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Waste collection routing: a survey on problems and methods

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Abstract

Waste collection is a vital service performed all over the world, which heavily relies on vehicle routing. Due to regulations and local conditions, the problems and their characteristics often differ greatly. This literature survey aims to review the current state of the art overlap in waste collection and vehicle routing literature. The most notable papers are categorized according to their underlying problem type, examined and brought into relation based on their common problem characteristics. The problem types comprise general, node and arc routing problems, with vehicle routing problems being the most common, followed by arc and location routing problems. Besides the use of intermediate facilities, which is naturally very common in waste collection literature, the authors point out other interesting characteristics found in the literature and in practical problems, such as uncertain demand, personnel planning aspects, alternative collection systems or vehicle types, and characteristics related to risk or sustainability. Additionally, the authors highlight prominent scopes and objectives as well as recent developments in this area. Overall, this survey provides a selective overview and calls attention to research gaps and possible future research directions.

Keywords Review · Survey · Waste collection · Routing · Operations research

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Abbreviations

ALNS	Adaptive Large Neighborhood Search
ARP	Arc Routing Problem
CARP	Capacitated Arc Routing Problem
GRP	General Routing Problem
GA	Genetic Algorithm
IF	Intermediate Facility
IRP	Inventory routing problem
LRP	Location Routing Problem
LNS	Large Neighborhood Search
MILP	Mixed Integer Linear Program
NSGA	Non-dominated Sorting GA
PVRP	Periodic VRP
PDP	Pick-up and Delivery Problem
RRVRP	Roll-on/Roll-off VRP
SA	Simulated Annealing
TS	Tabu Search
VNS	Variable Neighborhood Search
VRP	Vehicle Routing Problem
WaCo	Waste collection

1 Introduction

This work attempts to provide an overview of the most notable papers that overlap the areas of routing optimization problems and waste collection (WaCo). Although WaCo literature is vast, we have only included papers where routing is an essential aspect of the work. We have limited our search to peer-reviewed journals and conducted it via Google Scholar, using combinations of the following keywords: '~ waste', 'collection', 'routing', 'circular economy', 'location', 'sensor', 'transport', 'management' and 'recycling'. These keywords have also been used for queries on journal homepages to include the most recent publications. The research papers found were screened by overall quality, subjective relevance, and whether they seemed noteworthy in terms of addressing something significant or novel. We do not attempt to provide an exhaustive collection of WaCo literature, but rather highlight works and areas of particular interest to give a broad overview, reveal possible gaps in academic literature, and encourage further research by the WaCo routing community.

Since we do not provide an exhaustive collection of literature, we want to recommend some surveys for further reading. Two surveys have looked at strategic decisions in WaCo, namely Ghiani et al. (2014a) covering literature until 2012, and Van Engeland et al. (2020) covering literature until 2018. The former focuses on strategic and tactical issues in waste management, mostly location problems, and provides mathematical models of various problem variations. The latter provides an extensive literature review on strategic network design in reverse logistics and waste management, with a focus on literature involving transportation, and characterizes them by methodology, network configuration, objective, and decision variables, to name a few.

Malladi and Sowlati (2018) and Hannan et al. (2020) are literature reviews with a focus on sustainability. The former focuses on sustainability in a general inventory routing context. However, a major part of the literature is concerned with waste management, collection or reduction. Additionally, they include papers on the transport of returns and on the reduction of emissions. They demonstrate what areas of study have been the most popular and give suggestions for future research. The latter focuses on providing mathematical formulations for various objectives and constraints, presenting different modelling and solution approaches, and discussing the latest research on whether we can use optimization techniques to reach sustainable development goals.

Beliën et al. (2014) provide an excellent review of waste management problems with a focus on Vehicle Routing Problems (VRPs). They cover literature until 2010 and classify it by categories such as type of waste, scope, solution method and objectives. The review of Schiffer et al. (2019) focuses on VRPs and Location Routing Problems (LRPs) with intermediate stops, and shows application areas and popular problem variants. We particularly suggest the part where intermediate facilities (IFs) are used for replenishment or disposal.

Apart from the surveys dealing with mainly academic literature, there are papers with a more practical focus: Coelho et al. (2016) provide a survey on real-world logistics applications until 2015 where the VRP is applied in five key areas, one of them WaCo. Delgado-Antequera et al. (2021) present a model to calculate eco-efficiency assessments for municipalities, using recyclable waste as desirable and unsorted waste as undesirable output. The metric can be useful to compare government administrations or WaCo providers, which is also the main scope of Bel and Sebő (2021). They do not consider routing, but rather provide a study on the influence of proximity between competitors on the quality of service delivered. They find that firms deliver higher quality in areas where a comparison with competitors is easier. These findings can be used to evaluate and improve service quality from a practical point of view, and could be incorporated into more theoretical research as well.

The remainder of this paper is organized as follows. Section 2 gives an overview of the most noteworthy scopes and objectives in WaCo routing that go beyond the conventional goal of minimizing total routing distance. Section 3 classifies the research papers by standard problem types and highlights commonalities and special characteristics within those types. In Sect. 4 we highlight recent developments, while in Sect. 5 we show research gaps and provide impulses for future work.

2 Scope and objectives

The scope of WaCo literature is rather broad, as real-life WaCo planning has evolved historically over time, and collection systems in different cities might be similar but are rarely identical. Operations research literature is using commonalities to 'standardize' and simplify problems into known variants, but several problem-specific objectives, formulations and constraints are present in WaCo. In this section, we attempt to highlight the scope and objectives of WaCo literature that emphasize its special nature. For an overview of problem classifications from a purely operations research perspective, we refer the reader to Sect. 3.

A realistic depiction of WaCo routing problems often includes medium- and long-term planning decisions as well as short-term operational decisions. Strategic decisions influence the design of the collection network and range from location problems to allocation or composition problems. At some point, the locations of incinerators, vehicle depots, treatment or sorting plants, landfills and even collection bins need to be decided (e. g. Hemmelmayr et al. 2017). This also applies to problems where the locations are on separate islands that have to be visited by WaCo boats (Miranda et al. 2015). The collection area can be serviced as a whole or divided into sectors at a tactical level to be serviced separately (Cortinhal et al. 2016). The types of waste that are collected separately or together are equally relevant to the allocation and composition of collection bins (Blazquez and Paredes-Belmar 2020; Hemmelmayr et al. 2014; Hrabec et al. 2020; Inghels et al. 2016). After these tactical decisions, the collection is planned over several days, and a combined scheduling and routing problem is solved (De Bruecker et al. 2018).

Although the internet of things is on the rise in the literature, only very few cities have equipped all their bins with sensors to read the fill levels. When fill levels can be estimated, it is suitable to model them as stochastic demands (Akbarpour et al. 2021). Without sensors of some kind, fill levels can be predicted by using historical data (Ahmad et al. 2020). As imprecise as these methods might be, they are recent steps in managing missing information and bringing operations research closer to reality.

The most common objectives of routing problems, namely minimizing cost, distance or time travelled, are also the most common objectives in WaCo, while few works maximize profit, revenue or the amount of waste collected. About 23% of the literature presented address a problem with two or more objectives, so that in addition to minimizing costs, for example, workload balancing or the number of vehicles are considered. Figure 1 shows the distribution of the literature between single-objective and multi-objective problems, and lists the most common objectives for single-objective WaCo problems. The risk of transport, storage or further processing of general or hazardous waste to the surrounding population has also come into focus (Govindan et al. 2022; Ma et al. 2021). The inconvenience of incinerator or landfill placements, or the timing of the collection to control odour generation (Amponsah and Salhi 2004), is considered as well. This metric is especially relevant in hot and humid climates, and first had to be quantified, i. e. smelled and rated by volunteers. Furthermore, the environmental impact of transport emissions is of increased interest as well, and recently published work often focuses on minimizing carbon emissions as one of their objectives (Liu and Liao 2021). Figure 2 provides an overview of the objectives used in multi-objective WaCo routing problems.

