Municipal Solid Waste Collection and Management Problems: A Literature Review

Article *in* Transportation Science · November 2012
DOI: 10.1287/trsc.1120.0448

3 authors:

Jeroen Beliën
KU Leuven

Liesje De Boeck
University of Leuven, campus Brussels

Jonas Van Ackere
KU Leuven

Municipal Solid Waste Collection Problems: A Literature Review

Jeroen Beliën
Liesje De Boeck
Jonas Van Ackere

HUB RESEARCH PAPERS 2011/34
ECONOMICS & MANAGEMENT
DECEMBER 2011

Municipal Solid Waste Collection Problems: A Literature Review

Jeroen Beliën[1,2,*], Liesje De Boeck[1,2], Jonas Van Ackere

[1]Hogeschool-Universiteit Brussel, Faculty of Economics and Management, Research Center for Informatics, Modelling and Simulation, Warmoesberg 26, B-1000 Brussels, Belgium, 0032(0)26098271,

jeroen.belien@hubrussel.be, liesje.deboeck@hubrussel.be

[2]Katholieke Universiteit Leuven, Faculty of Business and Economics, Department of Decision Sciences and Information Management, Research Center for Operations Management, Naamsestraat 69, B-3000 Leuven, Belgium

*Corresponding author

This paper presents a review of the available literature on solid waste management problems, with a particular focus on vehicle routing problems. The available papers are classified into different categories with the purpose of providing the reader with a guide that facilitates his/her search for papers in his/her field of interest. For each category, a table is presented that gives a summary of how each paper scores from that perspective. Additional explanation is presented about the characteristics of each category using some key references. Finally, this paper discovers unexplored areas of research and identifies trends in the literature.

Key words: solid waste, vehicle routing problems, literature review

1. Introduction

The time waste was just some kind of leftover that had to be disposed of is long gone. With the realization that our resources are not inexhaustible came the awareness that our waste offers economic opportunities that have to be taken advantage of. While the recycling goal for some products containing glass, metal, etc. is clear, it is important to point out that even the garbage we put outside can be used to make electricity or can be used in other useful products.

While emphasizing the durability of waste, we have to think about running the waste cycle efficiently too. Waste management is more than just collecting waste. It is the collection, transport, processing, recycling, disposal and monitoring of waste materials. Numerous factors, such as environmental, economic, technical, legislational, institutional and political issues, have to be taken into consideration. Several important decisions have to be made. Amongst them is the opening of a new facility as available locations are becoming increasingly more scarce, or the expansion of a current facility. Secondly, we have to allocate trucks to certain disposal facilities. Thirdly, we need to develop efficient routes. Naturally, collection is the most important and costly aspect of the cycle because of the labor intensity of the work and the massive use of trucks in the collection process. According to Clark and Gillean [1] and Or and Curi [2], the collection activity accounts for approximately 80 % of all costs associated with waste disposal. Consequently, this paper gives a review of the available literature on waste management problems with a special focus on the collection of municipal solid waste. Literature about facility location and truck allocation are included as well to point the reader to the importance of these issues.

In the past, solid waste collection was carried out without analyzing demand and the construction of the routes was left over to the drivers. Cities, however, continue to expand. Because of this ongoing urbanization, the importance of an efficient collection system only increases. Optimally, there should be a method that tries to maximize the general acceptance of a solution. However, as this is hard to realize, different methods have been developed that focus on route length, costs, number of collection vehicles, etc.

In essence, the collection of waste is a Vehicle Routing Problem (VRP). This means that a solution has to be sought for servicing a number of customers with a fleet of vehicles. Generally, different types of models can be applied to solve the optimal routing problem: namely, linear programming, solution methods that use the Travelling Salesman approach or the Chinese Postman approach, hierarchical methods and several heuristics. A vehicle routing problem typically consists of a set of vehicles, stops and a depot. A vehicle starts from the depot, visits a number of stops and ends at the depot. Depending on the complexity of the problem one can add different characteristics such as different types of vehicles, number of disposal facilities (single or multiple), various types of constraints, etc. Two of the most basic VRPs are the Travelling Salesman Problem (TSP) and the Chinese Postman Problem (CPP). TSP belongs to the set of NP-hard problems, while CPP, can be solved in polynomial time. The addition of capacity constraints, however, turns the CPP in a capacitated-CPP, which is NP-hard too [3]. As NP-hard problems are difficult to solve, many papers rely on heuristics to solve this type of problem. Some authors choose to simplify their assumptions, therebyreducing the computation time needed to solve the problem. The TSP and CPP are explained in more detail in section 3.

The purpose of this paper is to guide the reader through the available literature on waste management problems. The different classifications in this review make it possible to select the papers of interest. If one is, for example, interested in a solution for a problem with various types of vehicles and several disposal facilities, a manuscript paperthat fits this description can be easily found. The different perspectives on the basis of which the literature is classified are the following:

- Type of waste (section 2)
- Scope (section 3)
- Solution method (section 4)
- Approach (section 5)

- Optimality of the solution (section 6)
- Type of resource (section 7)
- Disposal facilities (section 8)
- Objectives (section 9)
- Type of constraints (section 10)
- Type of analysis (section 11)
- Use of a Geographic Information System (GIS) (section 12)
- Location of the case study (section 13)

Each section concludes with an overview table in which the classifications of the publications on that specific category can be found. For the ease of the reader, the publications are put chronologically in these tables. During the search for publications, some other literature reviews were encountered dealing with VRPs in general. However, no reviews were found that specifically dealt with vehicle routing in a waste collection context. Toth and Vigo [4], for example, give an overview of vehicle routing problems with applications of the VRP in various domains, with a section dedicated to waste.

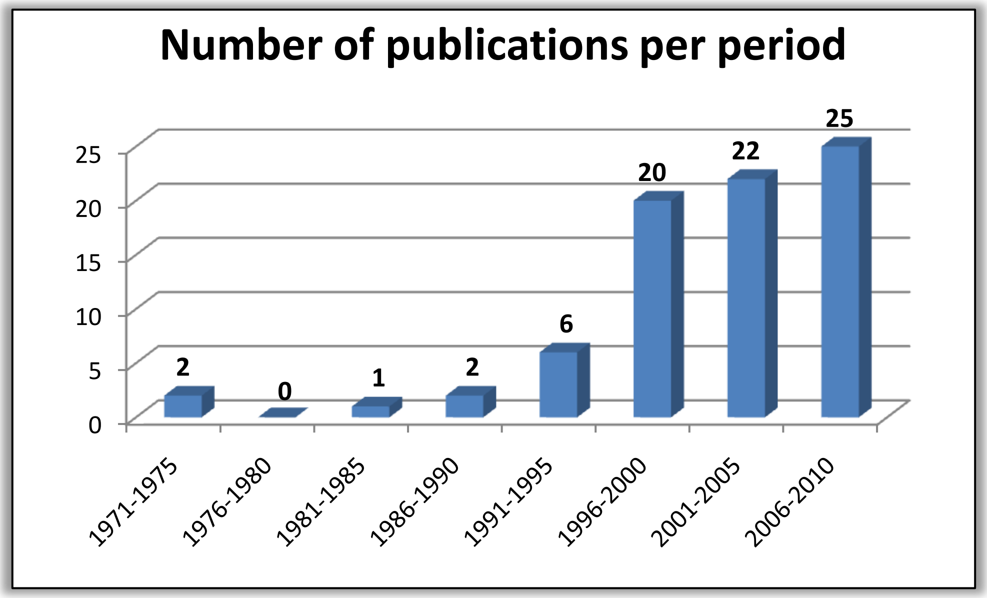

Figure 1: Overview of the evolution of the number of publications

Figure 1 visualizes the evolution of the number of publications. Papers on waste management vehicle routing problems have on the whole been published after 1995, which indicates that interest in this topic has increased from 1995 on. The majority of the papers are available in online databases like Elsevier, Science Direct, Sage, Academic Search Premier, Business Source Premier and others. After that, a screening of the references of the earlier found literature helped complete the search. By analysing the papers chronologically, trends in the type of solution method or software that was used, could be detected. The first publication regarding waste collection vehicle routing was by Beltrami and Bodin [5] in 1974. The most recent publication is by Benjamin [6] in 2010.

2. Type of waste

People associate waste collection with the periodic collection of household waste. However, the problem is more complex. Besides residential customers, waste companies also have industrial customers, whose requirements differ from typical residential wishes. Industrial customers typically produce larger amounts of waste, which requires another pick-up system. Also, the collection of recyclables is becoming increasingly important in a society where resources are perishable and environmental concern is growing. Finally, special attention is given to some publications that deal with hazardous materials. The following paragraphs provide more explanation about each type of waste.

Badran and Haggar [7] define municipal solid waste as a general term which encompasses all waste materials except hazardous waste, liquid waste and atmospheric emissions. Solid waste can be further subdivided into two general categories: residential and commercial. The residential category refers to the waste that is designated as ‘garbage’. The garbage class can be described as the waste that is gathered by the community services. The commercial category contains industrial and agricultural customers. These clients are much more dispersed and produce higher amounts of waste. The most important differentiator between residential routes and commercial routes is that the waste management company serves locations (commercial) instead of streets or quarters (residential). Moreover, the use of containers in commercial routes requires a different type of truck [8]. Bodin et al. [9] give a good summary of the differences between the residential routing problem and the commercial routing problem. The paper deals with containers that are so large that at most one container can be loaded at a time. After the loading, the container is dropped off at a disposal location. This can be an incinerator, a landfill or a recycling facility. Where commercial waste collection problems are concerned, the location of the disposal facility is more important than in the case of residential waste collection, due to the higher number of disposal trips that have to be incorporated. The use of multiple disposal locations can improve collection efficiency dramatically, because an unloading trip has to be made to a disposal location after each customer. Bodin et al [9] use a new measure to evaluate the quality of each proposed solution, namely the deadhead distance. The deadhead distance is measured by counting the distances travelling through roads that have already been travelled before. The main road to the disposal facility, for instance, is likely to be used many times.

Hazardous materials form the next class of waste. In this category, two major subdivisions can be identified, infectious materials and toxic waste. Hospitals and medical institutions typically have to dispose of their infectious materials. These require special treatment as they have to be brought to specific incinerators. Examples of publications that deal with the treatment of infectious materials can be found in Shih and Chang [10] and in Alagöz and Kocasoy [11]. Toxic waste represents substances which must in no circumstances be exposed to the public. Nuclear waste is a good example of toxic waste. The objective in collecting toxic waste differs considerably from the objective in a vehicle routing problem involving non-hazardous materials, where costs often play the most important role. In Marianov and ReVelle [12] the optimal solution maximizes the probability of survival, while Batta and Chiu [13] follow a different approach focused on the minimisation of damage. Moreover, papers dealing with hazardous materials consider totally different influencing factors. Batta and Chiu [13], for example, incorporate the impact of wind speed.

