Formulations and algorithms for rich routing problems
Veenstra, Marjolein

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Chapter 1

Introduction

In the last years, the customers’ shopping behavior has changed substantially. Due to the rise of e-commerce, the number of small orders has increased and the number of freight movements has rapidly grown. A large part of these movements needs to be delivered to customers’ homes, which may require multiple delivery attempts. We encounter an increasing diversity in delivery options. Where home delivery used to be the standard one, it is now also possible to deliver at attended or unattended pickup points from where customers can pick up their orders. A trend that we see nowadays is that customers become more aware of the environment and demand for environmental behavior. However, we still see that most of the delivery providers operate independently, which results in many vehicles on the road. These trends create many logistical challenges and tools are needed to support the decisions based on questions as how to coordinate the large number of delivery requests, where to locate pickup point facilities, and how to take into account congestion and delays arising from the large number of freight movements. In order to support decisions arising from these logistical challenges, new decision models are needed for this increasingly complex environment.

Many of the new logistical challenges involve vehicle routing decisions. We define routing decisions as the assignment of customers to routes and the determination of the sequence in which the customers are visited on those routes. Where the routing literature started with an isolated focus on routing decisions (see Dantzig et al., 1954), we now see that routing problems are not solved in isolation anymore but are studied in combination with other decisions. Examples are inventory-
routing problems, in which the inventory levels of products are determined in conjunction with the delivery of those products (see Coelho et al. (2013) for a review), the production-routing problem, in which the batch size in which products are produced are simultaneously determined with the routing decisions for those products (see Adulyasak et al. (2015) for a review), city logistics problems, which is the name for a collection of problems in which vehicle routes are generated for urban areas while taking into consideration the downside effects on congestion, safety and environment (Savelsbergh and Van Woensel, 2016), routing problems that also determine the exact position of the items in the vehicle and consider restrictions on their positioning (see Pollaris et al. (2015) for an review), routing problems combined with location decisions such as the location of the depots (see Prodhon and Prins (2014) for a review) and routing problems that consider time-dependent travel times (see Gendreau et al. (2015) for a review). In this thesis we focus on the last three areas.

Our aim is to model and solve four new problems that combine routing with other decisions. The first two problems (see Chapters 2 and 3) consider loading aspects in a routing context. The third problem (see Chapter 4) considers the location of pickup lockers in combination with routing decisions regarding home delivery and the replenishment of the pickup lockers. The fourth problem (see Chapter 5) considers traffic and delays in the delivery towards customers. More specifically, the first two problems can be categorized as pickup and delivery problems with loading constraints. In these problems, each item needs to be transported from a specific pickup location to a specific delivery location. Loading and unloading of the vehicle is operated in a last-in-first-out (LIFO) fashion. The third problem is a simultaneous facility location and vehicle routing problem. The delivery of items can occur via lockers, from where customers that are within the coverage distance of a locker can collect their items, or by home delivery. The fourth problem combines the time-dependent vehicle routing problem with the time-dependent shortest path problem. In this problem, a set of customer locations needs to be visited, where the travel times between the customers need to be computed as shortest path problems.

1.1 Vehicle routing problems with loading constraints

Due to the large increase in the number of small orders, consolidation of freight is needed, and thereby the loading of vehicles becomes more important. When loading
constraints, such as constraints on the relative position of the items in the vehicle or weight constraints, are not incorporated in the planning process of vehicle routes, the generated routes can be hard to implement in practice. If, for example, axle weight constraints are not taken into account, it is likely that some of the generated vehicle routes are not feasible in practice and manual changes are needed to make the route planning feasible (Pollaris et al., 2013). These changes are costly and the resulting routes will not be as efficient as the ones generated when simultaneously considering routing and loading decisions.

The incorporation of loading constraints in vehicle routing problems is fairly recent in literature (Pollaris et al., 2015). Different loading constraints can be distinguished for vehicle routing problems, such as (multi-)dimensional packing constraints, which ensure that items do not overlap and are correctly positioned inside the vehicle and sequence-based loading which ensures that items are placed in the vehicle without blocking access to items that need to be delivered earlier on the route. The incorporation of loading constraints in pickup and delivery problems is more complex than in the classical vehicle routing problem, since all items need to be picked and delivered at customer locations. Therefore, the items cannot be positioned when the vehicle leaves the depot, as in the classical vehicle routing problem, but the position of the items is determined and changed throughout the route. The literature in this area is also less elaborated. Most papers on the pickup and delivery problem with loading constraints combine one-dimensional loading with sequence-based loading.