The inclusion of vehicles with multiple compartments for WaCo is gaining relevance as well (Kiilerich and Wøhlk 2018; Reed et al. 2014). Whether multiple compartments are better than single-compartment vehicles depends on many factors, e. g. the density of bins, their size and fill levels, and the overall vehicle

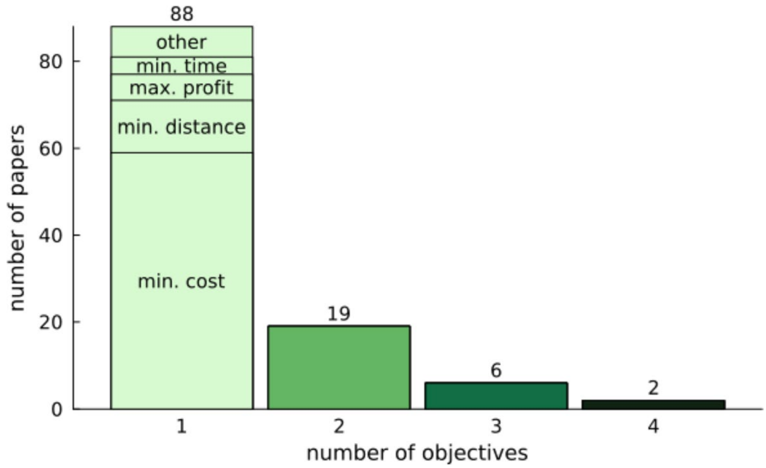

Fig. 1 Number of objectives considered in the literature and most common objectives in single-objective problems. The seven unnamed objectives, denoted as *other*, which are considered by only one paper each, are max. items packed, max. social welfare, min. average distance of vehicles, min. energy, min. number of collection sites, min. number of vehicles and min. risk. Two single-objective papers have each presented two different models with different objectives. They are therefore included twice, once for each objective

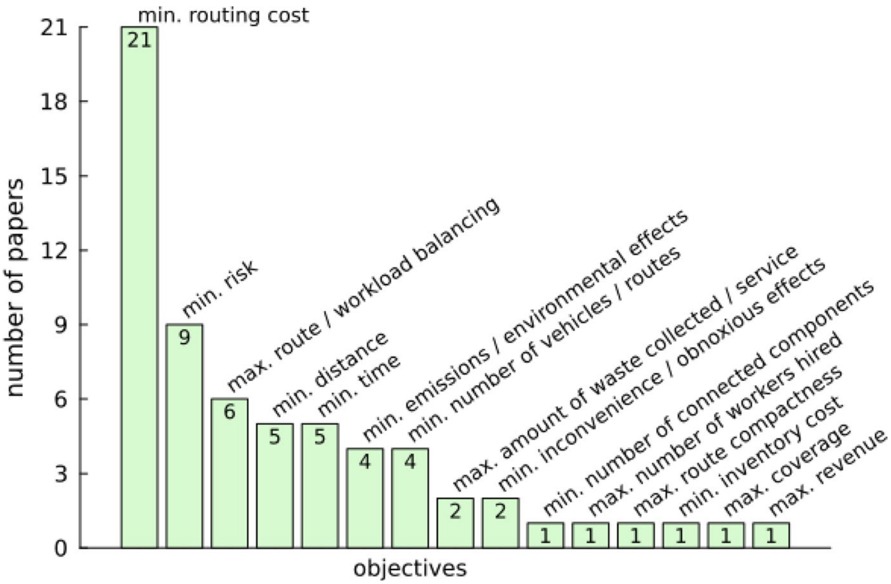

Fig. 2 Objectives considered in multi-objective formulations. Most papers consider min. routing cost as one of their objectives, in addition to other objectives

capacity. The compartment size can be fixed (De Bruecker et al. 2018; Elbek and Wøhlk 2016) or flexible (Henke et al. 2015), which then results in additional decisions for the optimization problem. In any case, the decision of whether to use vehicles with multiple compartments is primarily a financial one. If the option is generally feasible, a study is necessary to determine potential improvements.

Financial sustainability is unfortunately a prerequisite for recycling in many parts of the world. The alternative is to dispose of or burn the recyclable waste together with the undifferentiated household waste. Bogh et al. (2014) investigate the conflicts of interest arising from outsourcing the collection of recyclables in a system where this service is paid for by the citizens via mandatory tax. They optimize the overall financial sustainability of the system and propose a new payment structure. Financial sustainability is also a focus of collaborative routing problems, which is a problem variant rarely studied in the context of WaCo, where the goal is to exchange transportation requests between competitors to generate an allocation and routing solution that is preferred by every participant (Gansterer and Hartl 2018; Shao et al. 2020). On the other hand, explicit competition is not endured but rather encouraged in some instances, since it goes hand in hand with increases in service quality (Bel and Sebő 2021).

The different types of waste can be broadly classified into the following categories. The most cited one is that of municipal waste, which usually includes solid household waste. Often also construction and commercial waste are referred to as municipal waste. However, since their collection generally refers to fewer nodes with larger quantities, we have assigned them a separate category. Recycling waste includes items such as paper, cardboard, plastic, metal and glass, with the common goal to reuse these materials. Some papers consider recycling waste as a general category, without further specification, while others are dealing explicitly with a certain type. Akin to recycling is the collection of biological waste, food waste and vegetable oil, which are reused as compost, biogas or fuel. A timely collection is particularly relevant for food waste, which tends to attract vermin and can rot, thus leading to increased health risks and inconvenience due to filth and smell. Hazardous waste includes materials that, if not handled properly, pose a risk to human health or the environment in some way. We have categorized them into industrial hazardous waste, medical waste and electronic waste, which includes electronic devices and appliances that have reached the end of their useful life, such as computers, cell phones and televisions. Electronic waste contains a variety of hazardous materials and is collected to be partially recycled and partially disposed off properly.

The two main types of collection vehicles are single-compartment trucks and multi-compartment trucks, which can collect several types of waste at once. The configuration of the compartments can either be given, or be part of the optimization decision. Roll-on/roll-off trucks are a special case of single-compartment trucks that have a limited capacity of only a single or a few containers. They are commonly used for collecting construction and demolition debris or large quantities of commercial waste. Table 1 gives an overview of the types of waste and types of vehicles considered by each paper. Additional tables showing the literature by type of waste in relation to the type of problem are provided in the supplementary material.

Table 1 Overview of types of waste and types of vehicles used in the literature

Types of waste/vehicles	Single-compartment	Multi-compartment
Household, solid, residential, municipal	Ahmad et al. (2020); Akbarpour et al. (2021); Aliahmadi et al. (2021); Amponsah and Salhi (2004); Babaee Tirkolaee et al. (2018, 2019, 2022); Bach et al. (2016); Bel and Sebő (2021); Blazquez and Paredes-Belmar (2020); Cortinhal et al. (2016); Delgado-Antequera et al. (2020); Ghiani et al. (2005, 2014b, 2021); Gläser (2022); Gläser and Stücken (2021); Hrabec et al. (2020); Huang and Lin (2015); Inghels et al. (2016); Jin et al. (2021); Kuo et al. (2012); Liu and Liao (2021); Ma et al. (2021); Mes et al. (2014); Nuortio et al. (2006); Qiao et al. (2020); Rodrigues and Soeiro Ferreira (2015); Willemse and Joubert (2016); Wøhlk and Laporte (2018), barges: Miranda et al. (2015)	Gajpal et al. (2017); Kiilerich and Wøhlk (2018)
Recycling (general)	Cao et al. (2021); Cubillos and Wøhlk (2021); Del Pia and Filippi (2006); Hemmelmayr et al. (2013); Markov et al. (2020); Vidović et al. (2016); Wøhlk and Laporte (2022)★, paper, cardboard: Hemmelmayr et al. (2017); Osaba et al. (2017), plastic: Bing et al. (2014), glass, paper, plastic/metal: De Morais et al. (2022); Ramos et al. (2014), bulky: Aringhieri et al. (2018)	Reed et al. (2014); Zbib and Laporte (2020); Zbib and Wøhlk (2019), glass: De Bruecker et al. (2018); Henke et al. (2015), glass and paper: Bogh et al. (2014); Elbek and Wøhlk (2016)
Construction, commercial, non-hazardous industrial	Kim et al. (2006); Raucq et al. (2019)★; Shao et al. (2020); Yazdani et al. (2021), bulky: Hauge et al. (2014)★	
Biodegradable, food	Lavigne et al. (2021)	
Vegetable oil	Aksen et al. (2012, 2014); Cárdenas-Barrón et al. (2019); Montagné et al. (2019)	
Hazardous	Industrial: Alumur and Kara (2007); Rabbani et al. (2019, 2020); Samanlioglu (2013); Yu et al. (2020), biological (animal waste): Coene et al. (2010)	
Medical	Govindan et al. (2022); Nolz et al. (2014a, b); Osaba et al. (2019); Taslimi et al. (2020); Wu et al. (2020)	
Electric	Kim et al. (2009); Nowakowski (2017); Pourhejazy et al. (2021)	
Multiple types	Hemmelmayr et al. (2014); Wøhlk and Laporte (2019), bio and residual: Lavigne et al. (2022), dry and wet: Zhou et al. (2022)	Recyclables and used cooking oil: Erdem (2022)
Not specified	Battarra et al. (2014); Benjamin and Beasley (2010, 2013); Gruler et al. (2017, 2020); Kytöjoki et al. (2007); Lan et al. (2022); Moazzeni et al. (2022); Wøhlk and Laporte (2017)	

References marked with ★ denote a special case of a single-compartment vehicle, namely a roll-on/roll-off vehicle

3 Types of problems

Routing problems in the context of WaCo can be categorized into the following classes: Network design and Location Routing Problems (LRPs), General Routing Problems (GRPs), Arc Routing Problems (ARPs), Vehicle Routing Problems (VRP), Inventory Routing Problems (IRPs) and Pick-up and Delivery Problems (PDPs). Each class is introduced in its own section and the most notable papers of the recent years are described, further categorized and put in relation to each other. Nearly half of the literature presented model their problem as a VRP. The exact numbers of works per problem type can be seen in Fig. 3. For each paper we have put the focus on the main contribution, be it an intriguing objective, exciting constraints or a novel solution approach, and we attempt to introduce each paper with this focus in mind.