The last type of waste concerns recyclables. Recyclables relate to the concept of reverse logistics, which can be defined as the process of planning, implementing and controlling the efficient flow of goods and related information from the point of consumption to the point of final disposal [14]. Discarded consumer electronic goods are collected and delivered to a recycling centre for recycling and/or final disposal. More information about routing problems for recyclables can be found in Krikke et al. [15] and Kim, Yang and Lee [16]. In the latter, an example is given of the recyclable collection system in South Korea. There, specific laws oblige manufacturers of electronic goods to take responsibility of recycling their End-of-Life goods. Two different reverse logistics chains are stipulated. First, when a customer buys a new product, the old product of the customer has to be picked up and brought to the manufacturer's distribution centre free of charge. Second, a client can dispose of a product in a local authority collection centre without purchasing a new product. In this case, a fee has to be paid. The routing problem concerns the collection of the products in both types of collection centres and the planning of the routes for picking up the recyclables at the customers' homes.

The different classifications presented in this paper are sometimes related. The gathering of containers, for instance, is often related to a node routing problem (section 3) and papers that address hazardous materials often involve environmental constraints (section 10). The majority of the papers deal with garbage collection. The historical evolution shows that garbage collection formed the main focus in early studies. Later on, in the nineties, the interest in other types of waste problems increased, with a remarkable growing trend for recyclables.

Table 1 – Type of waste	
Garbage	[5] [1] [17] [18] [2] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35] [36] [37] [38] [39] [40] [41] [42] [43] [44] [45] [46] [47] [48] [8] [49] [50] [51] [52] [53] [54] [7] [55] [56] [57] [58] [59] [60] [61] [62] [63] [64] [3] [65] [66] [67] [68] [69] [6]
Skips / Containers	[70] [71] [72] [73] [74] [75] [8] [68]
Hazardous materials	[13] [27] [12] [10] [7] [11]
Recyclables	[25] [26] [76] [43] [46] [47] [52] [15] [59] [61] [77] [16]
Others / Not mentioned	[78] [79]

3. Scope

The next category deals with the scope of a publication. Models can be on a macro-scale or micro-scale level. Macro-scale modelling evaluates the entire solid waste management problem, including generation, collection and treatment. Micro-scale modelling, on the other hand, focuses on the location and assignment of different transfer stations to different processing and disposal sites and the establishment of routes for collection vehicles [21]. All papers in this literature review fall within the micro-scale category. In this category, we consider four subdivisions: case study, facility location, truck allocation and collection routing. The purpose of this perspective is to point the reader to the main theme of a paper. The majority of the publications focus on collection routing as this has the most impact.

Papers classified under case studies apply the solution presented to a real-life problem or to a hypothetical problem with invented data. An overview of the locations of the different real-life cases will be given in section 13. The importance of case studies is undeniable as 53 out of 78 publications use a case study to clarify their findings and to demonstrate the practical effect of their method.

The second subdivision gives examples of publications that consider facility problems. Facility problems can be divided into facility location problems and facility expansion problems. Finding a suitable location for a new disposal facility is often a difficult task. Increasing urbanization means land becomes more valuable. Additionally, available locations are becoming increasingly constrained by different types of environmental concerns. They are situated near certain neighbourhoods or contaminate the soil. Landfills, for example, can cause serious contamination of surface and ground water, eventually leading to public health problems. Incinerators or waste-disposal facilities, on the other hand, are detrimental to public health through air pollution emissions [25]. The model needs to incorporate the wishes of city boards, waste management companies, environmental activists, etc. Because their wishes can be very conflicting, multi-criteria decision analysis can be used to solve the facility location problem. Cheng, Chan and Huang [42], however, warn readers about the weaknesses of this method. After the application of the multi-criteria decision analysis, further analysis is required as input is based on subjective opinions of decision makers. Besides the location of a new facility, facility problems also address the expansion of existing disposal facilities. The future evolution of waste generation is a crucial factor for facility problems. As waste generation cannot be predicted precisely, uncertainty plays an important role in these kinds of problems. Section 5 will elaborate on the topic of uncertainty in waste collection problems. Of the 78 papers, 19 facility location papers were selected.

Papers on truck allocation problems study how trucks should be assigned to disposal sites. Not only is the capacity of the vehicles a determining factor, but the capacity of the disposal facilities also plays a major role. If travel distances were the only criterion for deciding the allocation of trucks to disposal sites, then allocating each truck to the nearest disposal facility solves the problem. However, such an allocation would tend to produce large queues at favoured disposal sites. Hence, mathematical models need to be developed to provide city administrators with a tool to make effective long-and short-term decisions relating to their municipal disposal system [24]. In truck allocation problems, the decision to be made is not the routing of the trucks but the timing of disposal trips. Letting a truck return to the disposal facility before its capacity is reached could assure that the truck is unloaded at a non-peak moment. Bhat [24] discussed how to deal with a problem with multiple disposal facilities, some with a more favourable location than others. Li, Borenstein and Mirchandani [65], on the other hand, solved a case with only one disposal site. The main objective of this paper is consequently the minimization of queuing at the disposal facility, while minimizing the fixed truck costs. Huang, Baetz and Patry [33] give an example of how to solve the truck allocation problem with grey programming. Grey programming is explained further in section 4. Truck allocation problems account for 13 publications.

The last and most important subdivision addresses collection routing problems. The introduction already gave some explanation about collection routing. Three types of waste collection routing problems can be further distinguished: communal site collection, container collection and kerbside collection. In communal site collection, a public place is marked by the local authority and it is shared by communities for dumping their solid waste. An example of this type of problem is discussed in Tung and Pinnoi [37]. The second type of collection routing problem is the solution method typical for industrial clients, where skips or containers are collected. The collection vehicles often have a specific loading device installed and have a capacity for only one container. An example can be found in Bodin et al. [9]. The third and probably best-known type of collection routing problem is kerbside collection. Householders put out their waste bins and retrieve them after the collection is carried out by the vehicle. The collection vehicles pass every street to pick up the garbage at a preset date. This is discussed in Sniezek and Bodin [56].

In communal site collection and container collection, collection vehicles only visit predetermined pick-up points. In kerbside collection, on the other hand, every house needs to be visited. Consequently, the number of spots to visit in communal site collection and container collection is significantly lower than the number of customers served in kerbside collection. A second difference between both collection systems is that they serve different types of clients. Container collection serves industrial clients, who generally have a greater amount of waste that needs to be disposed of, sometimes containing hazardous materials. Moreover, they are more dispersed around town. Kerbside collection, on the other hand, serves numerous residential customers, who typically have a small demand. Therefore, communal site collection and container collection problems are more suited to being modelled as a variant of the Travelling Salesman Problem (TSP), while kerbside collection problems are more suited to being modelled as a variant of the Chinese Postman Problem (CPP). The TSP identifies the least cost route of a single vehicle that includes every node in the network and then returns to the starting node. Unfortunately, this basic routing problem belongs to the set of NP-hard problems. The CPP identifies the least cost route of a single vehicle that includes every arc in the network. The CPP can be solved in polynomial time. Several assumptions are made in the TSP and the CPP that are not realistic for many practical vehicle routing problems. Firstly, they both assume that the vehicle has no load or time capacity constraint. Secondly, they assume that demand exists at every node in the network (TSP) or along every arc in the network (CPP). These assumptions are not appropriate in the waste collection context. Unfortunately, relaxing these assumptions makes the problem more difficult to solve. For instance, adding capacity constraints to the CPP results in a capacitated CPP which is a NP-hard problem. Consequently, TSPs are categorized as node routing problems, while CPPs are categorized as arc routing problems.

The model that most closely resembles the setting of kerbside collection is the Capacitated Arc Routing Problem (CARP). In this problem, a certain demand is specified for each arc. Moreover, there is a capacity constraint on the total demand a vehicle can serve. CARP belongs to the class of NP-hard problems too. Nuortio et al. [54] distinguish the arc routing and node routing problem in more detail. Population density, for example, can play a role in deciding which type to choose. Another important factor is the amount of detail required. If the problem data (capacities, demand) are specified in terms of streets, the arc routing modelling approach is more appropriate. If, on the other hand, the problem data (capacities, demand) is specified in terms of bins, the node routing approach is more likely to be adopted.

The node routing approach is, with 25 publications out of 53, slightly more used than the arc routing approach, which is applied by 23 papers. This can be explained by looking at evolution through time.

Node routing approaches were already studied in a waste collection context before 1990, while the real breakthrough for arc routing is only in the mid-nineties. 5 publications could not be categorized as there was not enough information to distinguish between a node-routing approach and an arc-routing approach.

When we take a closer look at the evolution of the different type of problems through history, it is remarkable that it took quite a while for collection routing to become popular. Except for the publication in 1974, it takes until the period 1996-2000 for collection routing to reappear in the literature.

Table 2 - Scope		
Case study	[1] [17] [18] [2] [26] [20] [21] [26] [29] [31] [76] [32] [33] [34] [35] [36] [37] [10] [38] [40] [41] [43] [80] [45] [72] [46] [47] [48] [74] [8] [49] [50] [51] [52] [53] [54] [7] [55] [56] [57] [11] [58] [59] [60] [61] [62] [77] [64] [3] [65] [68] [69] [16]	
Facility	[17] [2] [26] [20] [22] [23] [25] [26] [27] [79] [32] [35] [36] [38] [40] [42] [43] [7] [61]	
Truck allocation	[17] [13] [24] [29] [33] [35] [36] [80] [52] [53] [61] [77] [65]	
Collection routing	Node-Routing	[5] [28] [78] [30] [70] [76] [32] [9] [10] [40] [41] [44] [80] [71] [72] [73] [8] [49] [54] [55] [57] [11] [66] [69] [6]
	Arc-Routing	[18] [12] [31] [34] [36] [37] [38] [39] [45] [46] [47] [48] [74] [50] [56] [58] [46] [63] [64] [3] [67] [68] [16]
	Unclear	[51] [52] [15] [59] [60]

4. Solution method

The solution method category is the most extensive of all categories. This indicates that there is no perfect method to solve the type of problems mentioned in the previous section. There are methods that solve the problem to optimality, but the computation time of these solutions increases exponentially. Consequently, heuristic methods have been studied extensively. The solution methods can be divided into three major parts. The first part deals with methods that employ mathematical programming techniques, while the second part addresses heuristic methodologies. Finally, the last part includes all methods that could not be classified under the first two parts. Table 3 presents an overview of the different solution method categories.