A number of papers consider the pickup and delivery traveling salesman problem, which is a variant of the pickup and delivery problem that considers a single vehicle, with sequence-based loading. Namely, the pickup and delivery traveling salesman problem with FIFO loading (see Cordeau et al. (2010a) for a branch-and-cut algorithm and Wei et al. (2015) for a variable neighborhood search heuristic) and the pickup and delivery traveling salesman problem with LIFO loading (PDTSQL) (see Cordeau et al. (2010b) for a branch-and-cut algorithm and Wei et al. (2015) for a variable neighborhood search heuristic). Côté et al. (2012a,b) develop a branch-and-cut algorithm and a large neighborhood search heuristic for the extension of the PDTSQL with multiple stacks. In Chapter 2, we elaborate on the PDTSQL by allowing the LIFO constraint to be violated at a cost. The following four papers consider the pickup and delivery problem with sequence-based loading. Cherkesly et al.
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(2015a,b) propose branch-price-and-cut algorithms and a population-based meta-heuristic for the pickup and delivery problem with time windows and LIFO loading. Cherkesly et al. (2016) develop branch-price-and-cut algorithms for the extension of this problem with multiple stacks. Benavent et al. (2015) propose a branch-and-cut algorithm for the pickup and delivery problem with LIFO loading and a maximum route duration constraint. In Chapter 3, we extend the pickup and delivery problem with time windows and LIFO loading by allowing the LIFO constraint to be violated, which requires supplementary time.

1.2 Combined vehicle routing and facility location problems

The decisions where to locate facilities such as factories, warehouses and depots, are long-term decisions that have a large impact on the vehicle routes between facilities and from facilities to customer locations. While facility location decisions are made at a strategic level, routing decisions are made at a tactical or operational level. These two kinds of decisions are, however, interdependent and studies have shown that considering them independently can lead to excessive costs (Prodhon and Prins, 2014).

In the literature, decisions on facility location and vehicle routing are combined in the location-routing problem. A survey on location-routing problems is given by Prodhon and Prins (2014). In the classical location-routing problem, a set of potential depots and a set of customers are given. The problem is to determine which of the potential depots to open, to assign each customer to one open depot, and to construct vehicle routes from each depot to the customers assigned to it. In two-echelon location-routing problems (2E-LRPs) (see also Cuda et al. (2015) for a survey on two-echelon routing problems with a section dedicated to 2E-LRPs) two levels are considered. Routes in the first level start at one or multiple depots (main facilities) and visit the intermediate facilities (which correspond to the depots in the classical location-routing problem) for replenishment. Routes in the second level start at the intermediate facilities and visit the customers. There are a number of potential locations for the depots and a number of potential locations for the satellites. Nguyen et al. (2012a,b) propose metaheuristics for the 2E-LRP with a single, fixed depot. The
2E-LRP with multiple depots is studied by, e.g., Boccia et al. (2011) who provide multiple formulations and Contardo et al. (2012) who developed a branch-and-cut algorithm and an adaptive large neighborhood search algorithm.

In Chapter 4, we consider a new problem that combines facility location and vehicle routing decisions. In this problem a set of pickup lockers needs to be positioned from where customers can collect their orders. The pickup lockers need to be replenished from a central depot and the customers that are too far from an opened pickup locker need home delivery. This problem is a new variant of the 2E-LRP with a single fixed depot, a number of potential intermediate facilities and a set of customers. Customers within a prespecified distance from an opened facility do not have to be routed. The remaining customers are visited by vehicles positioned at the depot, from where the lockers are also replenished.

1.3 Time-dependent routing problems

Delays are caused by traffic congestions, which in turn result in a number of downside effects. This is emphasized by the Dutch Association for Transport and Logistics (TLN) that estimates that delays caused by traffic congestion result in a loss of working hours of truck drivers of more than 10% (Kok et al., 2012). In order to account for this loss in efficiency, more vehicles need to be on the road, resulting in more emissions and higher costs for the logistic companies. Moreover, when congestion is not taken into account during the generation of the vehicle routes, the delays can lead to working time violations and late arrivals at customer locations. Thus, it is important to properly include traffic congestion in routing models. This can be done by considering time-dependent travel times in the routing models, which implies that the time it takes to traverse a road depends on the time the vehicle enters it.