For most papers, we also describe or at least mention the solution method. An overview of these methods is given in the supplementary material. There, the papers are listed by their problem type under the respective solution method, and, for each method class, the size of the largest instance solved is given. The methods were roughly divided into exact methods, heuristics, metaheuristics, matheuristics and simheuristics. Since exact methods are usually used to solve rather small problems and WaCo problems tend to be quite large in practice, most authors, as can be expected, rely on (meta)heuristics to solve their problem. The few mat- and simheuristics we mention are used exclusively to solve VRPs and IRPs.

3.1 Network design and Location Routing Problems

The planning of WaCo networks requires strategic decisions concerning the positioning of collection bins, depots, landfills and processing facilities. Location choices are influenced by, e. g., the cost of land, regional legislation, available infrastructure, and, especially when choosing sites for waste treatment and storage, environmental concerns. We focus on location problems that take into account operational decisions: LRPs that simultaneously chose locations and a corresponding routing solution that defines customer visit sequences.

3.1.1 Network design problems regarding transportation modes and bin composition

One strategic decision concerns the selection of transportation modes, and their frequencies and itineraries. Inghels et al. (2016) study a multi-modal truck and water transport system in Belgium that brings household waste from collection centers to treatment facilities. They use a dynamic tactical planning model to decide on the service frequencies over a five-day planning horizon and the allocation of waste volumes to transport modes. They minimize mode-dependent transportation costs and costs associated with the environmental and societal impact of the selected mode.

Some works look at the composition of collection bins, their locations, number, types and sizes, since this has a large influence on the resulting operational cost. Hemmelmayr et al. (2014) solve a combined bin allocation and routing problem with

IFs for multiple periods. They study the trade-off between routing and bin allocation costs using both a hierarchical solution approach, solving the bin allocation problem exactly and applying a Variable Neighborhood Search (VNS) heuristic for the routing, and an integrated approach. Computational results on synthetic and real-world instances show the superiority of the integrated approach. Blazquez and Paredes-Belmar (2020) apply a similar hierarchical approach for the same problem, using a Large Neighborhood Search (LNS) heuristic for the routing. They reveal a positive impact of smaller bins and morning shift routes on the cost. In addition to bin composition and locations, Ghiani et al. (2014b) study the effect of the locations on the zoning of the territory whose goal is splitting the problem into smaller territories so that each can be served by a single capacitated collection vehicle while considering compatibility between different types of waste, bins and vehicles.

3.1.2 LRPs with alternative collection systems

Most literature covering WaCo LRPs do not question the underlying collection system, with the notable exception of Gläser (2022) and Gläser and Stücken (2021). Especially in densely populated urban areas, door-to-door collection systems reach their limits as collection vehicles obstruct traffic and bins are often rather small and have to be emptied more often. Therefore, they compare a bring-system where household waste is brought to central collection sites with either a door-to-door system (Gläser 2022) or an underground waste container system (Gläser and Stücken 2021). They introduce a service-type decision, allowing the collection systems to be merged rather than opting for just one. In Gläser and Stücken (2021) the authors extend the model of Hemmelmayr et al. (2014), a Periodic VRP (PVRP) with IFs and service choice with the goal to determine the optimal capacity, visit frequency and schedule for the sites. They assume a bring-system where the waste of many households is accumulated in large underground containers and extend the model to a periodic LRP with IFs and service choice by including the assignment of households to collection sites, which is limited by distance. In Gläser (2022), the author combines a door-to-door and a bring-system, thus creating a WaCo problem with a

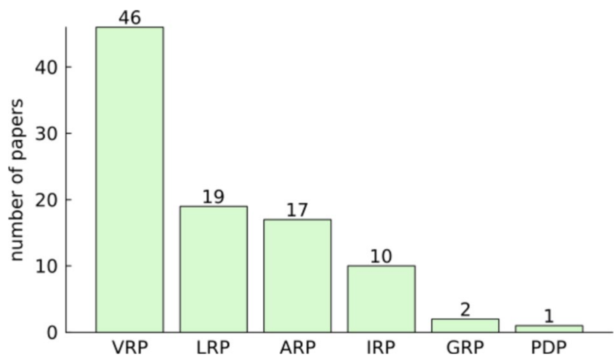

Fig. 3 Number of papers per problem type

service-type option, which they solve with an Adaptive Large Neighborhood Search (ALNS) for instances with up to 1,500 customers. In this regard, we also want to mention the work by Lavigne et al. (2021). They investigate scenarios which differ in collection rates, locations of the processing facilities, and whether a joint collection with the same vehicle or a separate collection of green and food waste is better from a cost perspective. As they assume a waste generation aggregation at a district level, they deal with multiple pick-ups for each location. They present a real-life case study with four scenarios for the Brussels capital region and use a Mixed Integer Linear Program (MILP) model to solve their problem.

3.1.3 LRPs maximizing area coverage and amount collected

The level of coverage is an important aspect of the location of collection bins, particularly for recycling waste, as citizens might dispose of it together with their general household waste instead. Incorporating area coverage consideration can also be relevant for general household waste, where it enables better estimations about the waste amounts generated at bin locations. Therefore, we want to mention the works by Cubillos and Wøhlk (2021) and Vidović et al. (2016) that consider the amount recycled to depend on the locations of the collection bins and their distances to the residents. Also, maximizing the area covered, along with minimizing collection costs, is explicitly part of their objective.

Cubillos and Wøhlk (2021) use a VNS heuristic for a real-world problem in Denmark, where they investigate the trade-off between recycling rates and transportation costs. Vidović et al. (2016) propose a novel network structure for a two-echelon LRP: Each city block has various possibilities for the location of collection points. The locations of transfer stations need to be selected as well. The transport routes between collection points and transfer stations are predefined, while the routes between collection points need to be established. For their problem, they use a two-phase greedy heuristic solution approach.

3.1.4 LRPs with uncertain demands

In LRPs with uncertain demands, the amount of waste generated is unknown and can only be estimated. Hrabec et al. (2020) use ellipsoidal uncertainty sets to model their uncertain decision-dependent quantities, while Yu et al. (2020) use discrete scenarios based on a probability distribution to model not only the amount and composition of the uncertain demand but also fluctuations of facility operations cost and transportation cost, as well as demographic changes. The former provide a mathematical model combining pricing and advertising aspects for the network design of a circular economy. They choose the locations of facilities, landfills and treatment options, and provide a routing solution. Uncertainty is handled by a robust optimization methodology. Their result is a mixed-integer second-order cone problem which is solved with state-of-the-art solvers and applied to a real-world problem with up to 200 cities in the Czech Republic. Yu et al. (2020) determine the location and size of treatment, recycling and disposal facilities, and the transportation among them by modelling a stochastic MILP. They use a sample average approximation-based goal programming, to reduce the exposure risk of the hazardous waste for the population and minimize cost.

3.1.5 LRPs considering risk

An explicit risk of handling medical, (industrial) hazardous or household waste, which can rot, is considered in several papers and ranges from risk due to transport along densely populated arcs, to prolonged storage at generation or transshipment points, and health hazards resulting from the locations of bins, disposal centers or processing facilities.

Both Govindan et al. (2022) and Alumur and Kara (2007) consider a bi-objective formulation including cost and a so-called population risk of medical waste in the former, and risk of transportation of hazardous waste in the latter. Govindan et al. (2022) model their problem as a multi-period LRP with a heterogeneous fleet, employ an augmented ε-constraint method, and use a stochastic scenario-based approach to deal with the uncertainty in the generation of waste. Alumur and Kara (2007) consider the routing and location decisions for treatment and disposal centers of different types of hazardous waste. In addition to mass balancing, capacity and compatibility constraints, they include a minimum waste volume for the opening of a treatment center.

Ma et al. (2021) study a multi-objective LRP where costs include the minimization of obnoxious effects of the recycling center as well as its opening and handling cost, vehicle routing cost and fixed costs. They use a simple clustering method for the location decision and the Clarke and Wright savings algorithm for the routing model, a VRP with intermediate stops. The complete multi-objective model is solved using the Non-dominated Sorting Genetic Algorithm (NSGA)-II. Samanlioglu (2013) considers multiple objectives as well, namely first, the transportation cost and fixed cost of establishing disposal centers, second, the risk involved in transporting hazardous waste along populated areas, and third, the risk to the population when placing a disposal center. They consider three different types of hazardous industrial waste and generate Pareto optimal solutions.