Table 3 – Solution method		
Mathematical programming	Linear	[12] [38] [52] [15] [65] [69]
	Mixed-integer	[2] [19] [26] [36] [9] [10] [42] [72] [8] [7] [56] [66] [16]
	Grey	[20] [22] [23] [33] [43]
	Non-Linear	[53]
	Dynamic	[38] [73] [55]
Metaheuristics	Local search / Neighbourhood search	[37] [44] [71] [45] [72] [46] [74] [75] [8] [51] [54] [62] [69] [6]
	Tabu search	[78] [40] [41] [45] [75] [57] [64] [69] [16] [6]
	Genetic algorithms	[32] [35] [43] [44] [45] [63] [69]
	Ant colony optimization	[46] [74] [49] [57] [62]
	Simulated annealing	[27] [8]
Other heuristics	Construction heuristics	[5] [18] [70] [31] [76] [37] [9] [80] [71] [72] [47] [75] [8] [50] [51] [54] [58] [59] [62] [67]
	Clustering / Partitioning heuristics	[9] [39] [51] [52] [69]
Other solution methods	Branch-and-bound	[26] [70] [31]
	Simulation	[1] [21] [24] [28] [43] [52] [55] [61] [77]
	Other	[17] [24] [79] [29] [30] [34] [9] [73] [65] [67]
	Unclear	[13] [25] [48] [11] [59] [60] [3] [68]

4.1. Mathematical programming

Mathematical programming or optimization is a set of methods developed to choose the best solution out of a set of alternatives. Basically, it seeks to maximize or minimize an objective function by choosing the values of real or integer variables. Meanwhile, several subfields and adjustments have come into existence, some of which are used in publications in this review.

Linear programming is the most basic form of mathematical programming. The objective function is linear and the constraints are equalities and inequalities that are linear too. Marianov and ReVelle [12] describe a linear programming model in a hazardous context. The model tries to find the route with the minimal cost and the minimum probability of accident. The downside of this type of model is demonstrated by Simonetto and Borenstein [52]. They showed that their linear programming formulation could not be solved within a reasonable computation time, because it had too many variables and constraints. Therefore, they developed a heuristic as well as a linear programming formulation. Krikke et al. [15] give an example of a linear programming model that is used in a recyclable waste context. They develop a linear model such that all orders with high priority are fulfilled at minimal cost. Costs seem to be the most appropriate objective function for linear models as 5 out of 6 papers have it as their main objective.

The most prominent class of mathematical programming used is mixed integer programming (MIP). In this review, thirteen publications mention the use of a mixed integer programming formulation. The 'mixed' indicates that some, not all, of the variables are subject to integrality constraints. Chang, Yang and Wang [19] give an example of an application of a MIP-formulation. They apply it to a facility location problem taking into account traffic congestion and noise control constraints. These constraints will be explained in section 10. Their main objective is to minimize costs taking into account discounted cash flows of all quantifiable benefits and costs over time. While the MIP approach is more appropriate for solving facility location problems, there are also examples of collection routing problems using MIP. Sniezek and Bodin [56], for instance, use a MIP-formulation to solve a Capacitated Arc Routing Problem (CARP). They too bump into the boundaries of mathematical programming as they diagnose that they could not solve problems having more than 500 arcs and 10 vehicles. Therefore, they use their model as an improvement procedure. For large problems, they extract a set of routes from a solution and solve a variant of the model over this region. Then, they replace the old routes by the new routes and repeat the process. A region with, for example, 2000 arcs and 40 vehicles can be solved by selecting five routes containing approximately 200 arcs. Subsequently, they resolve that portion of the network using their model while keeping the remainder of the solution fixed.

Municipal solid waste management includes a variety of factors. Many of these factors are subject to uncertainty. Moreover, the required information may not be known beforehand. Examples of such factors are uncertain waste generation and variable incinerator capacity. Most mathematical programming models solve this problem by using deterministic estimations of those values. An alternative approach is to mitigate the above problems by introducing the concept of grey systems and grey decisions into a grey mathematical programming framework (GMP). The GMP approach allows uncertain information to be directly communicated into the optimization processes and resulting solutions. Hence, feasible decision alternatives can be generated through the interpretation and analysis of the grey solutions according to projected applicable system conditions. A complete explanation of grey programming can be found in Huang [20]. Five publications that use GMP are included in this review, all of them written by Huang. Four of them deal with facility location, while the last one addresses truck allocation [33].

The last two types of mathematical programming are less frequently used. The first is the non-linear approach. The unit cost of processing garbage, for example, is not linear in time, as economies of scale or economies of scope reduce the cost of handling waste. Most papers ignore this as non-linear problems are more difficult to solve. Wu et al. [53], however, introduce a non-linear objective function for this problem. The last type of mathematical programming is a dynamic programming approach. This approach divides the main problem into several subproblems, each of them solved separately.

With 28 publications, mathematical programming represents an important part of the solution methods. Most publications that utilize mathematical programming address facility location. This suggests that heuristic approaches are more appropriate for collection routing. The categorization of the different mathematical programming models can be found in table 3.

4.2 Heuristics

Heuristics can be further classified into two important subdivisions. Section 4.2.1 discusses the class of metaheuristics, while section 4.2.2 describes construction and partitioning heuristics.

4.2.1 Metaheuristics

Metaheuristics try to find a good solution by iteratively improving a candidate solution. Because they make no or few assumptions about the problem being optimized, metaheuristics can search very large spaces of candidate solutions. The metaheuristics that have been studied in the context of waste collection include local search heuristics, tabu search algorithms, genetic algorithms, simulated annealing and ant colony optimization. We encountered 38 papers that use some kind of metaheuristic.

The most popular class within the metaheuristics are the local search heuristics. Local search tries to find a better solution by iteratively exploring the neighbourhood of the current solution. Fourteen papers use this type of algorithm. Bianchessi and Righini [75] present a local search algorithm using different types of neighbourhoods. Examples of neighbourhoods are all solutions created by deleting a customer from one tour and inserting him/her into another tour, or solutions created by the replacement of two arcs by two other ones.

Tabu search is the second most popular heuristic amongst the metaheuristics. Ten papers apply it. It uses a local search procedure until a stopping criteria has been satisfied. A tabu search heuristic, however, explores regions of the search space that are left unexplored by a standard local search procedure. Tabu search allows non-improving neighbourhood moves. By means of a tabu list, a short-term memory is held of the solutions that have been visited in the recent past. This way cycling or getting stuck at a local optimum is prevented. Bianchessi and Righini [75] apply their tabu search heuristic to an example that focuses on the number of collection vehicles. They conclude that the introduction of the tabu mechanism yields a sensible improvement compared with local search algorithms. The tabu search performed between 3 and 11% better in costs at the expense of an increase in computing time of about two orders of magnitude.

The next category includes genetic algorithms. These algorithms try to find potential solutions by mimicking natural evolution. Earlier solutions are used as parents to create kids by means of genetic operators like crossover, mutation, inheritance and selection. The algorithm starts from a population of candidate solutions. In the context of waste collection vehicle routing, such a candidate solution might represent a series of clients that have to be serviced. By applying genetic operators, new client series are created that inherit certain characteristics of their parents. Different objectives are possible within genetic algorithms. Chang and Wei [32] focus on minimization of distance travelled by collection vehicles as well as average walking distance to drop-off stations. Maniezzo [45], on the other hand, considers costs as the most important objective. Except for the publication of Chang and Wei [32] all publications assume a deterministic problem setting. Chang and Wei [32] present a stochastic approach, which deals with the uncertainties encountered in the waste planning process.

The fourth category of heuristics are the ant colony optimization methods. These simulate the behaviour of ants in their search for food. While wandering around, ants produce a pheromone trail. This trail is used by other ants to determine the shortest path. The pheromone trail of the shortest path will be stronger because the ants who return to the colony by this road will refresh the pheromone trail sooner than the ants who opted for a longer path. The higher pheromone level causes more ants to choose the short path and, eventually, a shortest-path is established. The same pheromone logic can be applied to vehicle routing problems and, consequently, in waste collection routing problems too. The ant algorithms can have different objectives. Karadimas et al. [49] describe an ant colony optimization strategy for minimizing collection time, while Bautista and Pereira [46] minimize the route length. Implementing forbidden turn constraints in ant colony optimization seems to be easier compared to other models, as three out of five publications implement this feature. More information about forbidden turns can be found in section 10, which deals with different types of constraints.

There are only two examples of papers that employ a simulated annealing heuristic, one for facility location by Muttiah, Engel and Jones [27] and one for collection routing by Sahoo et al. [8]. The logic of the heuristic has its origin in the annealing process in the metallurgic industry.

4.2.2. Construction and partitioning heuristics

Besides metaheuristics, there are two other types of heuristics that appear frequently. The first type contains construction heuristics and the second partitioning or clustering heuristics.

A construction algorithm is an algorithm that determines a tour according to some construction rules, but does not try to improve this tour. Figure 2 gives an example of a nearest neighbour construction heuristic. The heuristic chooses each time the node nearest to the present node as the next customer to visit. In practice, this type of heuristic is combined with a metaheuristic which takes the candidate solution of a construction heuristic as the solution to start from. That way, by combining construction heuristics and metaheuristics, close-to-optimal solutions are found. Amponsah and Salhi [47] give an example of a construction heuristic. They developed an algorithm that considers environmental aspects in solving the waste collection problem for developing countries.

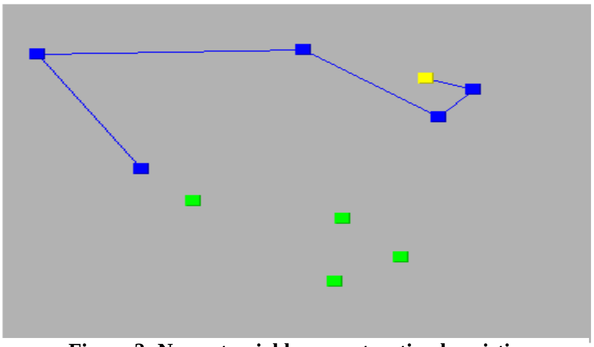
Figure 2: Nearest-neighbor construction heuristic

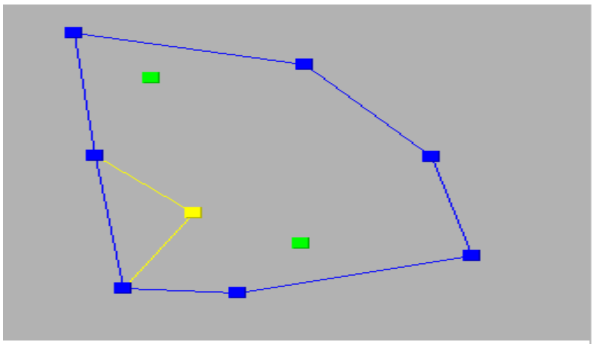
Figure 3: Insertion heuristic

Clarke and Wright developed a construction heuristic that was applied in different publications. De Meulemeester et al. [70], Hansmann and Zimmermann [67] and Beltrami and Bodin [5] all present a solution method based on the Clarke and Wright algorithm. An insertion heuristic (see figure 3) is a construction heuristic that starts with the creation of a convex hull and iteratively includes those nodes that increase the length the least. The process continues until all nodes are included. The insertion heuristic most frequently used in this review is the insertion heuristic of Solomon used by Tung and Pinnoi [37] and Sahoo et al. [8].

