order.

A very common in practice, and rather often supported feature, is multi-route planning, referring to the possibility that vehicles execute multiple routes within the planning horizon (Macedo et al. [44]). Even though multi-route is not a constraint as such, it impacts various other constraints such as time windows, maximum and minimum time limits, and compatibility. For example, from the time viewpoint, one must check the feasibility impact of each change not only to current route but also to routes preceding and following it. In a multi-route context one may in a few tools also limit the frequency and timing of "home visits".

More rarely supported issues are special geographic properties such as "visual beauty" constraints—a preference for routing plans that look nicely on the map. Such requirements have been observed with quite a few users. The beauty contest normally involves two subcriteria: compact routes and/or non-overlapping routes. The motivation for the preferred beauty may seem unclear. It is partly connected with a user belief that plans with compact routes are more efficient, which is not necessarily true. However, for instance in household newspaper delivery, it is not desirable that several carriers serve in the same area with the risk that neighboring subscribers receive their newspaper at very different times.

Some tools support detailed street routing constraints, like U-turns, turning penalties (Bräysy et al. [6]), street side management (e.g., meandering/zigzagging) (Irnich [38]), dynamic usability of roads (e.g., due to congestion or accidents), and hazmat (hazardous material) routing constraining the feasible path options (Akgün et al. [1]).

An important and common issue faced with transshipment loads is precedence constraints between different tours. That is, an order must have arrived to a terminal before it can be picked up by another route. This is, however, rarely supported explicitly, e.g., by unloading heavy orders first to save operating costs. On the other hand, according to Drexl [13], LIFO loading, i.e., delivering the last picked item first (pickup request A, pickup request B, deliver B, deliver A), is supported by half of the systems that he studied.

12.5 ▪ Algorithms

Information on the algorithms used by VRP tools is hard to acquire, as it is generally regarded as an important competitive factor. In practice, most of the tools are based on heuristics or metaheuristics, although exact methods are also utilized, the latter normally in a heuristic version. The solution methods are largely based on published research, although considerable adjustment and tailoring work has often been done in-house to accommodate a rich model. Some vendors have developed algorithms fully in-house.

The majority of the tools use a two-phase strategy that includes constructive and improvement or local search procedures (Bräysy and Gendreau [5]). The most commonly applied constructive heuristics include cheapest insertion (Solomon [60]), savings (Clarke and Wright [10]), nearest neighbor (Lin [42]), and cluster first-route second (Gillett and Miller [24]). These are implemented both in sequential and parallel versions; i.e., they construct the routes one at a time or all in parallel.

The most typical local search operators are relocate and exchange (Savelsbergh [57]), string exchange (Taillard et al. [62]), 2-opt and 3-opt (Lin [42]), Or-opt (Or [48]), Lin–Kernighan (Lin and Kernighan [43]), GENI (Gendreau, Hertz, and Laporte [21]), and large neighborhood search (Shaw [59]). In practice most systems are based on multiple operators.

The most common metaheuristic search strategies are tabu search (Glover [25, 26]), genetic algorithms (Holland [35]), and variants of simulated annealing (Kirkpatrick, Gelatt, and Vecchi [40]), such as threshold accepting (Dueck and Scheuer [16]). Several software solutions also apply dynamic programming (Powell [51]), guided local search (Voudouris and Tsang [65]), and variable neighborhood search (Mladenović and Hansen [45]). The applied exact solution methods are typically based on constraint programming (Rossi, Van Beek, and Walsh [56]), Branch-and-Cut (Gounaris et al. [31]), and column generation (Desaulniers, Desrosiers, and Solomon [11] and Oppen, Løkketangen, and Desrosiers [47]). In most software tools based on column generation, a heuristic variant is used.

Apart from the basic solution algorithms and their adaptations, real-life problem solving requires in some cases special tailored methods for specific tasks such as defining the visit days in periodic planning, splitting the orders, setting the delivery volume in inventory routing, and generating park-and-loop tours.

12.6 ▪ Implementation, Performance, and Price

Most of the vehicle routing tools are coded in C++. For the user interface, several vendors have used C# or Java. Some vendors have coded the whole system in Java. In rare cases also other languages, such as Delphi, have been used.