3.1.6 LRPs with multiple periods

The combination of LRP and multiple periods is particularly relevant for WaCo, since the number of containers to collect often vastly exceeds the fleet capacity of a single day. Hemmelmayr et al. (2014) and Hemmelmayr et al. (2017) incorporate multiple periods in their LRPs. The first paper, which mainly focuses on bin allocation, is already described at the beginning of this section. The latter succeeds in deciding the set of open depots, their capacity and the visit frequency to nodes for their collaborative recycling. They introduce a mathematical problem formulation and implement an ALNS to solve the problem.

Rabbani et al. (2019) build upon their previous work to solve an LRP for industrial hazardous WaCo considering risk by introducing stochasticity, a multi-period planning horizon and inventory decisions. They apply their algorithm in the automotive industry in Rabbani et al. (2020) and incorporate pricing decisions in their location-inventory routing problem in Rabbani et al. (2021). In Rabbani et al. (2019) they use an integration of NSGA-II and Monte Carlo simulation, while in Rabbani et al. (2021) a lexicographic optimization approach and an improved augmented ε-constraint method are applied.

3.2 General routing problems

General Routing Problems (GRPs) are modelled on a mixed graph which allows both arcs to be traversed and single nodes to be visited, thus combining node and arc routing. Although this can be a suitable formulation for WaCo problems in city-logistics, this type is by far the rarest. In that regard, we want to mention two notable works.

Pourhejazy et al. (2021) consider the collection of electronic waste with two request types: door-to-door demands which correspond to arcs that must be traversed, and on-call demands which correspond to single nodes called in for collection. In order to depict an acceptable service level, the authors assume time windows for the on-call demands and model the problem as a capacitated GRP with time windows. They maximize total profit, i. e. the gains from the door-to-door collection subtracted by operational costs, penalties for time window violations, costs for fuel consumption and wages. Hiring new drivers and overtime work is possible and subtracted from the gains as well. They generate an initial solution using Dijkstra's shortest path algorithm, and improve it with a neighborhood search procedure combined with Tabu Search (TS).

Bach et al. (2016) introduce a branch-and-cut-and-price algorithm for the mixed capacitated GRP. Their goal is to service each required node, arc and edge with one capacitated vehicle, minimizing the total traversal cost. Even if the authors do not describe a specific WaCo application, the GRP is a well fitting approximation for WaCo problems in city logistics, and the paper provides extensive testing on standard benchmark instances showing the quality of the proposed algorithm.

3.3 Arc routing problems

Modelling a WaCo problem as an Arc Routing Problem (ARP) can be particularly useful for curbside collection in densely populated urban areas, where the solution flexibility of a node routing formulation is superfluous. ARPs are often represented by an incomplete graph, where not every point is connected to every other point, unlike node routing problems, which are typically defined with a complete graph, making the problems significantly smaller and hence easier to solve. However, since these problems are less well studied, the solution methods are generally less powerful. Nevertheless, a few works mentioned here solve instances with more than 1,000 vertices or arcs.

For a further introduction to ARPs in WaCo, we refer to Ghiani et al. (2015). In this section, we introduce the most relevant ARPs in WaCo grouped by their most significant problem characteristic. Almost all the works presented consider capacities in some manner, be it capacitated vehicles, or capacities at the facilities where waste is consolidated, incinerated or otherwise processed. They are therefore called capacitated ARPs. Many works incorporate several problem characteristics, but are nonetheless mostly mentioned only once.

3.3.1 ARPs with location decisions

In some ARPs, facilities such as depots or incinerators need to be located on the graph or opened before routing sequences can be determined. These are called location-ARPs. Including location decisions shifts the problem from a purely operational level to a more strategic level, however, most LRPs concern location-node routing and for this we refer the reader to Sect. 3.1. The main location-ARPs until 2001 are described in a survey by Ghiani and Laporte (2001) including applications and algorithms.

A recent location-ARP is the work by Moazzeni et al. (2022) with electric vehicles, which attempt to provide road cleaning while minimizing the number of vehicles and total distance travelled. Simultaneously, the best locations of charging stations, dynamic charging arcs and WaCo centers need to be determined. By implementing dynamic charging arcs, the vehicles can be charged wirelessly by driving along the arc. They use a Genetic Algorithm (GA) and a grey wolf optimizer, with the latter outperforming the former in their case study located in Edmonton, Canada. Since some arcs have a higher demand than a single vehicle capacity, they allow demand splitting of arcs. The objective minimizes the sum of the establishment cost of WaCo centers, charging stations on vertices, dynamic charging along arcs, traversing arcs and servicing costs.

3.3.2 ARPs with multiple periods

The planning of WaCos over multiple days is a natural consequence of the fact that it is sufficient to empty containers for example once or twice a week, instead of daily. A plan for a single period is often the result of a preceding simplification, or a preceding implicit scheduling decision of the problem. Babaee Tirkolaee et al. (2018, 2019, 2022) deal with different variations of the periodic Capacitated Arc Routing Problem (CARP) for urban WaCo. Babaee Tirkolaee et al. (2018) consider uncertain demand and two types of vehicles with different capacities and cost structures, and minimize fixed and variable transportation costs. Babaee Tirkolaee et al. (2019) extend the problem to a bi-objective formulation, minimizing total collection costs (i. e. road traversal and vehicle usage) and the distance of the longest tour. In this work, they also allow vehicles to drive multiple trips per day. In addition, Babaee Tirkolaee et al. (2022) further extend the problem to include four different objectives: minimize the total cost (collection, transportation and disposal), minimize the total environmental emissions, maximize citizen satisfaction and minimize the workload deviation. By including all four objectives, they look at economic as well as environmental and social aspects. Although the size of the problems they consider remains relatively small, they apply various solution methodologies: a heuristic and Simulated Annealing (SA) in Babaee Tirkolaee et al. (2018), an ε-constraint method and a multi-objective invasive weed optimization algorithm in

Babaee Tirkolaee et al. (2019), and a hybrid multi-objective optimization algorithm based on SA and weed optimization that is compared to Pareto-optimal solutions obtained by the ε-constraint method in Babaee Tirkolaee et al. (2022).

3.3.3 ARPs with multiple compartments

Multi-compartment ARPs are used to plan the collection of multiple types of waste with a single vehicle. Having multiple compartments reduces the capacity for a single type of waste, but can lead to shorter routes, as arcs do not have to be traversed multiple times. When using vehicles with a single compartment, either each type of waste is collected by different vehicles, thus increasing travel time, or the multiple types are collected together and then sorted at the recycling center. Using multiple compartments allows the collectors to exploit both advantages of traversing arcs just once and keeping the waste sorted. Zbib and Wøhlk (2019) study the difference between four different strategic decisions in that regard: a collect-then-sort system, two sort-then-collect systems and a collect-to-incinerate system where sorting is superfluous. For all variants, they investigate the influence of multiple compartments on the total distance and the number of vehicles needed. Kiilerich and Wøhlk (2018) introduce five new CARP variations, out of which three are with multiple compartments. The collection vehicle either has the same amount of compartments as waste types to be collected (no-split) or less than that, in which case an additional decision regarding which waste types to collect with which vehicles becomes necessary (commodity-split). In a further expansion, they take a timing perspective into account. When planning over multiple days, the same compartments should collect the same type of waste to minimize cleaning and cross-contamination (multi-day commodity-split). They present large-scale instances with more than 10,000 nodes, based on real-life networks and waste data from different areas in Denmark, for the classical CARP and all of their five new variations. Zbib and Laporte (2020) also use these instances, solving the commodity-split multi-compartment CARP with heterogeneous vehicles. The problem aims to select the number of vehicles of each type, assign the compartments to waste types and route the vehicles. They use a decomposition approach on multiple levels to minimize total cost, and look at problems with up to six waste types and vehicles with up to four compartments.

3.3.4 ARPs with a focus on sustainability and environmental aspects

The consideration of environmental aspects is highly important for some waste types. As most works considering environmental aspects deal with LRPs or VRPs, see Sects. 3.1 and 3.18 respectively, we want to mention the work by Amponsah and Salhi (2004) who consider hot weather and the resulting smell of household waste in developing countries. The environmental impact depends on the cumulative amount of waste of an arc, which grows over time. They attempt to balance two objectives, the collection cost and the inconvenience due to the accumulating smell, and use a construction heuristic with a look-ahead strategy. The work by Ghiani et al. (2005) resulted from an initiative of the health department in Italy, which was concerned about public health after extensive budget cuts to the whole public sector, including

WaCo. In a cooperation between three universities and the health department, the problem was modelled and solved as a CARP with constraints covering road-network features, traffic congestion and equipment. The goal of minimizing the total distance was achieved by a cluster-first route-second heuristic.