Partitioning and routing heuristics are frequently used in two-phase methods. They can be divided into two types: cluster first-route second and route first-cluster second. In the first type, customers are clustered into groups and assigned to vehicles (phase I), after which efficient routes are designed for each cluster (phase II). In the second type, one constructs a travelling salesman tour through all the customers (phase I) and then partitions the tour into segments (phase II). One vehicle is assigned to each segment and visits the customers in accordance with the order in the travelling salesman tour. Generally, if there are a few tours to be formed with many pickup points on each route, it is more effective to form a giant tour and then partition the tour. If many tours have to be created, with a few pickup points on each tour, partitioning tours first will normally generate better results [5]. There are five papers that mention the partitioning strategy, mainly published after 2000. Arribas, Blazquez and Lamas [69] apply a cluster first-route second approach, by executing a bin clustering method followed by a local search improvement in phase I. In phase II, they apply a tabu search heuristic for the routing of the vehicles assigned to each cluster.

4.3 Branch-and-bound

The branch-and-bound method is utilised by three different publications. De Meulemeester et al. [70] developed an exact branch-and-bound algorithm to solve a complex routing problem associated with the collection and delivery of skips. They applied it successfully to random instances involving up to 160 customers. Their branch-and-bound method was capable of optimally solving a real-life problem in less than one second. Besides the development of an exact solution, they tested two other heuristics and compared the results with their optimal solution.

4.4 Simulation

Simulation was used in eight of the 78 papers and has applications in the three different domains (facility location, truck allocation and collection routing). Johansson [55], for instance, uses a stochastic discrete-event simulation model to solve a scheduling and routing problem. Simulation often allows for a relaxation of the assumptions made in analytical models, heterogeneous sets of containers and more complex planning policies.

4.5 Other solution methods

The papers classified under 'other' apply a unique solution method. There are several examples of papers in the 'other' class. Chang, and Wei [30] wrote a paper about Compromise programming. Ronen, Kellerman and Lapidot [17] use the model of Schuster and Schur. Eisenstein and Iyer [29] apply a Markov decision process and a continuous approximation method was used by Torres and Anton [34]. The heuristics that cannot be categorized in one of the previous categories are included in this category. The paper of Li, Borenstein and Mirchandani [65], for instance, uses an auction algorithm followed by a dynamic penalty method.

4.6 Unclear solution methods

The 'unclear' class is preserved for the publications for which it was impossible to determine the solution method. This can be due to several reasons. Sometimes the solution method cannot be distilled from the offered information. The paper of Ghose, Dikshit and Sharma [48] and the one of Santos, Coutinho-Rodrigues and Current [3] are examples of this. Another reason for a categorisation in the unclear class, is that the authors use a software program. Software developers, however, are reluctant to reveal the specifics of their program. Consequently, it is impossible to distract the solution method. MapInfo and Roadnet [11], LogiX [59], RouteView Pro™ [60] and Copert [68] are all examples of software applications. Some papers use the ARCGIS 3D Analyst [57], but it is known of this software package that it applies a construction heuristic.

5. Approach

The category 'Approach' distinguishes between the publications that study a purely deterministic problem setting and the publications that address a stochastic problem setting. No less than 58 out of the 78 papers employ deterministic models. When dealing with uncertain information, deterministic models use averages or fixed estimates. Stochastic models, however, incorporate uncertainty into their problem formulation. Real-life waste management collection problems are (nearly) always subject to uncertainty. For the facility location case, disposal facilities may have a stochastic capacity due to down time or failures. Truck allocation and collection routing problems are influenced by stochastic waste generation, traffic circumstances, etc. Grey programming is a mathematical modelling approach that incorporates uncertainty. Consequently, all the papers classified under grey programming with respect to the solution method are stochastic. Instead of using one fixed estimate for uncertain data, the grey programming approach works with lower and upper bounds. Reliable bounds can be obtained through interviews with experts, a process which improves the robustness of the model. The paper of Batta and Chiu [13] deals with the transportation of hazardous materials. The paper develops a deterministic model that is improved later on by introducing probabilistic information. The deterministic model tries to minimize the weighted distance travelled through streets situated within a threshold distance of population centres. Their stochastic model, on the other hand, incorporates the probability of accidental leakage. This way, the objective changes to the minimization of expected damage.

With respect to the evolution of deterministic and stochastic publications, we can see that the number of stochastic models remains fairly stable. After 1995, however, deterministic problems become more popular.

Table 4 - Approach	
Stochastic	[13] [20] [22] [23] [28] [29] [32] [33] [38] [53] [55] [61]
Deterministic	[5] [1] [13] [17] [18] [2] [19] [25] [26] [27] [30] [12] [34] [36] [9] [10] [39] [40] [41] [42] [43] [44] [80] [71] [45] [72] [46] [47] [73] [48] [74] [75] [78] [8] [49] [50] [51] [52] [54] [7] [56] [57] [11] [15] [58] [59] [60] [62] [63] [64] [3] [65] [66] [67] [68] [69] [16] [6]

6. Optimality of the solution

Exact solution methods can guarantee detection of the optimal solution. Several authors developed exact solution methods for waste collection problems. Dell'Amico et al. [73], for instance, present an exact dynamic programming model in a recyclable waste routing context. Based on computational experience, however, they admit that their dynamic programming model is impractical even for small-size problem instances. Consequently, authors rely on software to obtain an optimal solution for their problem. Ustundag and Cevikcan [66], for instance, use the Optimization Xpress Solver to find an optimal route in a municipal waste collection setting. Exact solution methods are often highly sensitive to growing problem dimensions. Although solutions using non-exact methods are only close-to-optimal, they require significantly less computation time. This makes them more applicable in reality. As in every business, time is money and waste management companies do not always have the time to run a model for days when adjustments need to be made quickly. Hence, the number of publications offering approaches that result into non-optimal solutions is considerably higher than the number of publications that present an exact method. Non-optimal solutions were applied by 63 papers while the number of publications with optimal solutions is only 13. In three papers, the optimality of the solution was unclear or irrelevant.

Table 5 – Optimality of the solution	
Optimal	[13] [26] [70] [33] [34] [10] [73] [48] [7] [56] [15] [66] [68]
Non-optimal	[5] [1] [17] [18] [2] [20] [21] [22] [23] [25] [19] [27] [28] [78] [79] [29] [30] [70] [12] [31] [76] [32] [35] [37] [9] [38] [39] [40] [41] [42] [43] [44] [80] [71] [45] [72] [46] [47] [73] [74] [75] [8] [49] [51] [52] [53] [54] [55] [57] [11] [58] [59] [60] [61] [62] [63] [64] [3] [65] [67] [69] [16] [6]
Irrelevant / Unclear	[24] [36] [77]

7. Type of resource

In a collection routing context, the collection vehicles are the resources. By choosing only one vehicle with a fixed capacity, the problem setting is considerably simplified. Bommisetty, Dessouky and Jacobs [76] solve the recyclable waste collection problem at an American university. Because of the limited amount of waste that needs to be collected, there is only one collection vehicle available. In many applications, however, one vehicle to collect all waste is not sufficient. Consequently, the model is extended to multiple vehicles of the same capacity. This is the typical context for the collection of containers, where the vehicle can only load one container at a time. Aringhieri et al. [72] and Bodin et al. [9] provide an example of a publication where a homogenous fleet of vehicles picks up containers.

Different capacities often correspond to different vehicle sizes. This has implications for the solution method as different vehicle classes have to be incorporated into the model. In small city centres with tiny alleys or bridges and roads with weight restrictions, it is possible that certain arcs along the network can no longer be serviced by certain vehicle classes. This is referred to as a vehicle/site dependency in the literature [56]. Vehicles can differ in capacity, daily capital cost, length of the workday, crew size, loading system and other characteristics. The loading system, for instance, impacts the size of the network. Some vehicles require that refuse bags are thrown in at the side of the vehicle (side-loading) while other vehicles require that employees throw in the refuse bags at the back of the vehicle (rear-loading). Traversing an arc with a side-loader implies that only one side of the road has been cleared. This means that each edge in the network has two arcs of opposite direction, corresponding to the left and the right side of each street. Traversing a street with a rear-loader, however, makes it possible to work with edges. Once an edge has been crossed, no further service is required. Angelelli and Speranza [40], for instance, exemplify this by distinguishing between three systems to pick up waste. In the traditional system, a three-man crew goes from house to house and throws the refuse bags into the rear of the truck. The second system is a side-loader system, while the third system is a side-loader system with demountable body. In this review, we classify the papers into three classes with respect to the collection vehicles: papers with multiple types of collection vehicles, papers with a single type of collection vehicle and the cases where it is impossible to determine the collection fleet characteristics.

The number of multiple vehicle papers continuously increases: 34 publications out of 78 use multiple vehicle classes, while 16 use a model with a single vehicle class. Nowadays, multiple vehicles classes are required to model realistic situations. This probably explains the downward trend for models using a single vehicle class. For 29 papers, it is not possible to determine the number of vehicle classes or this aspect is not important.

Table 6 – Type of resource	
Multiple	[1] [17] [2] [26] [21] [22] [23] [28] [30] [33] [34] [36] [38] [39] [40] [45] [49] [73] [48] [75] [8] [50] [51] [52] [55] [11] [58] [60] [77] [64] [3] [67] [16] [6]
Single	[13] [18] [78] [29] [70] [31] [76] [9] [80] [72] [74] [56] [62] [65] [68] [69]
Not clear / Not mentioned	[5] [20] [24] [25] [26] [27] [79] [12] [32] [35] [37] [10] [41] [4] [42] [43] [44] [46] [71] [47] [53] [54] [7] [57] [59] [15] [61] [63] [66]

8. Disposal facilities

The next category deals with the number of disposal facilities incorporated into a model. A solution method for a problem with only one disposal facility substantially differs from a model for a problem with multiple disposal facilities. The difference between the two situations is illustrated in figure 4. The left part of figure 4 is an example of a problem with a single depot. Once the vehicle reaches its full capacity, the location of the collection vehicle plays no role. The vehicle always has to return to that specific disposal facility. In the right part of figure 4 however, there are three depots, which makes the problem more complex. Additional decisions have to be made. First of all, one has to choose to which disposal facility each vehicle returns (truck allocation). Second, one has to decide when a vehicle returns to a disposal facility (collection routing). When the collection vehicle is in the proximity of a disposal facility, it might be better to do the disposal trip, even when the vehicle is not fully loaded.

Although the situation with a single disposal facility seems less realistic, there are certain contexts where a method starting from a single disposal facility is desirable. If the number of disposal facilities is very small compared to the amount of waste that needs to be collected, a solution method that incorporates only one disposal facility becomes viable. Consequently, 24 papers still use a single dumping site. Amponsah and Salhi [47] describe such a context in a developing country, where there is only one disposal facility that has to service a large region. Since the handling of hazardous waste or recyclable materials requires specific care, the number of suitable disposal facilities is often limited. In these cases, a single disposal facility is not exceptional. Batta and Chiu [13] address a single disposal facility problem in a hazardous waste context, while an example of recyclable materials is given by Bommisetty et al. [76].

The number of publications that incorporate multiple disposal facilities exceeds the number of publications with a single disposal facility. While 45 papers address multiple disposal facilities, only 26 papers address a single disposal facility. The overview of the classification of this category can be found in table 7.