Mostly, the software is designed for Windows (Vista, 7, etc.), but in several cases also Linux and UNIX are supported. The standard implementation type is local installation, but a web version, Software as a Service (SaaS), components, and client-server variants are also commonly available.

Multi-threading or parallel computing is supported by about half of the systems. However, all approaches seem to be based on rather straightforward task parallelization with a limited number of cores used simultaneously. The significant computing power offered by *Graphic Processing Units* (GPUs) is not yet utilized in commercial systems, to our best knowledge. We return to parallel computing issues in Sections 12.7.3 and 12.8.

In the development, the vendors test their software most often with direct customer data or with synthetic problems based on customer data. Academic benchmarks are also commonly used, and some vendors have also created their own test problems.

Regarding computation time, a fair comparison between the systems is hard due to different hardware and the impact of problem type and solution quality. For example, according to Drexl [13] complex loading problems can cause a five-fold increase in run time. The computation times reported by the vendors may also not be reliable. The reported computation times to solve a routing problem with 100 delivery points varies from a few seconds up to a few minutes on an average desktop computer. When the number of stops is increased to 5000, the execution time range increases from 10 minutes to several hours. Some systems are not capable of solving problems of that large size. According to the survey of Partyka and Hall [50], the computation time to solve a 1000-point routing problem with hard time windows varies from seconds to 10 minutes. Such figures are difficult to assess, however, without detailed knowledge of the instance, the computer, and the quality of the solution.

The maximum problem size that is soluble by the systems is hard to define, as most of the vendors do not specify a maximum size. Another complicating factor is the usage of various aggregation mechanisms (Oppen and Løkketangen [46]) that often reduce the problem size considerably (10-fold is typical). Without aggregation mechanisms the reported maximum sizes vary from a few thousand up to 100.000.

Comparing the solution quality of the software is also very challenging. The first difficulty is that with real-life problems the output depends on the used map data and accuracy of the *Shortest Path Problem* (SPP) calculation. For example, according to the OPT-LOG investigation (Hallamäki et al. [32]), it was concluded that there are significant differences in address coding and street data accuracy between the tools. Some systems did not, e.g., consider turning restrictions or allowed driving directions and hence were able to report better results than the others. Comparing the different tools based on results reported by vendors is also unreliable, as the used computation time may not be comparable and possible manual intervention is not known. However, tests carried out by an independent academic group using software installed on university computers so that the differences in map data were corrected revealed significant differences already in small-scale problems of about 100 stops. The difference between the worst and best solutions in terms of total distance was more than 10%, and it increased in the case of larger problems (Hallamäki et al. [32]).

A basic, single-user license of routing software for commercial use costs 15,000 Euros on average. This does not include customizing and preparatory training of users (Drexl [13]). Analyzing the average price can be misleading also because systems differ a lot in their target market, special features, and integration capabilities. The vendors agree that from the viewpoint of basic static daily routing the markets are rather mature, but there are good business opportunities in the more strategic arena (ability to simulate strategic scenarios whereby all dimensions of the business are taken into account: fleet composition, network design, time windows redesign, etc.). It is also important to be able to combine IT and optimization modeling skills with business consulting. From the viewpoint of adapting the software according to the customer requirements, the vendors can be split in two. It is a common strategy to offer a software off the shelf without any tailoring. It is also very common that various tailoring services are used to create interfaces and to better adapt the system to the problem in question.

12.7 ▪ VRP Technology Survey

As mentioned in the introduction, we have conducted a survey by circulating a questionnaire to 50 vendors of VRP technology in the international market that we were able to identify. The questionnaire was circulated in February 2012, and we received the latest response in June 2012. We received 10 comprehensive responses from nine companies in the VRP tool market. The number of responses is admittedly low, but in our opinion, interesting, high quality information was received from what we regard as a good cross-section of vendors. It includes major players with a large customer base, as well as small enterprises established fairly recently. The companies vary in age between 5 and 33 years, but some have not offered VRP tools during the whole company lifetime. Some companies have not disclosed the number of customers or installations, but the concrete numbers we have received are between 2 and 1500. One vendor reports thousands. The reported number of employees involved in the development of vehicle routing technology is between 2 and 100, whereas the total number of employees varies from 2 to 650. The responding companies are all based in North America and Europe. Several have offices in different countries, and a couple have offices in more than one continent. The set of respondents is probably not representative of the full set of VRP tool vendors. There is reason to believe that the respondents will be more interested in academic research and have closer ties with academia than the average VRP technology vendor.