3.3.5 ARPs with mobile depots

So-called mobile depots are mobile collection facilities, where smaller WaCo vehicles can deposit their load. This combination of collection vehicles is usually motivated by road segments that are inaccessible for the larger collection vehicles. The smaller collection vehicles, also called satellites, can be standard vehicles, but can also come in the form of small electric vehicles, electric bikes or even garbage collection persons with bag who can reach otherwise inaccessible locations on trails or in parks. The research for ARPs with mobile depots in a WaCo context is quite scarce, with the notable exception of Del Pia and Filippi (2006). In their work, the standard WaCo vehicles are too large for some of the narrower streets. They, therefore, act as mobile depots and compactors for the smaller satellites, as well as collection vehicles if the street is wide enough. However, the mobile depots can also stay stationary, or only reposition themselves to other locations without collecting anything themselves. They attempt to minimize the sum of total satellites in use and the compactor tours' duration by applying a heuristic with a rendezvous procedure to synchronize vehicle encounters.

3.3.6 ARPs with intermediate facilities

IFs are collection or transshipment locations where waste is either consolidated, recycled, incinerated, or simply stored, that are different from the vehicle depot. Since they are often located at the outskirts of cities, large detours are often necessary to empty the collection vehicles. Rodrigues and Soeiro Ferreira (2015) consider the CARP with multiple intermediate facilities, landfills in their case, that are limited in the number of visits per day. Therefore, it is necessary to balance the visits between the facilities, and it is not possible to always choose the nearest one. Willemse and Joubert (2016) further include time restrictions and a mixed graph with vertices, undirected edges linking two vertices, and directed arcs linking two vertices. They compare four construction heuristics minimizing either total cost (including deadheading times) or fleet size.

3.3.7 ARPs of a larger size

Most CARPs in the literature, whether applied to a real-world case study or not, tend to consider small problem sizes, with the notable exception of the work by Wøhlk and Laporte (2017, 2018, 2019) whose problem size for a case study in Denmark is up to 11,640 nodes. In Wøhlk and Laporte (2017) they compare six different greedy algorithms to solve a minimum cost perfect matching problem on an undirected complete graph. Wøhlk and Laporte (2018) develop a heuristic for obtaining solutions for the CARP quickly, and test it on their large case study, while Wøhlk and

Laporte (2019) extend the problem to include multiple periods and several waste types. The research question there is to determine how much the solution fitness deteriorates if collections are synchronized to reduce the inconvenience to the residents. They first make collection districts that correspond to a day of the week and route those using the algorithm developed for Wøhlk and Laporte (2018).

3.3.8 ARPs with city logistic aspects

When solving ARPs for WaCo in the context of city logistics, many other conditions could be considered: traffic, one-way streets, large graphs and time windows for containers near vulnerable groups, for example, schools, to name a few. In that regard, we want to draw attention to the work of Cortinhal et al. (2016) and Jin et al. (2021). The former apply sectoring to decompose a large problem into several smaller ones, and that attempt to minimize the driving time for each vehicle and balance the workload among the sectors while adhering to constraints concerning vehicle capacity and time. They obtain good quality solutions using a hill climbing and TS heuristic for random and real-world instances based on a refuse collection system in Portugal. Jin et al. (2021) consider the fact that during garbage collection there is no parking allowed on the serviced arcs as to facilitate the collection. In addition to minimizing travelling and service costs, penalties for necessary no-parking intervals in certain time windows are introduced. They provide a problem formulation with these time-dependent penalty costs, as well as capacity and time window constraints, and solve it with dynamic programming and a VNS-inspired heuristic with different neighborhood operators and a perturbation phase.

3.4 Vehicle Routing Problems

The VRP is by far the most used model for routing problems in WaCo. Using a VRP model for WaCo problems is useful when there are single collection nodes scattered over an area, contrary to the door-to-door collection system which is usually modelled as an ARP. In commercial WaCo, where garbage is collected from businesses, nodes often have additional constraints such as time windows or site dependencies. Other common characteristics include IFs, sustainability, risk considerations, stochasticity, decisions related to personnel planning and multiple periods. The latter can be represented as a so-called periodic problem, where schedules are planned and repeated, or simply a consideration of future periods without having a repeating schedule. Suitably, the PVRP was first introduced in a WaCo problem setting by Beltrami and Bodin (1974). In practice, it is common to consider a planning horizon of several days or weeks. Nevertheless, less than 20% of the papers mentioned here consider multiple periods or plan periodic schedules. As there were always other interesting problem characteristics, we did not dedicate a separate paragraph to this one. Most research combines several problem characteristics, however, each work is mentioned only in the section related to its most prominent attribute.

3.4.1 VRPs with intermediate facilities

Disposal or processing facilities are the most common characteristic in WaCo problems, as vehicles must be emptied when they are full. If this is possible at the depot, the problem can be modelled as a VRP with multiple trips, otherwise as a VRP with IFs. Of the more than 40 papers mentioned in this section, 26 consider at least some kind of facility to dispose or process the waste collected, while some others assume disposal at the depot.

Angelelli and Speranza (2002) first introduced the concept of IFs for a PVRP. Since most papers include disposal facilities in some form, we mention here a few, where more than one disposal trip is possible and the method places special focus on their positioning in a route. Hemmelmayr et al. (2013) provide an exact problem formulation for the PVRP with IF and propose a hybrid solution method based on VNS which uses dynamic programming to insert the visits to the IFs. Benjamin and Beasley (2013) use this procedure based on dynamic programming to improve their heuristics for their VRP with time windows. For a real-life rich WaCo problem in Belgium, Lavigne et al. (2022) present a memetic algorithm with a sequential split procedure, which splits a giant tour into single routes, inserts IFs, and further splits the pick-ups, if profitable, before improving these solutions via local search. Inspired by a WaCo problem in Switzerland, Markov et al. (2016) solve a VRP with IF, a heterogeneous fleet, a flexible vehicle-depot assignment, time windows, driver breaks and site dependencies, i. e. not all streets are accessible for all vehicles, for which they propose a MILP and a multiple neighborhood search heuristic. Some papers consider time windows or capacity restrictions at the IFs which are, in practical applications, often given by business hours and the amount of waste which can be processed in one day. Capacity restrictions are, among others, considered in Qiao et al. (2020), Yazdani et al. (2021), Lavigne et al. (2021) and in the case study of Hemmelmayr et al. (2013).

3.4.2 VRPs with time windows

Time windows are often considered in residential WaCo near schools or hospitals, or due to business hours in commercial locations. About 25% of papers mentioned in this section consider time windows of some kind. Most prominent is the work by Benjamin and Beasley (2010) that considers time windows at the customer locations, IFs and the depot, as well as rest periods for drivers. For each customer, they define a neighbor set as a set of customers which are within a certain distance and have a compatible time window. They present a VNS and a TS both based on these neighbor sets, and a hybrid VNS, where the neighborhood is searched via TS. The proposed metaheuristics are tested on the instances introduced by Kim et al. (2006) with up to 2,092 customers and 19 waste disposal facilities.

3.4.3 VRPs with stochastic data

Although the demand is rarely known precisely in WaCo applications, there are surprisingly few papers that assume demand to be stochastic. The same applies to travel times, which can fluctuate greatly, especially in urban traffic. Stochastic demand is considered by Kuo et al. (2012) and Aliahmadi et al. (2021) for real-world problems in Indonesia and Iran, respectively. Kuo et al. (2012) solve the problem with a hybrid metaheuristic combining particle swarm optimization and GA, Aliahmadi et al. (2021) formulate a bi-objective problem minimizing cost and time and solve it with the ε-constraint method. Larger instances are solved with an NSGA-II. Gruler et al. (2017) consider multiple depots and stochastic demands, while Gruler et al. (2020) consider stochastic travel times for a real-life problem in Spain. In both cases, a simheuristic combining a biased randomized Iterated Local Search (ILS) metaheuristic with Monte Carlo simulation is used. Like Gruler et al. (2020), also Yazdani et al. (2021) consider stochastic travel times in their real-world case study in Sydney, Australia, and use a simheuristic to solve it. Hu et al. (2018) describe a VRP with time windows not specifically for, but applicable to WaCo, assuming both demands and travel times to be stochastic. They propose a robust optimization model based on route-dependent uncertainty sets and a two-stage algorithm based on a modified ALNS heuristic for large instances, minimizing the number of routes in the first stage and the total travel distance in the second.