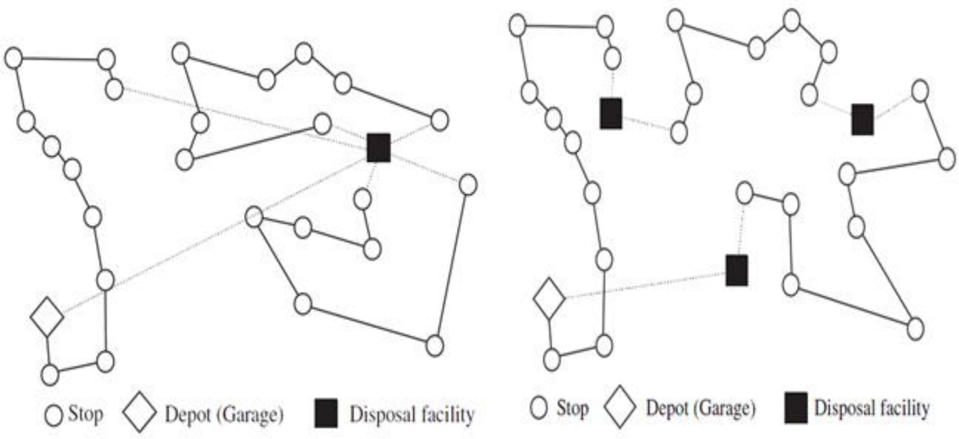

Figure 4: A single (left) vs. a multiple (right) disposal facility routing problem [63]

Table 7 – Disposal Facilities	
Single	[13] [78] [29] [30] [76] [34] [37] [9] [10] [39] [40] [72] [47] [73] [48] [50] [54] [55] [56] [62] [63] [64] [3] [67] [68] [69]
Multiple	[5] [1] [18] [2] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [79] [70] [12] [32] [33] [35] [36] [38] [41] [42] [43] [80] [71] [45] [74] [75] [8] [51] [52] [53] [7] [11] [15] [58] [59] [60] [61] [77] [65] [66] [16] [6]
Unclear	[17] [31] [44] [4] [46] [49] [57]

9. Objectives

Naturally, every publication has a clear objective. Usually, this objective is the formulation of a model that optimally solves the problem or gives a close-to-optimal solution within an acceptable time limit. Defining this optimum, however, is not straightforward. The minimization of distance, costs and time are the most frequently used objectives, but numerous papers include other kinds of objectives. Not all papers have one, clear objective. Some papers focus on route distance, but define costs as a side objective. Other papers use a multi-objective mathematical model. In recent years, the number of publications using multi-objective models has increased as the problem setting becomes increasingly complex. If a paper has a clear main objective, the number of the reference is put in italics in table 8.

The first objective is the minimization of required trucks. This objective is applicable in the situation where no fleet of collection vehicles is available. A certain number of collection vehicles is needed to serve every customer. By focussing on this objective, investments can be reduced. It is not sure, however, that costs are minimized this way. It could be more cost efficient to collect the waste with more vehicles, because costs can rise if employees are forced to work overtime due to the lack of vehicle capacity. Capital restrictions, however, might necessitate this kind of objective. Bianchessi and Righini [75] developed a model that focuses on the minimization of collection vehicles. This objective can be combined with other types of objectives. Kim, Kim and Sahoo [51] combine it with the minimization of travel time and a maximization of route compactness. Route compactness is a measure that is categorized under ‘other route objectives’, which will be explained later on in this section. The minimization of the fleet was applied by twelve of the 78 papers.

The most popular objective within this category is the minimization of costs. Facility location problems and truck allocation models are often dealt with in terms of a cost objective function. The main advantage of minimizing costs is that different types of goals can all be expressed in terms of the same monetary unit. References in italics in the costs class focus on costs, while the others have costs as a side-objective. This way, a clear division is made between papers that use them as the main objective and papers that simply use costs to compare different situations or express everything in the same monetary unit. It is, for instance, possible to convert a model that minimizes the total distance to a model that minimizes costs. A simple calculation of the saved fuel through the reduction of travelled kilometres alters the target function from kilometres to costs. The cost objective was used by 52 of the 78 papers, while only 33 publications had it as its main objective. Wu et al. [53] give an example of a model that uses the minimization of costs in a facility location problem. Viotti et al. [44] use a genetic algorithm that focuses on minimum length. However, Viotti et al. [44] admit that minimum distance is not always a guarantee for minimum costs. They clarify this with a shortest duration example. Collection during the night, for instance, will experience less traffic congestion but also higher labour costs. The collection will go faster, but it is not assured that it will be cheaper. Therefore, they decided to introduce a fitness function that evaluates solutions based on cost calculations. Thus, while their main objective is minimum distance, they introduce a cost objective to make better decisions.

The third class is preserved for the papers that incorporate environmental impact into their models. The objectives within this class are diverse: Minimizing ecological damage when dealing with hazardous materials [13], minimization of greenhouse gasses [77], minimizing fuel consumption [64] and [68], etc. Finally, a special example of a publication that addresses ecological impact is the study of waste collection in developing countries by Amponsah and Salhi [47]. As resources are limited in those countries, waste collection cannot be done as frequently as it should be. Consequently, the waste starts to decay and smell. The objective is, besides the minimization of costs, the minimization of inconvenience due to smell. This illustrates that waste collection is not similar throughout the world. Although the nature of the problem is the same, a different location can cause different implications for the model.

Hansmann and Zimmermann [67] present one of the few papers that focus on the minimization of personnel as their main objective. They use a three-phase approach, where the first phase consists of a crew minimization model. This approach can be useful in countries where personnel costs represent the main cost for waste management companies (e.g. salary costs in developed countries).

The next two objectives are often used in heuristic approaches for a waste collection problem: the minimization of the route length and the minimization of collection time. The difference between the two is that the latter takes traffic circumstances into account by focussing on time instead of distance.

The last two classes are called ‘other personnel related objectives’ and ‘other route related objectives’. Both classes include some exceptional objectives that need to be explained further. Balancing the workload among collection vehicles [17] is an example of a personnel related objective. Collection teams can get frustrated if other teams have a shorter or lighter route. By balancing the workload, the personnel stays satisfied. If a route is in a highly populated area, the waste density will be higher compared to an equally long, rural route. A possible approach to balance the workload is to compare the number of refuse bags that was picked up per kilometre [8]. Archetti and Speranza [74] give another example of an objective that is categorized as personnel related. They measure the amount of containers collected per working hour. The last example is a measure that indicates how long each crew has to wait at the disposal facility [24]. When there is only one disposal facility, it is presumable that queuing originates at that facility. When queuing each time harms the same teams, these teams start complaining. Introducing an additional objective that takes into account the waiting time of a vehicle at the disposal facility could prevent this type of problem.

The last class of objectives are the ‘route related objectives’. The paper by Ronen, Kellerman and Lapidot [17] includes, besides route related measures, personnel related measures too. The distance from the depot to the first customer or the number of left turns are examples of this. Chang and Wei [32] use a routing ratio as a performance index. The routing ratio is the ratio between the total routing distance and the total distance in the network links. Another important objective to highlight in this class is route compactness. Route compactness depicts how the stops are grouped into a route. No or less route overlap is considered more compact and more favourable. Not only are compact routes cheaper, they are also clearer for the collection route planners and drivers. Route compactness can be measured by counting the number of crossovers between different routes. Sniezek and Bodin [56] applied this measure.

Besides costs, route length is the most popular objective as 29 of the 78 papers focus on route length. While costs have been popular since 1970, the increase in route length papers only began after 1995. With increasing attention towards the environment, it is peculiar that environmental objectives have been incorporated rarely. Only seven papers mention environmental impact in their model.

Table 8 - Objectives	
Required number of trucks	*[5] [1]* [9] [39] [71] *[75]* [8] *[51]* [11] [63] [69] [6]
Costs	[1] [17] [18] *[2] [26] [20] [21] [22] [23] [24] [25]* [26] *[27]* [79] [29] [30] *[12] [31] [76] [33] [35] [36]* [37] *[10] [38]* [40] *[42] [43]* [44] *[45] [46] [47] [73] [74]* [8] *[52] [53] [7] [55] [56]* [11] *[15] [58]* [59] [60] *[61]* [64] *[65]* [66] [68] [69] [16]
Environmental impact	*[13]* [26] [79] [47] *[77] [64] [68]*
Number of teams / personnel	[17] [79] *[67]*
Route length	*[5]* [17] *[78] [29]* [30] *[70] [32] [34]* [10] *[39] [40] [41] [44] [80]* [46] *[48] [75]* [8] *[50] [54] [57]* [11] [60] *[62]* [63] *[3] [66] [16]* [6]
Total collection time	*[18] [28]* [30] *[9]* [71] *[72] [49] [51]* [11] [59] [60] [69]
Other personnel related	[17] [24] [39] [74] [8] [50] [51] [63] [67]
Other route related	[17] [32] [34] [45] [46] [74] [8] [51] [56] [57] [58] [62] [63] [3]

10. Types of constraints

The more constraints added to the model, the more realistic it becomes. The different types of constraints can be categorized. One of the first types of constraint is the capacity constraint. In the case of a facility location problem [26], disposal facilities are often subject to a capacity constraint, while in a collection routing problem, the capacity of a vehicle is often limited [36]. However, a model formulation does not necessarily need a capacity constraint. If the amount of waste that needs to be collected in a route never exceeds the capacity of the truck, then the capacity of the truck is no longer significant. Next to the capacity constraints, there are labour constraints. Labour constraints are comparable with capacity constraints in that they impose limits on the amount of waste that can be processed. In a facility location problem, the number of working hours of each employee is limited, while in a collection routing problem, the duration of the shift of each crew has to be taken into account. Labour constraints can influence the problem in another way too. It is, for instance, possible that there are enough vehicles left, but that all drivers are already assigned to a vehicle. In this case, the labour constraints rule out the override capacity constraints.

A second class of constraints are the demand constraints. Demand has to be met as it is not acceptable that refuse bags are left on the street because the waste management company fails to service all its customers. An example of such a constraint is to ensure that at least one collection vehicle passes by every node or arc that has demand [7].

The third class of constraints are the feasibility constraints. This class includes constraints that prevent the solution method from proposing an infeasible solution. An example is a constraint that prevents the occurrence of subtours. Once customers are designated to a collection vehicle, it is possible that subtours originate. A subtour is a tour that visits only a part of the customers. By combining all the subtours, all customers are visited. However, the distance a collection vehicle travels between subtours is ignored, which justifies the introduction of subtour elimination constraints [45]. The number of subtour elimination constraints can be large, but it is possible to reduce them by using certain variations of these constraints. More information can be found in the paper of Bautista, Fernandez and Pereira [62]. Another type of feasibility constraints are mass balance constraints. An example can be found in Huang et al. [38]. These constraints assure that the total flow of waste that departs from a source arrives at its destination. Hence, no waste is 'lost' on the road [42].