In this section, we expand and illustrate some of the general insights presented above with a more detailed treatment of questionnaire responses from tool vendors on a selection of aspects. For several reasons, the responses are kept anonymous. However, a full list of the vendors that responded is found in Table 12.1. The issues covered by the questionnaire are information on time dependency, uncertainty management, real-time planning, types of service interfaces, as well as applied parallel computing technology. In addition, the questionnaire covered critical success factors and key strengths, relation to VRP research, and important future research topics.

Also, responses are described in some detail for the treatment of new and emerging technologies and the future of the VRP business in Sections 12.8 and 12.9, respectively.

12.7.1 ▪ System Architectures and Service Interfaces

This issue is important, as the system architecture and supported service interfaces define how the vehicle routing functionality may be made available to the user, the hardware resources needed, the associated costs, the support for collaborative planning by multiple users, and the flexibility to configure the system. There are many system architecture options, and we can only introduce and describe the major ones here.

The simplest alternative is local, monolithic installation of the full system on a PC. All questionnaire respondents provide this option. It consists of a single user vehicle routing decision support system with a GUI, some form of database, and possibly interfaces to external systems such as ERP, mobile communication, and tracking systems. Such a

Table 12.1. *Responding VRP technology providers.*

Company name	Contact information	Email	Web site	Product name(s)
GIRO Inc	75 Port-Royal Street East, Suite 500 Montreal Quebec H3L 3T1, Canada	info@giro.ca	http://www.giro.ca	GeoRoute, GIRO/ACCES
GTS Systems and Consulting GmbH	Raiffeisenstr. 10 D-52134 Herzogenrath, Germany	info@gts-systems.com	http://www.gts-systems.de	TransIT
MJC2 Limited	33 Wellington Business Park Dukes Ride, Crowthorne Berkshire, RG45 6LS, UK	info@mjc2.com	http://www.mjc2.com	DISC, REACT
Optrak Distribution Software Ltd	Orland House, Mead Lane Hertford, SG13 7AT, UK	vrs-sales@optrak.com	http://optrak.co.uk	Optrak
ORTEC	Europe: Houtsingel 5, PO Box 75, 2700 AB, Zoetermeer, The Netherlands. USA: 3630 Peachtree Road NE, Suite 800, Atlanta, GA 30326, USA	info@ortec.com	http://www.ortec.com	ORTEC
Optit srl	Via Selice, 47, 40026 Imola (BO), Italy	info@optit.net	http://www.optit.net	EasyRoute, OptiRoute
Procomp Solutions Oy	Kiviharjuntie 11, 90220 Oulu, Finland	tuomas.kemppainen@procomp.fi	http://www.procomp.fi	R2
PTV AG	Haid-und-Neu-Strasse 15, 76131 Karlsruhe, Germany	karlsruhe@ptv.de	http://www.ptvgroup.com	SmarTour
Spider Solutions AS	P.O. Box 124, Blindern, 0314 Oslo, Norway	info@spidersolutions.no	http://www.spidersolutions.no	Spider 5

system works fine for most applications, at least if the operations have limited size and complexity or do not need support for multi-user planning.

It may be convenient to separate the GUI from the rest of the system, for instance to achieve centralized installation and management of the software for multiple, possibly decentralized users to limit investment and maintenance costs. This requires a client/server architecture, of which there are many types. The client/server model is composed of distributed applications that partition tasks between the providers of a resource or service, called servers, and service requesters, called clients. Clients and servers typically communicate over a computer network, for instance the Internet or a local area network, on separate hardware. Several VRP tool vendors offer client-server solutions for their product. A so-called thin client architecture, where basically only the GUI is run on the clients and the application processing (business logic) and data storage are executed on the server(s), is supported by a majority of our respondents. The hardware platform for thin clients may even be personal digital assistants, smartphones, or tablet computers. In contrast, so-called fat clients, where more of the application logic is executed on the client, are supported by two of our respondents. A three tier architecture, where there is separation between presentation, logic, and storage, is mentioned by one responding vendor.