3.4.4 VRPs with decisions related to personnel planning

Especially in practical problems, constraints from personnel planning are often included in the routing model. These include mandatory lunch breaks, maximum shift duration, or an effort to fairly distribute the workload between vehicles. Kim et al. (2006) deal with a VRP with time windows with multiple IFs in North America in which they consider driver lunch breaks and workload balancing, in addition to minimizing the number of vehicles and total travel time, and maximizing route compactness. Delgado-Antequera et al. (2020) minimize travel costs and maximize route balancing in a bi-objective WaCo problem with estimated demands in Spain. De Morais et al. (2022) solve a real-world problem in Portugal where they assume real-time information from sensors and maximize profit while considering shift duration constraints and workload balancing via penalty terms in the objective function. For a multi-objective problem in China with two different types of waste, Zhou et al. (2022) combine a NSGA-III with SA to minimize the distance and amount of leakage and maximize workload balancing.

In the context of glass WaCo, De Bruecker et al. (2018) solve a combined shift scheduling and PVRP with IF with a case study in Belgium. Here, contrary to most papers in this field, all locations are visited as specified, but bins are only emptied when their fill level exceeds a certain threshold, while vehicles are only emptied when one of the compartments is full. The objective is to minimize weekly labor costs. They present a mathematical formulation of the shift scheduling model considering legal constraints and a model enhancement heuristic which iteratively combines simulation and optimization.

3.4.5 VRPs with risk considerations

The management and collection of hazardous waste often impose specific characteristics and challenges on route planning problems. Taslimi et al. (2020) consider the transportation of medical waste. They use a decomposition method to solve a load-dependent PVRP, minimizing the transportation risk depending on the weight transported as well as the risk of storage at the nodes. Coene et al. (2010) address a real-world PVRP concerned with the collection of animal waste from slaughterhouses, butchers and supermarkets in Belgium and France. Their disposal facilities have time windows, and vehicles must only be emptied at the end of a day at one of these facilities if the vehicle is not in use the next day. There are different risk categories associated with waste, and vehicles assigned to a certain category cannot be used to transport waste of another category. They treat these categories separately and study various two-stage approaches: several cluster-first and route-second, and one route-first and cluster-second approach.

3.4.6 VRPs with a focus on sustainability and environmental aspects

Routing problems with aspects related to sustainability like recycling, reverse logistics or circular economy have recently seen increasing interest. Besides papers where sustainability is treated in a standard way, some research really puts it into focus. In Kim et al. (2009), end-of-life consumer electronic goods are collected for recycling in South Korea. They solve a standard VRP for each recycling center with a TS heuristic. The problem described by Ramos et al. (2014) is a multi-product, multi-depot VRP that addresses the collection of recyclable waste and minimizes CO_2 emissions alongside the distance travelled. The authors implement a decomposition method, apply it to a case study in Portugal and study different economic and environmental scenarios. In Qiao et al. (2020), the goal of reducing carbon emissions is addressed by including carbon emission costs, which are proportional to fuel consumption, into the objective, and by balancing the workload at the disposal sites to avoid congestion and waiting times. In a plastic WaCo problem in the Netherlands (Bing et al. 2014), routes are evaluated by their eco-efficiency, which concerns the trade-off between various environmental impacts, social issues and costs. Using different scenarios, the authors study collection alternatives and the effects of changes therein. Another development in routing and also WaCo is the increasing use of electric vehicles. For example, Erdem (2022) solves a very specific, rich WaCo problem for recyclables and used oil in Turkey in which, to reduce emissions, a heterogeneous fleet of electric vehicles is used. Finally, Gajpal et al. (2017) consider alternative fuel-powered vehicles.

3.4.7 VRPs of a larger size

Most VRP research, including WaCo applications, target rather small problems with only a few hundred customers. In contrast, Lan et al. (2022) consider multiple depots, disposal facilities and trips, and implement a memetic algorithm to solve instances with up to 3000 collection sites, 3 depots and 3 disposal facilities in their real-world case study in China. Nuortio et al. (2006) deal with a PVRP for municipal WaCo in Finland with up to 3386 nodes and a planning horizon of up to four weeks. They consider various types of waste simultaneously and vehicles which are capacitated by both volume and weight. The goal is to choose the collection days based on a given interval for each type of waste. The authors use a hybrid insertion heuristic to generate initial routing solutions and improve those with a combination of guided local search, VNS and threshold accepting. The containers are scheduled by urgency and collection interval and later improved by relocate and exchange operators guided by their main metaheuristic. Another real-world WaCo problem in Finland was solved by Kytöjoki et al. (2007). They propose a VNS for a standard VRP minimizing route costs and present efficient implementation techniques to speed up the optimization to solve even very large-scale instances with up to 20,000 customers.

The recent works by Arnold et al. (2019) and Accorsi and Vigo (2021) solve even larger problems. They introduce solution methods for the VRP with up to 30,000 customers and solve the WaCo instances by Kytöjoki et al. (2007).

3.4.8 Roll-on/roll-off vehicle routing problems

Industrial waste or large amounts of commercial waste are often gathered in large containers. In contrast to standard household WaCo, these containers are not emptied on site, but are picked-up, taken to the disposal site to be emptied and brought back, or are replaced by empty containers. This leads to an interesting problem where vehicles can only transport very few containers, or even just one, simultaneously, called the Roll-on/roll-off Vehicle Routing Problem (RRVRP). Bodin et al. (2000) first describe a RRVRP where tractors pick-up large waste containers from shopping malls and construction sites, and transport them individually due to their size. Although very similar to a Pickup and Delivery Problem (PDP), the problem was initially formulated as a VRP where each pickup and delivery pair, albeit placed at two different locations, can be viewed as a single node due to the direct transportation made necessary by the full-truckload characteristic. They present a mathematical programming formulation, two lower bounds and four heuristic algorithms for their full-truckload VRP with one IF. Wy and Kim (2013) and Derigs et al. (2013) tackle the same problem as Bodin et al. (2000). They minimize the number of vehicles and non-productive (deadhead) time, and deal with four different types of requests. The additional requests would grant the problem a classification as a proper PDP, however due to its origin, we have kept the historical denomination and categorization. In their problem, general containers are just replaced with empty containers upon collection. But some customers have their own waste containers, so they are picked-up, emptied and brought back. First-time customers are delivered an empty container without a full one being collected, and end-of-contract customers get their containers collected without replacement. Wy and Kim (2013) develop a customized LNS, while Derigs et al. (2013) use an approach combining local search and LNS, both reporting similarly good results on the instances of Bodin et al. (2000). Baldacci et al. (2006) introduce a fifth kind of request, where partially filled containers can be relocated between customer locations, omitting the trip to the disposal site, and consider multiple disposal facilities and inventory locations, They model the problem as a time-constrained VRP on a multigraph and solve it with an exact method. Wy et al. (2013) extend the original problem by three more request types and add multiple depots, container storage yards and time windows for customers.

Aringhieri et al. (2018) deal with a real-world RRVRP in Italy, in which full containers must be picked-up to be emptied and replaced by empty containers. There are different types of containers and waste materials, and recycling and material processing facilities. The objective is to minimize the number of vehicles and total route duration, considering a limited number of spare containers. They introduce a formal problem definition and implement a neighborhood-based metaheuristic.

Contrary to the full-truckload RRVRPs mentioned above, Hauge et al. (2014) describe a case where vehicles can transport up to eight skip containers. They propose a generalized set partitioning formulation for this problem and a hybrid column generation approach using a TS heuristic to generate new columns. Raucq et al. (2019) describe a real-world problem in Belgium with multiple waste and container types, multiple stock depots for empty containers, time windows at customers and depots, and a heterogeneous fleet with two types of vehicles, which can carry one or two containers, respectively. They reformulate their roll-on/roll-off WaCo problem as a generalized VRP with time windows and propose a novel column generation approach to solve it.

3.4.9 VRPs with other characteristics

In this section we address interesting VRP variants of practical relevance, which incorporate characteristics not already mentioned in previous sections. These include the two-echelon VRP, clustered VRP, VRPs with split-deliveries, packing or loading and multiple compartments. In all cases, the literature is rather scarce in the field of WaCo, indicating potential for future research.

Especially in big urban areas, landfills are often far away from the urban center. In these cases, it makes sense to use transshipment facilities where the waste collected in the urban area with smaller WaCo vehicles can be transferred into larger trucks, which then transport the waste to landfills or other processing facilities in rural areas. Ghiani et al. (2021) solve this two-echelon problem by planning the routes and the synchronization of both types of vehicles in two phases. In addition to providing a mathematical model, they propose a matheuristic for the collection phase and a heuristic for the transportation phase. They minimize the number of collection vehicles and test their two-stage approach on instances with up to 1,000 collection points. Cao et al. (2021) describe a two-echelon reverse logistics network for the collection of recyclables with an electric heterogeneous fleet. The authors use a hybrid method combining an LNS and a GA to minimize transportation costs, fixed costs and penalty costs incurred for violating time windows.