The next two classes of constraints are restrictions that are imposed by outside interference. Waste management companies do not incorporate these constraints deliberately. Examples are environmental and political constraints. Constraints categorized as political, however, are diverse. MacDonald [25] gives an example of a political constraint in the recyclables market. As the waste management companies lack the incentive to recycle, a certain recycling percentage is imposed by law. Huang, Baetz and Patry [33] incorporate a similar type of obligation with regard to recycling. Another example of a political constraints is the lobbying aspect in the selection of a new site in facility location problems. The city government often has a preference for one particular site, although this is not necessarily the optimal location. Cheng, Chan and Huang [42] incorporate this preference of some political parties into the facility location formulation. Another example of a political constraint is given by Nuortio et al. [54] who deal with time windows imposed by law, for picking up certain types of waste.

The next class is that of time windows. A time window defines for each customer when their garbage can be picked up. Papers that incorporate these time windows are Taillard et al. [78], Kim, Kim and Sahoo [51], and Ombuki-Berman, Runka and Hanshar [63].

The class of environmental constraints contains the constraints that reckon with the increasing environmental burden. They appear in three different settings: noise control, traffic congestion and hazardous materials. Noise control is designed especially for the busy city centres where the amount of noise for the surrounding neighbourhoods can be very disturbing. Chang, Yang and Wang [19] give additional information. Traffic congestion constraints reduce the burden on traffic in rush hours. Hence, preference is given to serving the busy roads of the network in periods of low traffic density.

Introducing time windows is a possibility for preventing traffic congestion. Instead of using a time interval given by a customer, waste management companies designate a time window to each customer in a period of low traffic density. This way the burden on traffic in peak traffic periods is reduced. Ghiani et al. [50] solved their traffic congestion issues this way. Finally, when hazardous materials are collected, the objective function often focuses on the minimization of environmental damage. Marianov and ReVelle [12], however, used environmental constraints to incorporate environmental concern into their model.

The next class includes the constraints related to driver lunch breaks. One cannot expect from a crew that they work non-stop all day. Therefore, waste management companies allow the crew to take a break, usually between 11 a.m. and 1 p.m.. The timing of a lunch break could be determined after having composed the routes. However, due to time windows, it is possible that entering a lunch break between 11 a.m. and 1 p.m. implies that some stops after the break no longer fall within their time window. Consequently, considering lunch breaks when designing the routes prevents this kind of problem. Examples of publications that include a driver lunch break are Bhat [24]. A further explanation about the implications of including a lunch break can be found in Kim, Kim and Sahoo [51].

Finally, the class of forbidden turn constraints addresses one-way streets or streets that are too small to be entered by the vehicle. An example can be found in Bautista, Fernandez and Pereira [62] and in Bautista and Pereira [46], where even the traffic lights are incorporated into the model. Avoiding these traffic lights can save time.

It was not possible to distinguish the types of constraints clearly for all the publications. For 26 of the 78 papers, the paper has been categorized as unclear or not mentioned. Figure 5 visualizes the evolution of the type of constraints. Although there are significantly more papers with environmental constraints than the seven papers that have political constraints, 14 publications dealing with ecological issues is rather low. The period 1996-2000 was the interval with the highest number of publications including environmental constraints. One would expect an increasing trend as public awareness of this matter has only increased since then. Finally, recent solution methods address an increasingly complex context. More and more recent papers incorporate time windows, driver lunch breaks and forbidden turns into their model.

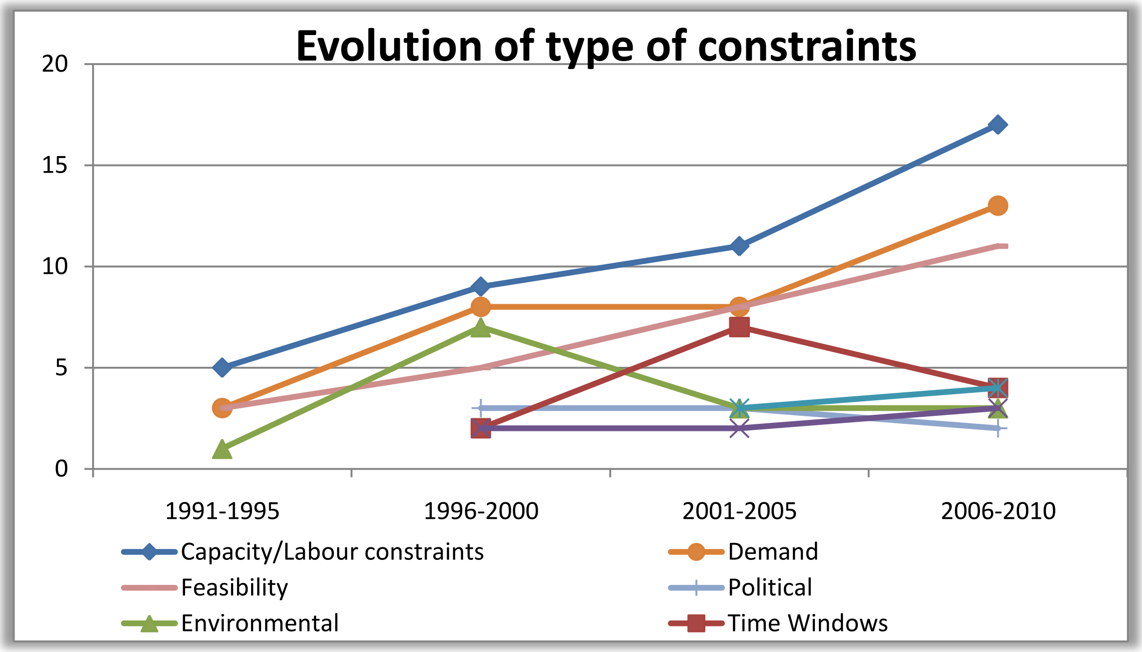

Figure 5: Evolution of types of constraints

Table 9 – Type of constraints	
Capacity / Labour	[5] [2] [19] [20] [22] [23] [25] [26] [78] [30] [31] [32] [33] [34] [36] [10] [38] [40] [41] [42] [43] [45] [46] [73] [74] [8] [52] [53] [7] [55] [56] [15] [58] [61] [62] [63] [3] [65] [66] [67] [69] [16] [6]
Demand	[5] [20] [22] [23] [25] [26] [30] [31] [32] [33] [34] [36] [10] [38] [40] [41] [43] [73] [74] [8] [53] [7] [55] [56] [15] [61] [62] [63] [3] [65] [66] [67] [16]
Feasibility	[5] [2] [19] [20] [25] [30] [33] [35] [9] [10] [38] [42] [43] [71] [45] [73] [8] [52] [53] [7] [55] [56] [61] [62] [65] [66] [67] [16]
Political	[25] [33] [35] [10] [38] [42] [54] [58]
Time windows	[78] [9] [45] [73] [48] [74] [8] [50] [51] [54] [58] [63] [6]
Environmental	[19] [25] [26] [12] [33] [34] [35] [36] [42] [50] [51] [57] [58] [69]
Driver lunch break	[24] [29] [8] [51] [54] [63] [6]
Forbidden Turns	[45] [46] [8] [57] [58] [62] [3]
Not Mentioned / Not Clear	[1] [17] [13] [18] [21] [24] [27] [28] [79] [29] [70] [76] [37] [39] [44] [80] [72] [47] [75] [49] [11] [59] [60] [77] [64] [68]

11. Type of analysis

In section 5, the distinction between a deterministic and a stochastic approach was made. With 58 out of 78 publications, a deterministic approach was clearly the most frequently used. The downside of deterministic models, however, is that these models are less robust. This requires that additional analyses are made. These analyses can be divided into four different types: statistical analysis, sensitivity analysis, scenario analysis and an analysis of heuristics by comparing solution quality with computation time. The purpose of these analyses is habitually an attempt to measure how a change in the input data impacts the results.

Huang et al. [38] apply a statistical analysis. They analyse their solution by evaluating the characteristics of various situations for different significance levels. Secondly, Karadimas et al. [49] analyse the route length obtained by several runs of their ant colony optimization. They conclude that the found route lengths follow a Gumbel distribution. Finally, Ustundag and Cevikcan [66] divide the waste bins that have to be collected into three zones according to their distance from the disposal facility. They carry out an ANOVA analysis to determine whether the increase of waste quantity in each of the zones has a significant impact on the total costs. It appears that the further the working zone is removed from the disposal facility, the more strongly the total operational cost is influenced by changing waste quantities. Ustundag and Cevikcan [66] used RFID technology to register the amount of waste as well as the exact position of each waste bin. These were the only three examples of publications using statistical analysis.

Eighteen out of 78 papers present a sensitivity analysis to get better insight into the factors that impact their results. Different types of problem require different types of input data to be analyzed. In facility location problems, for example, the cost of the new depot is uncertain. Kulcar [36] provides an example of a publication that uses a sensitivity analysis regarding the cost of the new facility. In collection routing problems, changes in the average speed of a collection vehicle, changes in the vehicle capacity or in the shift time of a crew can have an impact on the results. These changes were studied by Santos, Coutinho-Rodrigues and Current [3]. Ghiani et al. [50] give an example of a sensitivity analysis on waste generation.

Scenario analysis is the process of analyzing future events by considering alternative possible outcomes. Instead of showing one exact picture of the future, it presents several alternative future developments. This way, possible future outcomes and the development paths leading to those outcomes become observable. This is not done by using extrapolation of the past or by relying on historical data, but by trying to consider possible developments and turning points. Hence, the uncertainty of system components is modelled by a small number of subproblems that are derived from the underlying problem, which corresponds to different scenarios. By studying these subproblems and their optimal solutions, one may be able to discover similarities and trends and eventually come up with a ‘well hedged’ solution to the underlying problem [23]. As for the rest of the analyses, scenario analysis increases the robustness of the solution. McLeod and Cherett [59] used a scenario analysis to test some different strategies which waste management companies can apply. They tried to determine the impact of two things. First of all, they focussed on the impact of having the vehicle depot at the same place as the disposal facility. Secondly, they investigated the difference between alternate weekly collection and weekly collection. Yeomans, Huang and Yoogalingam [43] examine the future developments of their Solid Waste Reduction Unit (SWARU) by applying a scenario analysis. They test four scenarios: keeping SWARU at its current capacity, operating SWARU at its maximum designed capacity, being able to let the capacity vary at any value between its minimum and maximum capacity and a fourth, realistic possibility where SWARU would be closed due to legislative requirements. By examining the results of these four scenarios, they gained insight into possible future development paths.

By analyzing the solution quality vs. the computation time needed, the performance of a heuristic can be compared with other heuristics. Consequently, a class is introduced to categorize all the publications that use a 'solution quality vs. computation time' measure. Benjamin and Beasley [6], for instance, present three kinds of metaheuristics: tabu search (TS), variable neighbourhood search (VNS) and variable neighbourhood tabu search (VNTS). They conclude that the proposed solutions of the three heuristics are of similar quality. Hence, it is justified to consider the lowest computation time to determine the optimal method. According to their results, VNS was the appropriate method. 15 papers used this kind of statistic.