In the past decade, SaaS has become a popular model for making software available. The definition of SaaS is arguably somewhat fuzzy, but it is most commonly used to denote a client/server like architecture where the GUI is provided by a web browser and the communication is based on the Internet. In this way, there is no need for client software installation if the users have access to a web browser, so the functionality is available virtually anywhere. The supported client hardware may include smartphones and tablet PCs. The software is installed and maintained centrally by the solution provider. Hence, the users do not need to invest in expensive hardware or worry about software maintenance or updates; these tasks are outsourced to the SaaS provider. Modern SaaS solutions have a so-called multi-tenant architecture, where one instance of the software is used to serve many users, potentially from different organizations. SaaS is one type of cloud computing, and multi-tenancy is regarded as a vital characteristic of cloud computing.

Centralized vehicle routing services offered through the web, i.e., VRP cloud computing, also pose challenges. As we know, VRP resolution is computationally demanding, and the demand pattern for a centralized VRP service will be unpredictable. The VRP SaaS provider will either have to dimension its computational resources according to an estimated peak demand, possibly with automatic load balancing, or be able to rapidly reconfigure the number of processes and the supporting hardware. Another form of cloud computing is utility computing, a.k.a. demand computing or elastic computing, in which computational resources and storage may be allocated dynamically according to need. As far as we know, no VRP technology vendor currently offers elastic computing. Data security is another general problematic issue in SaaS solutions. A VRP cloud computing provider will access and store company-specific data that may be critical to the user company, e.g., customer database, performance indicators, prices, etc., so care must be taken to protect sensitive information.

The SaaS model gives new opportunities for pricing. The common one-time software license model is typically replaced by a more fine-grained model where the user company pays for the actual use of the service. The price may depend not only on the number of VRPs solved but also on their complexity.

Five of our respondents answer that they provide a web GUI to their VRP tool, whereas two offer a SaaS solution, the latter probably with a multi-tenant architecture. Cloud computing is mentioned as a major emerging technology by one VRP technology provider.

We do not have enough information to estimate the distribution of installations over the various system architecture alternatives. We suspect that currently the majority of implementations utilize the basic local installation or thin client types of architecture. In our opinion, SaaS will become the most used approach.

All but one technology provider state that they tailor their solution to various types of customer demands, whereas the last one answers that tailoring is kept at a minimum. A different but related issue is the level of consultancy services offered. Tailoring is normally paid by the customer. Some VRP technology vendors receive major revenues, in some cases the lion's share, from pure consulting based on their portfolio of tools, for instance the development of static routes, optimizing fleet size and mix, or transportation network design for a transportation provider.

Finally, we note that there are vendors of VRP technology that offer a VRP solver as a software component, an optimization "engine" that must be somehow integrated with a larger system. For some vendors, this is their only product; they do not provide a GUI. Hence, their market consists predominantly of large organizations with in-house ICT departments, large ICT system (e.g., ERP) providers, and ICT consultant companies. The functionality of a VRP component may be exposed as a web service that constitutes the core of a SaaS VRP solution.

12.7.2 ▪ Time-Dependent Information, Uncertainty, and Dynamics

In the early years of VRP technology, VRP tools were almost exclusively used for static planning. The routing plans generated were supposed to be valid over a relatively long time horizon. Changes in the planning information would occur, and these could motivate a plan revision that was typically performed by replanning from scratch with the updated information. This "modus operandi" still works well for VRP applications with limited dynamics but poorly in highly dynamic applications such as urban courier service.

More recently, the introduction of tracking and tracing technology (positioning and tracking systems, barcoding, RFID) for vehicles and goods, on-board computers, and mobile communication has enabled ready access to updated information on fleet and order status in highly dynamic settings. Tight integration with external business systems such as ERP also enables rapid access to updated order information such as new order arrivals, cancellations, and changes in order size. Traffic conditions constitute an important source of dynamics for VRP planning. Historical speed profiles for roads are electronically accessible for large parts of Asia, Europe, and North America, e.g., through GIS and vehicle navigation systems, and can be used in predictive planning. Electronic access to real-time traffic information is available for many areas. The coverage of such information is proliferating and the use is increasing, both in real-time route finding and VRP planning systems. Some VRP technology vendors report that they have functionality for editing electronic road data, as GIS and vehicle navigation system providers may not offer the necessary quality or responsiveness to change. Moreover, methods for solving dynamic VRPs, i.e., VRPs where information changes rapidly and reactive replanning must be performed even while the plan is being executed, have matured. Another enabling factor for real-time planning is the general performance of VRP solvers. It has increased tremendously, due to both the rapid development of VRP algorithms and the general exponential performance increase of computers.