The clustered VRP is particularly applicable to real-world WaCo problems. The customers are grouped into clusters, and vehicles must service all customers in a cluster before leaving it again. Inspired by a real-world case in Italy with 385 collection locations, Battarra et al. (2014) present two exact algorithms and introduce the concept of visual attractiveness into the evaluation of their routes. They test their algorithms on multiple benchmark instances and a set of real-world instances.

Split deliveries, or split collections, are part of the works by Lavigne et al. (2021) and Huang and Lin (2015). The former deals with a WaCo problem in Belgium with multiple depots and IF, as well as multiple pick-ups per location. The goal is to determine the necessary (minimum) number of vehicles per depot and minimize the total driving distance. There are at most two pick-ups allowed before visiting one of the IFs, which have a fixed capacity. They provide a MILP formulation and solutions for different bio-waste treatment scenarios, however no method to solve larger instances. Huang and Lin (2015) describe a real-world setting in Taiwan, with a so-called block collection system where residents must personally bring their waste to a designated stop point. The problem can be described as a split delivery PVRP with multiple trips, where collection points must be visited at different times on each collection day, to allow residents with daytime jobs to dump their waste. The locations of collection points need to cover all residential blocks and are selected by a set-covering problem. The resulting multi-trip split-delivery VRP with pick-up and delivery is solved by a heuristic based on ant colony optimization.

In WaCo scenarios where pieces of waste, due to their size and shape, are cumbersome to handle, it may be worthwhile to integrate the routing with a packing problem. By combining a VRP and a container loading problem in a case study in Poland, Nowakowski (2017) solve a routing problem for bulky electronic waste such as refrigerators or washing machines. The goal is to create visit sequences that allow for compact packing, maximizing the number of items packed into the vehicle.

In contrast to the usual case of a fixed number and size of compartments in multi-compartment trucks, Henke et al. (2015) describe a glass WaCo problem arising in Germany, where both the number of compartments and their size are part of the optimization decisions. They propose a model formulation and a VNS to solve randomly generated and real-world instances.

3.5 Inventory Routing Problems

IRPs integrate inventory management decisions with operational decisions such as visit schedules and routing sequences. For a comprehensive review of IRP model variants and solution methods, the interested reader is referred to Coelho et al. (2014), and, for a review of IRPs with a focus on sustainability, to Soysal et al. (2019). Usually, the inventory modelled in IRPs is at the customer locations. In WaCo, this would imply that the amount of waste at customer locations is known and the changes in fill levels can be modelled, e. g. by using previously known waste generation rates or sensor information. In cases where a daily collection is not necessary, WaCo problems are often modelled as periodic problems with known demand quantities, and a repeating schedule is planned. In practical applications, the advantage of this setting is that drivers and teams have always the same routes and can therefore operate very efficiently, knowing the exact layout of buildings, the locations of the bins and the challenges in the street network. However, in situations where waste generation fluctuates greatly over time, a periodic schedule is inapt, but it may still be useful to plan over several periods. In this section, we first want to point the reader to a special case of IRP arising in the context of waste oil collection that considers one central inventory. All papers mentioned here consider selective and periodic IRPs. We then refer to some real-world IRPs with decentralized inventory before focusing on stochastic and dynamic IRPs.

3.5.1 IRPs with a centralized inventory

Inspired by a real-world problem in Turkey, Aksen et al. (2012), Aksen et al. (2014) and Cárdenas-Barrón et al. (2019) deal with a selective and periodic IRP. To meet production goals, a biodiesel production company with its own oil inventory collects waste vegetable oil from facilities like hospitals or hotels, and can further purchase virgin vegetable oil. The aim is to obtain a periodic collection schedule minimizing the total costs composed of transportation, inventory holding and purchasing costs. In this selective problem, one must not only decide on the schedule, the tours and the number of vehicles, but also which customers to collect from each day and how much virgin oil to purchase. Aksen et al. (2012) first introduce the problem and formulate two single-commodity flow-based MILPs differing in the visit schedule generation. Aksen et al. (2014) propose an ALNS with various specifically tailored move operators to solve more realistic instances and test it using the lower bounds generated by the original MILP and partial relaxation of Aksen et al. (2012) and a new relaxation without routing. Cárdenas-Barrón et al. (2019) propose a new valid inequality for the MILP and implement a reduced cost heuristic based on a reduce and optimize approach.

3.5.2 IRPs with decentralized inventory

In a setting similar to the one described above, Montagné et al. (2019) solve a selective IRP with multiple periods. In contrast to the problem described above, there is an inventory at each collection node with a known accumulation rate and a capacity that must not be exceeded. Instead, collection costs are incurred at each node in relation to the quantity collected. The objective is to minimize the sum of transportation, pick-up and fixed costs. Similar to Aksen et al. (2014), they propose a MILP relaxation without routing for their problem and propose a greedy constructive heuristic based on shortest path and split procedures.

In a completely different setting inspired by a real-world problem in Denmark, Elbek and Wøhlk (2016) solve a multi-period IRP concerned with the combined collection of glass and paper. Since the two commodities must be handled separately, one multi-compartment vehicle with two compartments whose size may vary from day to day is used to collect the waste and transport it to separate treatment facilities. From real-world data, they observe highly fluctuating waste accumulation rates and thus assume the fill levels to be stochastic. The aim is to plan collections for a period of a few days in a rolling horizon framework while preventing overflows and minimizing the total operational cost. They use a construction heuristic for the first period and then re-optimize the solution in the subsequent periods using a VNS and a future cost function. The same real-world problem is dealt with by Bogh et al.

(2014) although there the authors focus on the sustainability of the problem and suggest a new payment structure for the collection service.

3.5.3 Stochastic and dynamic IRPs

In WaCo applications, the demand at locations usually becomes known only upon collection. This demand is often assumed to be deterministic, which results in a significant simplification. Even when sensors are used, it makes sense to assume demands to be stochastic, as sensors are often error-prone and inaccurate. An advantage of using sensors is that one can, for example, introduce threshold levels to trigger dynamic collection visits. We refer to some papers where the uncertainty regarding inventory levels is integrated into the model and solution approach.

Nolz et al. (2014b) deal with a stochastic collector-managed IRP arising in France, where each day an uncapacitated vehicle visits a subset of pharmacies to collect previously unknown amounts of infectious medical waste. The objective is to minimize the routing costs while keeping the visits balanced, i. e. not visiting too early, which disrupts the business unnecessarily, or too late, which leads to excess inventory accumulation. The problem is formulated as a two-stage stochastic optimization problem with recourse, with fixing the visit days in the first stage, minimizing travel, fixed and expected inventory costs, and performing the routing in the second stage, minimizing the sum of unitary excess inventory costs and penalty costs incurred by a visit to a pharmacy where the threshold inventory level has not been reached. They use a multi-start ALNS algorithm to solve their problem. The authors solve a similar problem in Nolz et al. (2014a), where, instead of using a weighted sum in the first stage, they use a bi-objective approach to minimize routing costs and expected inventory costs. Their solution approach builds on their previous work.

Another real-world IRP with stochastic demands is described by Markov et al. (2020). They have a sensor in each bin which sends information on the fill level once each day. As the goal is to reduce overflows and route failures, they model the dynamic probability-based cost of these events and incorporate it into the objective function, thus minimizing the sum of expected overflow and emergency collection cost, routing cost and the expected route failure cost. The problem is then solved with an ALNS with an integrated forecasting model.

In Mes et al. (2014), the authors deal with a stochastic and dynamic WaCo IRP where travel times are stochastic and dynamic collection is made possible by the assumption that all underground containers are equipped with sensors. In addition to the standard IRP, they allow containers to overflow and minimize transportation, handling and penalty costs incurred by overflows. Containers are categorized into three types, depending on their fill level and how urgent they need to (or shall not) be picked-up to avoid overflow penalties. They use a heuristic based on these urgency types to decide which containers to pick up on which days, and tune their input parameters with optimal learning techniques.

3.6 Pick-up and Delivery Problems

Most WaCo problems are best modelled as VRPs, ARPs, or IRPs. However, one reason for using a PDP model is the presence of different pick-up or delivery locations for the transported units. This is usually only given if containers are not emptied when serviced but rather transported as a whole, or when containers, bins, or skips have different destinations depending on their type of waste and ownership (e. g. a customer wants *their* empty bin back instead of a generic empty bin). We want to point out here the similarity to RRVRPs found in Sect. 3.26. We have come across only a single paper modelling a WaCo problem as a PDP, namely Wøhlk and Laporte (2022). They solve the problem of transporting skips between recycling centers and treatment facilities with some kind of roll-on/roll-off vehicle. Depending on the content, skips are picked-up and brought to a corresponding recycling center. Once emptied, they are either brought back to their original collection point, or to any other collection point where a skip of equal type was picked-up from, depending on the property situation. The authors model both versions mathematically and develop a VNS which they apply to real-life instances in Denmark.