In the literature, time-dependent travel times are considered in various routing models. For an overview we refer to Gendreau et al. (2015). Three commonly studied time-dependent routing problems are the time-dependent shortest path problem (TDSPP), the time-dependent traveling salesman problem (TDTSP) and the time-dependent vehicle routing problem (TDVRP). The TDSPP aims to find a path between two given nodes that minimizes the travel time (see Chabini (1998) and Ding et al. (2008) for different algorithms). The TDTSP aims to find a least-duration tour starting and ending at the depot and visiting all customers exactly once (see Albiach
et al. (2008) for a transformation of the problem into an asymmetric graphical traveling salesman problem and Cordeau et al. (2014) for a branch-and-cut algorithm). In the TDVRP a fleet of vehicles is used to visit a set of customers under a set of constraints (see Hashimoto et al. (2008) for an iterated local search heuristic and Dabia et al. (2013) for a branch-and-price algorithm). In Chapter 5 we make a contribution to the field of time-dependent routing problems by introducing a new problem that combines the TDSPP and the TDVRP.

1.4 Outline

In Chapter 2, we introduce the pickup and delivery traveling salesman problem with handling costs (PDTSPH). In the PDTSPH, a single vehicle has to transport loads from origins to destinations. Loading and unloading of the vehicle is operated in a LIFO fashion. However, if a load must be unloaded that was not loaded last, additional handling operations are allowed to unload and reload other loads that block access. Since the additional handling operations take time and effort, penalty costs are associated with them. The aim of the PDTSPH is to find a feasible route such that the total costs, consisting of travel costs and penalty costs are minimized. We show that the PDTSPH is a generalization of the pickup and delivery traveling salesman problem and of the pickup and delivery traveling salesman problem with LIFO loading. We give a mathematical formulation for the problem and propose a large neighborhood search heuristic to solve it.

In Chapter 3, we introduce the pickup and delivery problem with time windows and handling operations (PDPTWH). In this problem, a pickup and delivery problem with a homogeneous fleet of capacitated vehicles is considered, where the compartment is rear-loaded and operated in a LIFO fashion. A time window is given for each pickup or delivery location, which specifies the time interval during which service must start. Rehandling operations require supplementary time, which can be constraining because of the time windows. Setting the time for a rehandling operation equal to zero reduces the PDPTWH to the pickup and delivery problem with time windows, while setting it to infinity imposes a pure LIFO strategy. We define two rehandling policies. For both policies, rehandling is only allowed at delivery locations and there is no specific reloading order for the rehandled items. Under the first policy, only compulsory rehandling is allowed, i.e., only items that are blocking
access to the delivered item are allowed to be rehandled. Under the second policy, in addition to compulsory rehandling preventive rehandling is allowed, i.e., also items that are not blocking access to the delivered item are allowed to be rehandled. For each policy, we propose a branch-price-and-cut algorithm with an ad hoc dominance criterion for the labeling algorithm used to generate routes.

Chapter 4 introduces a simultaneous facility location and vehicle routing problem that arises in health care logistics in the Netherlands. In this problem, the delivery of medication from a local pharmacy can occur via lockers, from where patients that are within the coverage distance of a locker can collect their medication, or by home delivery. The aim of the problem is to determine which lockers from a set of potential locker locations to open and to generate routes that visit the opened lockers and routes that visit the patients that are not covered by the opened lockers, while minimizing the routing costs and the opening costs of the lockers. We formally define this problem and solve it by applying a branch-and-bound algorithm to this mathematical formulation. Moreover, we propose a fast hybrid heuristic to solve the problem.

In Chapter 5 we introduce the time-dependent shortest path and vehicle routing problem (TDSPVRP). In the TDSPVRP, a set of homogeneous vehicles is used to visit a set of customer locations dispersed over a very large network, such that the travel times between any two customers must be computed as a time-dependent shortest path problem. The travel time of each arc is time-dependent and therefore the shortest path between two locations changes over time. The aim of the problem is to simultaneously determine the sequence in which the customer locations are visited and the arcs traveled on the paths between each pair of consecutively visited customers, such that the sum of the arrival times of the vehicles back at the depot is minimized. We are the first to formally define and solve this problem, giving bounds to it. We test our formulation on a set of real-life instances generated from a dataset of the road network in Québec City, Canada. Our results indicate that neglecting traffic can impose substantial delays for the visits, which would require more trucks and more mileage to perform the same deliveries. Our work adds a new research avenue to city logistics and congestion/emission studies.

The remainder of this thesis is as follows. Each one of Chapters 2–5 introduces, models and solves one of the problems described above. These chapters are all based on published, submitted or working papers and can therefore be read independently.
Chapter 6 provides conclusions and remarks for future research. Chapters 2–5 are based on:


**Chapter 5** Veenstra, M., Coelho, L.C., 2016. The time-dependent shortest path and vehicle routing problem. Working paper.