All these developments have enabled VRP planning based on more accurate information, as well as real-time (dynamic) replanning. Tool vendors including our respondents have exploited these opportunities in different ways. Most VRP tools we know of support speed profiles to make travel time predictions more accurate. A majority of our survey respondents somehow support reactive re-planning. The simplest way is through functionality for locking parts of the plan that have become history, and for replanning with updated information. Typically, these functionalities are not invoked automatically, but they are controlled by the human planner. In some tools, more sophisticated replanning algorithms are used that minimize plan disruption. The more advanced VRP tools have the ability to invoke automatic replanning when deviations from the plan become sufficiently large.

Another discriminatory aspect between VRP tools is the richness of sources of real-time information and their nature. They vary from driver and customer phone calls that need manual planning actions to a number of sources of electronic messages that may be handled automatically, often provided by third party software services. Among the external sources of real-time information are on-board computers, smartphones, business software, goods tracking systems, positioning systems, and traffic information systems. Barcoding, RFID tagging technologies, and proof of delivery systems support more or less the automatic status update of deliveries. Many VRP tools update the order status automatically, most often through integration with third party software services.

The issue of real-time planning is related to handling of uncertainty, an inherent aspect of real-life planning. We have seen no reports of VRP tools that utilize fully fledged stochastic VRP methods. Several vendors, however, report that they support the use of simulation techniques, e.g., for assessment of plan uncertainty and robustness. Some also report that they utilize prognoses, typically based on historical data, to predict demand that is included in the plan.

12.7.3 ▪ Parallel Computing

Given the computational hardness of industrial VRPs, the importance of quality vs. response time performance in the competition between VRP system vendors, and the embarrassingly parallel nature of many VRP solution methods, it is no wonder that providers have utilized parallel computing to boost tool performance.

Our VRP tool survey shows that the majority is designed for PC platforms. Modern PCs have a parallel and heterogeneous processor architecture, with several identical general computing cores that also support multi-threading and task parallelism, and one or more hardware accelerators, e.g., *Graphic Processing Units* (GPUs), each consisting of hundreds of simpler cores, that may be used for data parallelism, also known as stream processing. Software based on sequential algorithms can neither fully exploit current PC hardware nor profit from the general increase of computational performance that will be based on increasing levels of parallelism in a heterogeneous architecture.

Of the 10 tools in our survey, eight utilize task parallelism, one only for specific subtasks such as shortest path calculation. As far as we know, no commercial VRP tool utilizes GPU acceleration or other forms of stream processing, not to mention heterogeneous computing. One vendor states that GPU computing is now the most important technological trend and discloses current development efforts for a GPU implementation. We return to this trend in Section 12.8.

12.7.4 ▪ Relation to VRP Research

In some contexts, a dichotomy is portrayed between the VRP scientific community on the one hand and the industrial VRP community on the other. First, many VRP technology vendor companies are spin-offs from a university or research center. In many cases, there is still an umbilical cord, for some companies to several alma maters. Four out of nine companies in our survey say they have strong or substantial connections to researchers in academia or applied researchers. One states that connections with individual researches are the most rewarding. A couple of vendors have employees with part time positions in both camps. We must reiterate, however, that the respondents probably are more interested in academic VRP research than the average VRP software company.

Scientific research takes place also in the VRP tool industry, although publication of results may be selective, for obvious reasons. Two companies explicitly state that they contribute to scientific publication; several have paper referees on their payroll. With only one exception, all respondents state that they are keeping close tabs on the scientific VRP literature. Most participate or attend major VRP conferences, and several are active conference sponsors.

In our questionnaire we asked whether the VRP algorithm in use was taken from the literature or developed in-house. The typical answer is "both", which should not come as a surprise, with the specification that they have utilized published algorithms as a basis for in-house extensions. Typically, extensions and modifications are needed because the tool is based on a richer, more general VRP model than the variants studied in the literature. Several vendors, however, claim their VRP algorithm, or major parts of it, is developed completely in-house. Supposedly, some of these algorithms contain innovations that would be publishable in the scientific literature. Competition is a natural hindrance for publication.