Remarkably, not a single publication applied any kind of analysis before 1990. Moreover, before 2000, not a single publication compared solution methods based on the solution quality and computation time. A possible explanation is that, before 2000, there were insufficient solution methods available to allow for a comparison on computation time. Table 10 visualizes the categorization based on type of analysis.

Table 10 – Type of analysis	
Statistical analysis	[38] [49] [66]
Sensitivity analysis	[13] [2] [20] [21] [25] [26] [79] [35] [36] [37] [50] [52] [53] [7] [15] [3] [65] [69]
Scenario analysis	[13] [25] [26] [35] [42] [43] [47] [49] [52] [53] [7] [56] [57] [11] [15] [58] [59] [77]
Solution quality vs. computation time	[78] [31] [37] [9] [41] [71] [72] [46] [47] [73] [75] [54] [61] [62] [6]

12. Use of a Geographic Information System (GIS)

In the past, one had to rely on relational databases to develop the routes. Typically, the attributes for records in a relational database include name, billing information and address. The waste management company had to enter the address information manually into their system. Moreover, waste management firms could not determine customers' proximity to other customers or routes to support decisions about routing. With the arrival of GIS, this process was considerably facilitated. A GIS tightly integrates spatial information with managed data. Based on a customer's address, a GIS provides spatial information about each customer, including their location in a coordinate system. Moreover, it is possible to include the geometry of the customer's pickup site. Combining this information with street maps makes it possible to display unique aspects of the data.

Chang, Lu and Wei [30] distinguish three types of modules in a GIS: a query module containing the data, the analysis module and a data output module that presents the results in a spatial way. Because a GIS can model the streets and other landmarks, it is repeatedly used in a collection routing environment. However, it can be used in dealing with a facility location problem too. In a facility location problem, different points of view can be considered. GIS can generate maps of the road network, the waterways, land use, sensitive sites, geology, inclination, ..., which takes the decision-making to a new level [81].

In a paper published in 2009, Tavares et al. [68] add an extra feature to the GIS by incorporating elevation, thereby creating a 3D-GIS system. The 3D models are generated in the shape of polylines based on contours that reflect the terrain relief through the introduction of an additional coordinate: the elevation. Consequently, a new type of objective can be introduced as the new information allows for a more detailed calculation of fuel consumption. A 2D system can propose a route that is shorter in distance but consumes more fuel compared to a route proposed by a 3D system. Tavares et al. [68] obtain two different solutions in a case study in Cape Verde. The first solution is based on the shortest route criterion. This route contains many more height meters than the second route which is generated based on a least fuel consumption criterion. The shortest route is 1,8 % shorter than the least fuel consumption route, however it consumes 8% more fuel. Software packages containing GIS are already available. The ARC GIS Network Analyst, for example, was used in two publications of Karadimas et al. [57] and [58].

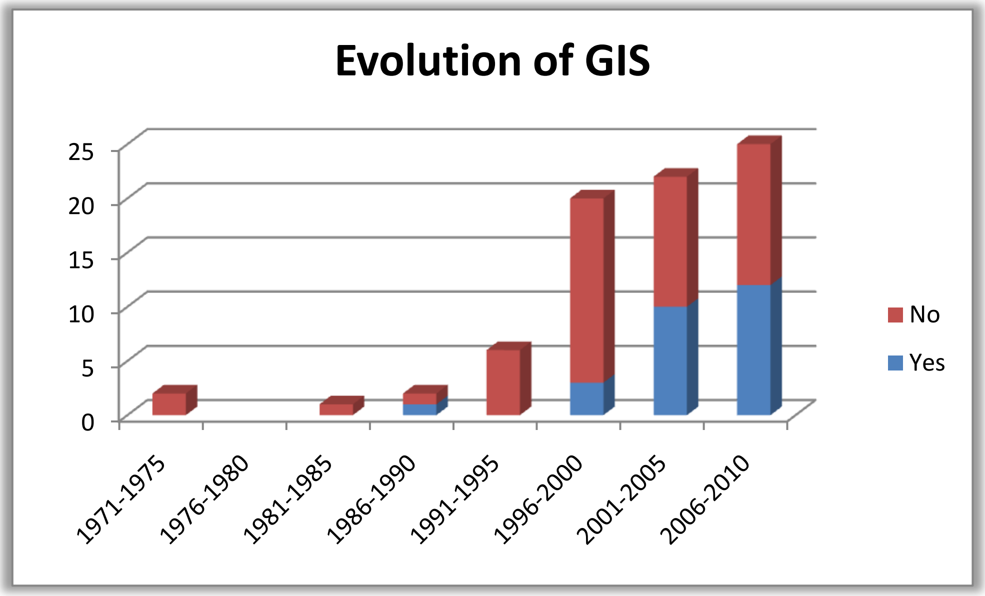

Figure 6: Publications that use a Geographic Information System

Figure 6 visualizes the increasing popularity of GIS in a collection routing context. Nevertheless, as GIS was used by only 26 of the 78 papers, it seems that GIS is not yet fully accepted by academics researching waste collection problems. Bodin et al. [18] were the first to introduce a GIS into their solution method in 1989. From then on, it took until 1996 before the GIS was reused in a publication [25]. After 2000, approximately half of the papers use a GIS. With the introduction of a 3D GIS, the road to more environmental concern lies wide open.

Table 11 – Use of a GIS	
Yes	[18] [25] [27] [30] [10] [39] [80] [45] [46] [48] [75] [8] [49] [51] [55] [57] [11] [58] [60] [77] [64] [3] [66] [68] [69] [16]
No	[5] [1] [17] [13] [2] [19] [20] [21] [22] [23] [24] [26] [28] [78] [79] [29] [70] [12] [31] [76] [32] [33] [34] [35] [36] [37] [9] [38] [40] [41] [42] [43] [44] [71] [72] [47] [73] [74] [50] [52] [53] [54] [7] [56] [15] [59] [61] [62] [63] [65] [67] [6]

13. Location of case study

Many publications use a case study to test their solution method. The continent in which a case study is situated can have an influence on the type of solution method, objectives and constraints. Consequently, it seems useful to give a representation of the location of these case studies by continent. This categorisation can be found in table 12. In developing countries, the waste collection process is not comparable with that in developed countries, due to limited resources. Deficiencies in the management of solid waste are very pronounced in cities and towns of developing countries. Many areas within urban centres receive little or no attention. Because of the direct relationship between the people's good health and a clean environment, it is believed that diseases occur due to a disturbance in the delicate balance between man and his appropriate treatment of waste [21]. Models in developed countries, on the other hand, mostly try to limit personnel cost.

The majority of the case studies have been carried out in Europe, North America or Asia. Europe is best represented in the case studies with 26 examples, while North America has twelve cases and Asia eleven. In 25 of the 78 publications, it was not possible to determine the location as there was no case study or hypothetical data were used. The evolution of the publications through history reveals two remarkable trends. First of all, examples of publications with a hypothetical case study or no case study at all are mainly situated before 2000. After 2000, the number of publications without a case study decreases sharply. Secondly, all the examples of case studies in Africa and Oceania took place after 2005. A possible explanation for this is that the efficiency of the waste collection process in the more developed countries has already been studied extensively. The waste collection problems in developing countries, on the other hand, bring new challenges like disease control and poor infrastructure.

Table 12 – Location of the case study

Africa	[7] [64] [66] [68] [69]
Asia	[17] [19] [21] [26] [30] [32] [37] [10] [48] [66] [16]
Europe	[2] [79] [70] [36] [40] [42] [44] [80] [71] [46] [74] [49] [50] [54] [55] [57] [11] [15] [58] [59] [60] [62] [77] [3] [66] [6]
North America	[1] [20] [29] [76] [33] [35] [43] [8] [51] [53] [61] [66]
Oceania	[66]
South America	[18] [52] [65] [66]
No Case / Hypothetical case	[5] [13] [22] [23] [24] [25] [27] [28] [78] [12] [31] [34] [9] [38] [39] [41] [45] [72] [47] [73] [75] [56] [63] [67] [6]

14. Conclusion

This paper reviews the literature on municipal solid waste management problems. By categorizing the existing publications into different perspectives, this paper can help guide future researchers to the papers of interest. The selected manuscripts contain four main types of waste (section 2): garbage, containers or skips, hazardous materials and recyclables. Each of them has its specific requirements.

In section 3, the manuscripts are categorized based on their scope, resulting in three different classes. A first class of papers addresses facility problems, where decisions have to be made concerning the expansion of current disposal facilities or the location of new facilities. The second class deals with allocating collection vehicles to disposal facilities. The last and most important class of papers addresses the collection routing problem. As collection routing is the most expensive process in the waste management cycle, the focus of this literature review lies on collection routing problems. The collection routing problems are further divided into node routing problems and arc routing problems. Each problem type has its own characteristics and applications. The next section discusses the different solution methods. We distinguish between five types of mathematical programming, seven types of heuristics (five metaheuristics and two other heuristics), simulation and branch-and-bound (section 4). Furthermore, two sections are devoted to characteristics of the different types of solution methods. Section 5 distinguishes between a deterministic and a stochastic approach, while section 6 clarifies whether the solution is optimal or not. In section 7, the manuscripts are categorized according to the type of resource. Some manuscripts take only one type of collection vehicle into consideration, while others address different types of collection vehicles. In section 8, the manuscripts are classified according to the presence of multiple disposal facilities or single disposal facilities. As a single disposal facility reduces the complexity of the problem considerably, there are specific settings in which the use of models with a single disposal facility is appropriate. The next section describes the different types of objectives. Some papers focus on distance or time, while others focus on the minimization of personnel or costs. Since several papers have different objectives, the main objective of the paper is put in italics in the overview table at the end of section 9. Next, the different constraints are discussed including special cases like the introduction of a driver lunch break, time windows and forbidden turns (section 10). The review continues with classifying the papers based on the type of analysis. After obtaining a solution, further analysis is often desirable. These analyses can be divided into four types: statistical analysis, sensitivity analysis, scenario analysis and a comparison of the solution quality and the computation time (section 11). Section 12 gives more explanation about Geographic Information Systems and finds out that they are becoming increasingly popular. Half of the publications after 2000 take advantage of a GIS. The last section displays the location of the case studies by continent. A different continent often corresponds to a different problem setting. Due to limited resources, the primary concern of waste management companies in developing countries is improving public health rather than minimizing the travelled distance (section 13).

Each section concludes with a table where the classification is displayed. Each category is further exemplified through the citation of key references and by expounding on the features of that perspective. The main contribution of this review is to facilitate the tracing of published work in relevant fields of interest, as well as identifying trends and indicating which areas of research should be subject to future research. It is remarkable that there are a surprisingly low number of papers that deal with environmental problems. The minimization of fuel consumption, for instance, will become increasingly important in the light of growing environmental regulations. However, it is possible that the introduction of 3D-GIS models has paved the way for the rise of environment related solution methods.

Acknowledgements

We thank Mark Corner for proofreading this paper with respect to the English language.

References

1. **Clark, R. M.; Gillean, J. I.** Analysis of solid waste management operations in Cleveland, Ohio: A case study. *Interfaces.* 1975, Vol. 6, Issue 1, Part 2, pp. 32-42.