4 Recent developments

In this section, we attempt to highlight academic research that presents new developments in the field of WaCo. These encompass the use of sensors, changes to traditional delivery and collection systems to incorporate the collection of waste into existing replenishment routes, and the composition of vehicle fleets.

4.1 Sensors

There have been recent developments in the literature on WaCo routing that focus on the use of sensors to improve route planning and decision-making. The approach that has gained the most attention is the use of sensors to track the fill levels of waste bins, which can help to optimize routes by only sending vehicles to collect full waste bins. This results in a dynamic collection problem, often modelled as a *reverse* IRP, where the flow of goods is reversed (i. e. collecting instead of delivering goods) and overflows might happen instead of stockouts, and often assume full sensor coverage (Hannan et al. 2018; Jorge et al. 2022; Lozano et al. 2018; Mes et al. 2014; Ramos et al. 2018; Roy et al. 2022; Wu et al. 2020). Sensor data can also serve only as information about a specific point in time, while the actual fill levels are estimated, and the sequencing decisions are made based on the data obtained (Jorge et al. 2022; Ramos et al. 2018). In some cases, the sensor information is assumed to be uncertain, and the demand is modelled in a stochastic fashion (Markov et al. 2020), resulting in a stochastic reverse IRP. Equipping all WaCo bins of an area with sensors can be very costly. Therefore, before this investment is made, it is prudent to compare the operational cost of equipping or not equipping bins with sensors (Elbek et al. 2017; Johansson 2006).

Sensor placement is a key consideration. In some cases, complete coverage of all waste bins may be necessary, while, in other cases, partial coverage may be sufficient, with sensors placed on a representative sample of bins to estimate fill levels for the entire population of bins. Most literature assumes full coverage, i. e. each bin is equipped with a sensor. This assumption is often not realistic due to the number of bins and the resulting high financial investments. In this case, one either has to decide on the number of sensors to use, or assume a fixed number of sensors and only decide on where to place them (Lopes and Ramos 2023). The decision on which bins to equip with sensors may also be externally given, e. g. if some bins are considered a priority because they are close to public buildings or in tourist areas (Anagnostopoulos et al. 2015), or based on optimization requirements (Cubillos et al. 2022), e. g. bins with high demand or far from the depot. However, obtaining predicted demands for bins without sensors is not trivial, but recent methods for predictions seem promising (Cubillos et al. 2021). Finding the optimal placement for a limited number of sensors can be an optimization problem of its own and can be considered as a tactical decision for the subsequent routing problem. Hoogendoorn et al. (2022) consider the problem of deciding which bins to equip with sensors and analyze their impact on the collection planning by using, for the first time in the related literature, an exact stochastic solver for routing optimization. Several important insights into the nature of the problem and settings were obtained by the computational results, where also potential sensor inaccuracy is taken into account.

In many cases, only one sensor value per day is used, as in standard IRP models the inventory level is usually considered at only one point in time per day. However, most types of sensors provide more frequent readings, allowing for more accurate modelling and better demand forecasts. Considering a continuous rate of the demand, as is proposed by Alarcon Ortega et al. (2020) and Alarcon Ortega and Doerner (2023) for the (stochastic) IRP, could also be beneficial in WaCo. For example, for locations that are serviced every second day, it makes a considerable difference whether the site is visited at the beginning or at the end of the day. In these cases, it is conceivable that continuous modelling of demand could help prevent overflows and enable better route planning in general.

4.2 Circular economy

One of the main challenges in WaCo routing is to design efficient, cost-effective and environmentally sustainable routes. This is particularly important in the context of recycling and circular economy, as the collection and transportation of recyclable materials can be resource-intensive and generate a significant amount of greenhouse gas emissions. Usually, the delivery of new goods or fresh products is planned and operated separately from WaCo, except for long-established deposit systems like the milk run. In terms of efficiency, simultaneous pick-ups and deliveries have a lot of potential, like it has been applied to the simultaneous newspaper distribution and recycling (Osaba et al. 2017), medical goods distribution and pharmaceutical WaCo (Osaba et al. 2019), and fresh produce delivery and empty packaging collection (Kumar et al. 2022). With these problems, the main challenge is considering the often unknown quantities that need to be collected. A possible solution approach is the use of a lasso solution strategy where in the first part of the route, capacity is created by delivering goods to customers, thus enabling simultaneous pickups and deliveries for the second part of the route, and finally revisiting the first customers for the remaining pickups (Hoff et al. 2009). WaCo routing can play an important role in the circular economy by combining the delivery and collection of various goods, leading to less driven distance. This can help to reduce the environmental impacts of WaCo and promote the development of a more sustainable supply chain.

4.3 Hybrid and electric vehicles

There has also been a focus in recent literature on the use of hybrid and electric vehicles in WaCo routing problems. The use of those vehicles offers several potential benefits over traditional carbon fuel-powered vehicles, including reduced fuel costs, lower emissions and lower maintenance costs. Important aspects are the range of the vehicles and the availability of charging infrastructure and thus the optimization of routes with these restrictions in mind, while also deciding between full or partial charging, as a full charge usually takes a long time. Between fuel vehicles and electric vehicles, electric vehicles have been shown to be more cost-efficient (Yang et al. 2022), especially in combination with multiple compartments. Furthermore, between fuel, electric and hybrid vehicles, the latter are offering the most flexibility (Masmoudi et al. 2022). Since a WaCo company will not upgrade its whole fleet at once, and different vehicle types have different distance and capacity constraints, a look at combined fleets is recommended (Książek et al. 2021). Overall, the use of alternative fuel vehicles in WaCo routing is a promising area of research that has the potential to significantly improve the sustainability and cost-effectiveness of WaCo operations.

5 Outlook

The field of WaCo routing has made significant progress in recent years with the adoption of advanced technologies such as sensors and algorithms that have helped to improve the efficiency, sustainability and quality of this important service. However, there is still much work to be done in this area, and there are many promising opportunities for future research and development.

Artificial intelligence and machine learning methods could be better utilized and integrated into the optimization algorithm to further optimize routes and schedules. The use of these methods can help, for example, to optimize routes in real-time or create better schedules, by taking into account factors such as traffic conditions or weather forecasts. They are also especially promising for fill level prediction, particularly in combination with area coverage estimations. Literature for new methods is quite scarce in routing problem in general (see Abdallah et al. (2020) for a recent survey) and although first steps of using such technologies have been made (Accorsi et al. 2022), it has not been applied to a WaCo context.

The explicit consideration of greenhouse gas emissions should be brought more into focus. These are affected not only by distance but also by the type of collection, waste and transportation mode (Eisted et al. 2009). Considering findings like these might result in changes in strategic decisions that can have a vast and long-lasting influence on greenhouse gas emissions.

In order to make routing solutions as realistic as possible, it is important to include precise estimations of various parameters. One of those parameters is the service time, e. g. the time of loading or unloading the WaCo trucks. Most often a single value is given, independent of vehicle or bin type. First steps into identifying system characteristics and their influence on service time have been made (Carlos et al. 2019; Giel and Dąbrowska 2021) and we advocate for a widespread inclusion of these results in future WaCo routing research with the aim to generate more precise and more practicable solutions.

Planning simultaneous pick-ups and deliveries as part of a circular economy is important for reducing transportation in WaCo because it allows for more efficient routes and fewer vehicles on the road. By coordinating pick-ups and deliveries, the amount of time and resources spent on transportation can be reduced, ultimately leading to cost savings and a reduction in emissions. However, we have identified a research gap in the area of PDPs in WaCo, since circular economy and simultaneous pick-ups and deliveries have not been studied much in this context or have not been modelled as such.

In practice, WaCo plans are often repeated. This has the advantage that both people and businesses can adjust to the time of collection and that drivers and teams can work *their* routes efficiently. Nevertheless, we were surprised to find that the majority of the literature does not consider multiple periods or periodic schedules. Here we also see potential for further research.

Other real-world aspects have received little attention in the literature so far. Overflowing bins, for example, often occur in practice but should usually be avoided. With more accurate demand estimates and their integration, further methods could be developed that try to avoid overflows. Another example is the one of split collections, e. g. to avoid route failures due to capacity constraints, or when large quantities have to be collected. Split deliveries are a common characteristic in VRP literature, but have rarely been considered as split collections in the field of WaCo routing.

Overall, the future of WaCo vehicle routing is bright, and there is great potential to continue improving the efficiency and sustainability of this vital service. By leveraging new technologies and working collaboratively, we can make significant progress in optimizing WaCo routes and schedules, thereby contributing to more sustainable and liveable communities .

6 Supplementary information

A supplementary document is provided to this paper. It includes a list containing a collection of links with instances available for download, tables with overviews of the literature by problem type and by both problem and waste type, and several figures showing the solution methods used by the literature included for each problem type.

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Declarations

Conflict of Interest None.

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