The communication between the two communities is two-way. Unmet requirements from industry and key bottlenecks in VRP tools are communicated from users via tool vendors to academia and research institutes. Hence, industry participates in forming the VRP research agenda. Benchmarks with standard test cases for computational experiments are important to VRP research. There are a few examples of scientific benchmarks that are based on, or at least heavily inspired from, real-life cases.

The vendors in our survey seem to diverge on the role and importance of benchmarks to the VRP business. Some of them do not regard academic benchmarks as interesting, as they are too stylized. Instead, they use case data from customers. Most answer that they use a combination of academic benchmarks, test instances developed in-house, and customer data. Synthetic, in-house test instances are often generated from a set of customer data. One vendor emphasizes that their tool's performance on the Gehring and Homberger *VRP with Time Windows* (VRPTW) benchmark (Homberger and Gehring [36]) is a key strength that is probably also used in sales and marketing. Another describes the usefulness of academic benchmarks in the prototyping of new algorithms. Yet another says it would be nice if the run for the best new VRPTW algorithm would be replaced by the run to solve difficult rich VRPs with flexible algorithms and benchmarks would be made available for such problems, a view that seems to be common among vendors. One VRP tool provider is actively sponsoring work on producing benchmark real-life problems for academia and highlighting, for instance at scientific conferences, the need to use real-life problems in academic research. A few companies state that there is no need for additional standard benchmarks, but one would welcome large-scale and difficult instances for basic VRP versions.

In our view, it would be fruitful to both "camps" if the VRP industry could publish their benchmarks based on real-life cases, and the researchers in academia would focus their work more strongly on rich VRPs, i.e., comprehensive VRP definitions that include all important aspects of some industrial application. This view is supported by many questionnaire responses where the vendors would like to see a closer interaction and stronger link between their industry and academia. Yet, many companies actively participate in applied research projects with partners ranging from users via tool providers to academia.

12.7.5 ▪ Important Future Research Topics

The respondents mention a broad spectrum of important research topics. Several are related to rich VRPs, meaning VRP definitions that adequately represent a broad range of constraints and criteria that are found in real-life applications. Uncertainty, dynamics, and solution robustness are related aspects mentioned. Several companies advocate large-sized instances as a key topic for future research. The need to study integrated problems that cover larger parts of the value chain and extended problems with decisions that are beyond routing is also mentioned by several vendors. The main issues here include modeling and representation, as well as flexible solution algorithms. More specific topics related to richness include a general framework for handling complex constraints (such as the constraint programming methodology), the effect of real complex constraints on solution methodology, and the impact of problem richness and size on the performance of algorithms. Topics like multi-criteria problems, efficient handling of soft constraints, route compactness (see the discussion on visual beauty criteria in 12.4.3.3 above), driver issues, and loading issues are also often encountered. We also consider problems with time dependencies, complex trip structures, multi-modal planning, and modeling of real costs important.

The impact of real-time data and time-varying information such as rush hour speeds is mentioned by several respondents. One vendor describes GPU parallelization as an important research topic, not only as an implementation issue. A related issue mentioned is improvement of basic optimization performance.

12.7.6 ▪ Critical Success Factors and Key Strengths

It is interesting to note the respondents' views on critical success factors for the VRP tool industry and what they regard as key strengths of their own solution. Not surprisingly, these tend to have considerable overlap. The main success factors mentioned are marketing power, strength, and credibility in the market, customer focus and close relation to customers, and long-term relationships with customers. One must also consider expertise, reliability, cost, know-how of consultants, good demos, ability to deliver tailored solutions, and user-friendly, intuitive GUIs. Identified additional key success factors are coupling of technical skills with business consulting ability and experience, software integration possibilities, rich optimization model and accompanying high-performance solvers, ability to model all operational constraints, real-time features, and service-oriented models.

The key strengths mentioned include very fast return on investment, intuitive and customizable GUI and workflow, modern system architecture, flexible import/export interfaces, and integration of real-time information. Furthermore, the vendors consider full multi-user support, configurable solvers based on rich models, emission calculation, fast and reliable trip planning algorithms, integrated algorithms for loading, and sophisticated rush-hour modeling as important strengths. It is also important to have configurable objectives, a rich set of cost components, strong solution algorithms that yield high quality solutions even for complex, large-sized instances, fast and well-scalable systems, high-quality results on benchmarks, and fast shortest path calculation.

12.8 ▪ New and Emerging Technologies

VRP tools are based not only on methods for modeling and solving VRPs inspired from the OR literature and general software engineering methods but also on several underpinning methods and technologies that are utilized to provide the necessary information and computational resources. The main technologies described above include GIS, positioning, tracking and tracing, and mobile communication. Although there are still challenges, these technologies are fairly mature. There are commercial, external providers of software (services) that VRP technology providers may utilize, often with application interfaces or message protocols that have become industry standards.

On this background, and based on our questionnaire, the most important new and emerging technologies are quantum processors, cloud computing and SaaS, parallel computing and GPUs, and smartphones and tablet PCs. It is also important to utilize speed profile databases, forecasting models and data mining, and technologies for real-time information.

As was expected, the responses vary widely from “blue skies” basic research topics that are far from commercialization, such as quantum computers, via technologies that are emerging and have not been utilized in commercial VRP tools yet, to mature technologies for which there are already commercial service providers that VRP technology vendors may use, such as transportation telematics. Even for mature technologies that offer high value to VRP technology providers, the cover and quality of information are major bottlenecks.

Several VRP tools support *smartphones and tablet PCs* as client platforms. They are typically used as terminals for drivers but may also be used for general purpose clients. *Technologies for real-time information* include vehicle tracking and goods tracing technologies, and traffic information systems, as briefly discussed in Section 12.7.2 above. Reasonably accurate information on travel distance, travel time, and travel cost, as well as a good reactive planning capability, are prerequisites for a successful VRP tool in dynamic applications.

The coverage, level of detail, and quality of available GIS road network and address data are improving rapidly but still vary considerably between regions and countries. Likewise, road instrumentation and other technologies for real-time monitoring of traffic have become mature. There are well-known live traffic services by major providers that may be accessed through the web and via smartphones and car navigation computers. However, there are still many uncharted areas, and there are methodological challenges regarding the use of real-time traffic information in a VRP context.

In predictive planning, *speed profile databases* based on historical data are important for increasing the accuracy of travel time and cost predictions. Some electronic road information vendors provide good speed profiles, but again the cover and quality vary widely between regions. It is clear that the quality and cover of both static and dynamic information from GIS and transportation telematics systems are improving rapidly. This development will enable a more widespread use of VRP technology.

Another key technology and business model that supports a wider exploitation of VRP tools is SaaS. It lowers the investments needed for implementation and maintenance of a VRP tool, and enables a more fine-grained pricing model that may attract new users, small- and medium-sized companies in particular. In Section 12.7.1 above we discuss *cloud computing and SaaS*.

One of the more recent, less mature, and less understood underpinning technologies mentioned above is *heterogeneous computing based on new PC architectures*. For routing applications, there is still a large gap between the requirements and the performance of today’s optimization-based decision support systems. The ability to provide better solutions in a shorter time will give substantial savings through better optimization performance of existing tools. Moreover, applications that are too complex to be effectively solved by the technology of today may become within reach of the optimization technology of tomorrow. More integrated, larger, and richer routing problems may be solved.

Further performance increase will result from a combination of better optimization algorithms that are implemented in more efficient ways on more powerful computers.

More than that, the new PC architecture, and the prospects for general PC performance that will partly be based on stream processing accelerators such as the GPU, call for novel VRP algorithms. Early investigations by the research community indicate a large potential for performance increase of VRP solvers. GPU-parallelization is already used in real scientific computing applications, as well as in other applications of discrete optimization, for instance bioinformatics.

It should be clear that heterogeneous computing including utilization of modern GPUs may significantly increase the performance of commercial routing tools and hence boost their improvement effects in industry. VRP technology vendors can hardly ignore the opportunities for performance increase offered by recent and future developments in PC hardware. While the development efforts involved in task parallelization of sequential VRP solver software may be low or moderate, the cost of developing software that also exploits data parallel accelerators such as the GPU is considerably higher. For a tutorial and literature survey focused on routing problems, we refer the reader to Brodtkorb et al. [8] and Schulz et al. [58].

12.9 ▪ The Future of the Vehicle Routing Business

Software tools for vehicle routing have been around for more than 30 years. This fact is often taken as an indication of success for VRP science. Despite the huge improvement potential in transportation and logistics, it is our opinion that the growth of the VRP technology business has been moderate, even if we consider the general slumps in the economy that the world has seen over the past decades. In fact, economical setbacks may sometimes motivate the use of optimization technology. Lack of awareness among potential users is one explanation for the limited growth; another is the lack of ready access to the necessary basic information; a third is the investments needed in terms of money and human capital. The expertise needed to operate VRP tools is often considerable. Finally, model richness and planning performance may be inadequate for important applications. All these hindrances seem to be diminishing.

We asked the software vendors about their views on the future of the VRP business. In summary, they emphasize that there are still a lot of challenges, but the market is growing rapidly and that there will be a continued evolution of the business. The VRP technology still has a low adoption percentage, and many large distribution companies do not use it. The pure routing applications are already relatively mature, but the vendors also think that there are a lot of market opportunities and numerous problem types that have not been considered yet, e.g., identifying new business models for transportation and logistics. In the future, customers will become more sophisticated and demanding, expecting more powerful and flexible solutions rather than just being satisfied with the "industry standard off-the-shelf" approach, and there will be stronger requirements on customer service and timeliness. There shall also be stronger demands for strategic planning functionality, and sustainability will grow in importance. We also see stronger requirements on solving more integrated problems in the value chain, and intermodal transport planning, E-mobility, and social aspects are growing in importance. Clearly, there are differing opinions on the future prospects for the business, but there seems to be a good alignment of views between vendors on important requirements for the future.

12.10 ▪ Summary and Conclusions

The first vehicle routing decision support system was available on the market more than 30 years ago. The huge research efforts devoted to the VRP since its first definition in 1959, the accompanying scientific results, the industrial relevance of this family of problems, and the general improvement of underpinning technologies and computational power, are all factors that have enabled the creation of a successful international VRP technology business. Today, we can identify more than 50 VRP technology vendor companies. Despite the still existing large potential for improvement in transportation and logistics through better coordination, the growth of the VRP business has been rather slow, and most of the companies are small.

In this chapter, we have first given a general description of vehicle routing software with basic functionalities, input and output, model properties, solution algorithms, implementation, and performance. Second, we have given a more detailed account of responses to a questionnaire survey. Nine VRP technology companies have provided product information regarding time-dependent information, uncertainty, real-time information and real-time planning, types of service interface, and parallel computing. Moreover, the survey covers the responding companies' views on critical success factors and key strengths, the relation to VRP research, future research topics, new and emerging technologies, and the future of the VRP business. We cannot claim that the cross-section of responding vendors is representative, but in our opinion their views on these important aspects are interesting.

According to our survey, the software vendors consider the integration possibilities, real-time features, rich optimization models with excellent solvers, and ease of use of the system important from the business viewpoint. There is a growing interest in service oriented models, such as the Software as a Service (SaaS) model, whereby the software vendor generates solutions and manages data from their own servers (Partyka and Hall [50]). Real-time optimization is also becoming more and more important due to consolidation of field equipment and progress in computational power and technology. Customers will become more sophisticated and demanding, expecting more powerful and flexible solutions rather than just being satisfied with the "industry standard off-the-shelf" approach. This requires an easily extensible general framework for handling various constraints and objectives as well as the efficient implementation of basic elements.

A majority of the responding vendors seem to have a positive outlook on the future of their business, despite conservative customers and the current economical crisis in large parts of the Western world. On our own account we would like to mention the business opportunities that should exist in the developing countries with rapid economic growth, although commercial dissemination and exploitation of VRP software requires a high-quality information and communication infrastructure.

Many VRP technology provider companies have their origins in academia, and many still have good connections with individual VRP researchers or research groups. It is interesting to observe that several of our respondents would like to see a tighter interaction between industry and academia, primarily for discussion of recent scientific results, unmet user requirements, and technology bottlenecks, as well as concrete exchange of case information and test data.

The authors have observed clear signs of increasing interaction between industry and academia in recent conferences. We believe that both VRP science and VRP business have ample, hard, and exciting work ahead and a bright future that can be made even brighter through tighter collaboration.

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