2. **Or, I.; Curi, K.** Improving the efficiency of the solid waste collection system in Izmir, Turkey through mathematical programming. *Waste Management & Research.* 1993, Vol. 11, pp. 297-311.

3. **Santos, L.; Coutinho-Rodrigues, J.; Current, J. R.** Implementing a multi-vehicle multi-route spatial decision support system for efficient trash collection in Portugal. *Transportation Research Part A.* 2008, Vol. 42, pp. 922-934.

4. **Toth, P.; Vigo, D.** *The Vehicle Routing Problem.* s.l. : SIAM, 2002.

5. **Beltrami, E. J.; Bodin, L.** Networks and vehicle routing for municipal solid waste collection. *Networks.* 1974, Vol. 4, pp. 65-94.

6. **Benjamin, A. M.; Beasley, J. E.** Metaheuristics for the waste collection vehicle routing problem with time windows,driver rest period and multiple disposal facilities. *Computer & Operations Research.* 2010, Vol. 37, pp. 2270-2280.

7. **Badran, M. F.; El-Haggar, S. M.** Optimization of municipal solid waste management in Port Said - Egypt. *Waste Management.* 2006, Vol. 26, pp. 534-545.

8. **Sahoo, S.; Kim, S.; Kim, B.-I.; Kraas, B.; Popov Jr., A.** Routing Optimization for Waste Management. *Interfaces.* 2005, Vol. 35, Issue 1, pp. 24-36.

9. **Bodin, L.; Mingozzi, A.; Baldacci, R.; Ball, M.** The Rollon-Rolloff Vehicle Routing Problem. *Transportation Science.* 2000, Vol. 34, Issue 3, pp. 271-288.

10. **Shih, L.-H.; Chang, H.-C.** A routing and scheduling system for infectious waste collection. *Environmental Modeling and Assessment.* 2001, Vol. 6, pp. 261-269.

11. **Alagöz, A. Z.; Kocasoy, G.** Improvement and modification of the routing sysem for the health-care waste collection and transportation in Istanbul. *Waste Management.* 2007, Vol. 28, pp. 1461-1471.

12. **Marianov, V.; ReVelle, C.** Linear, non-approximated models for optimal routing in hazardous environments. *Journal of the operational research society.* 1998, Vol. 49, pp. 157-164.

13. **Batta, R.; Chiu, S. S.** Optimal Obnoxious paths on a network: Transportation of hazardous materials. *Operations Research.* 1987, Vol. 36, Issue 1, pp. 45-54.

14. **Rogers, D.; Tibben-Lembke, R.** Reverse Logistics: Stategies et Techniques. *Logistique & Management.* Vol. 7, Issue 2, pp. 15-26.

15. **Krikke, H.; le Blanc, I.; Van Krieken, M.; Fleuren, H.** Low-frequency collection of materials disassembled from end-of-life vehicles on the value of on-line monitoring in optimizing route planning. *International Journal of Production Economics.* 2007, Vol. 111, pp. 209-228.

16. **Kim, H.; Yang, J.; Lee, K.-D.** Vehicle routing in reverse logistics for recycling end-of-life consumer electronic goods in South Korea. *Transportation Research Part D.* 2009, Vol. 14, pp. 291-299.

17. **Ronen, R.; Kellerman, A.; Lapidot, M.** Improvement of solid waste collection system: the case of Givatayim, Israël. *Applied Geography.* 1983, Vol. 3, pp. 133-144.

18. **Bodin, L.; Fagin, G.; Welebny, R.; Greenberg, J.** The design of a computerized sanitation vehicle routing and scheduling system for the town of Oyster Bay, New York. *Computers and Operations Research.* 1989, Vol. 16, pp. 45-54.

19. **Chang, N.-B.; Yang, Y. C.; Wang, S. F.** Solid-waste management system analysis with noise control and traffic congestion limitations. *Journal of Environmental Engineering.* 1993, Vol. 122, Issue 2, pp. 122-131.

20. **Huang, G. H.** Grey mathematical programming and its application to municipal solid waste management planning. *Open Access Dissertations and Theses. Paper 3089 http://digitalcommons.mcmaster.ca/opendissertations/3089.* 1994.

21. **Tin, A. M.; Wise, D. L.; Su, W.-H.; Reutergardh, L.; Lee, S.-K.** Cost-benefit analysis of the municipal solid waste collection system in Yangon, Myanmar. *Resources, Conservation and Recycling.* 1995, Vol. 14, pp. 103-131.

22. **Huang, G. H.; Baetz, B. W.; Patry, G. G.** Grey fuzzy integer programming: an application to regional waste management planning under uncertainty. *Socio-Economical Planning Science.* 1995, Vol. 29, Issue 1, pp. 17-38.

23. **Huang, G. H.; Baetz, B. W.; Patry, G. G.** Grey Integer Programming: An application to waste management planning under uncertainty. *European Journal of Operational Research.* 1995, Vol. 83, pp. 594-620.

24. **Bhat, V. N.** A model for the optimal allocation of trucks for solid waste management. *Waste Management & Research.* 1996, Vol. 14, pp. 87-96.

25. **MacDonald, M. L.** A multi-attribute spatial decision support system for solid waste planning. *Computational, Environmental and Urban Systems.* 1996, Vol. 20, Issue 1, pp. 1-17.

26. **Chang, N.-B.; Wang, S. F.** Solid waste management system analysis by mulbiobjective mixed integer programming model. *Journal of Environmental Management.* 1996, Vol. 48, pp. 17-43.

27. **Muttiah, R. S.; Engel, B. A.; Jones, D. D.** Waste disposal site selection using GIS-based simulated annealing. *Computers & Geosciences.* 1996, Vol. 22, Issue 9, pp. 1013-1017

28. **Wang, F. S.; Richardson, A. J.; Roddick, F. A.** SWIM - A computer model for Solid Waste Integrated Management. *Computational, Environmental and Urban Systems.* 1996, Vol. 20, Issue 4-5, pp. 233-246.

29. **Eisenstein, D. D.; Iyer, A. V.** Garbage collection in Chicago: A dynamic scheduling model. *Management Science.* 1997, Vol. 43, Issue 7, pp. 922-933.

30. **Chang, N.-B.; Lu, H. Y.; Wei, Y. L.** GIS technology for vehicle routing and scheduling in solid waste collection systems. *Journal of Environmental Engineering.* 1997, Vol. 123, pp. 901-911.

31. **Mourao, M. C.; Almeida, M. T.** Lower-bounding and heuristics methods for a refuse collection vehicle routing problem. *European Journal of operational research.* 1998, Vol. 121, pp. 420-434.

32. **Chang, N.-B.; Wei, Y. L.** Siting Recycling drop-off stations in urban area by genetic algorithm-based fuzzy multiobjective nonlinear integer programming modelling. *Fuzzy Sets and Systems.* 1998, Vol. 114, pp. 133-149.

33. **Huang, G. H.; Baetz, B. W.; Patry, G. G.** Trash-Flow Allocation: Planning under uncertainty. *Interfaces.* 1998, Vol. 28, Issue 6, pp. 36-55.

34. **Torres, O. A.C.; Anton, F. R.** A continuous Approximation Model for Vehicle Routing in Solid Waste Management Systems. *Investigacion Operativa.* 1999, Vol. 8, Issue 1,2,3, pp. 109-153.

35. **Rubenstein-Montano, B.; Zandi, I.** Application of a genetic algorithm to policy planning: the case of solid waste. *Environment and planning B: Planning and Design.* 1999, Vol. 26, pp. 893-907.

36. **Kulcar, T.** Optimizing solid waste collection in Brussels. *European Journal of Operational Research.* 1999, Vol. 90, pp. 71-77.

37. **Tung, D. V.; Pinnoi, A.** Vehicle routing-scheduling for waste collection in Hanoi. *European Journal of Operational Research.* 1999, Vol. 125, pp. 449-468.

38. **Huang, G. H.; Sae-Lim, N.; Liu, L.; Chen, Z.** An interval-parameter fuzzy-stochastic programming approach for municipal solid waste management and planning. *Environmental Modeling and Assessment.* 2001, Vol. 6, pp. 271-283.

39. **Sniezek, J.; Bodin, L.; Levy, L.; Ball, M.** Capacitated Arc Routing Problems with Vehicle-Site Dependencies: The Philadelphia Experience. [book auth.] P. Toth and D. Vigo. *The Vehicle Routing Problem: Discrete mathematics and its applications.* s.l. : SIAM. Philadelphia, 2001, pp. 247-254.

40. **Angelelli, E.; Speranza, M. G.** The application of a vehicle routing model to a waste-collection problem: two case studies. *Journal of the Operational Research Society.* 2002, Vol. 53, pp. 944-952.

41. **Angelelli, E.; Speranza, M. G.** The periodic vehicle routing problem with intermediate facilities. *European Journal of Operational Research.* 2002, Vol. 137, pp. 233-247.

42. **Cheng, S.; Chan, C. W.; Huang, G. H.** An integrated multi-criteria decision analysis and inexact mixed integer linear programming approach for solid waste management. *Engineering Applications of Artificial Intelligence.* 2003, Vol. 16, pp. 543-554.

43. **Yeomans, J. S.; Huang, G. H.; Yoogalingam, R.** Combining Simulation with Evolutionary Algorithms for optimal planning under uncertainty: an application to municipal solid waste management planning in the regional municipality of Hamilton-Wentworth. *Journal of Environmental Informatics.* 2003, Vol. 2, Issue 1, pp. 11-30.

44. **Viotti, P.; Polettini, A.; Pomi, R.; Innocenti, C.** Genetic Algorithms as a promising tool for optimisation of the MSW collection routes. *Waste Management Research.* 2003, Vol. 21, 292-298, pp. 292-298.

45. **Maniezzo, V.** Algorithms for large directed CARP instances: urban solid waste collection operational support. *Technical Report University of Bologna, Department of Computer Science 2004-16.* 2004.

46. **Bautista, J.; Pereira, J.** Ant Algorithms for Urban Waste collection algorithms. *Ants LNCS.* 2004, Vol. 3172, pp. 302-309.

47. **Amponsah, S. K.; Salhi, S.** The investigation of a class of capacitated arc routing problems: the collection of garbage in developing countries. *Waste Management.* 2004, Vol. 24, pp. 711-721.

48. **Ghose, M. K.; Dikshit, A. K.; Sharma, S. K.** A GIS based transportation model for solid waste disposal - A case study on Asansol municipality. *Waste Management.* 2005, Vol. 26, pp. 1287-1293.

49. **Karadimas, N. V.; Kouzas, G.; Anagnostopoulos, I.; Loumos, V.** Urban Solid Waste collection and routing: the ant colony strategic approach. *International Journal of Simulation.* 2005, Vol. 6, Issue 12-13, pp. 45-53.

50. **Ghiani, G.; Guerriero, F.; Improta, G.; Musmanno, R.** Waste collection in Southern Italy: solution of a real-life arc routing problem. *Inernational Transportation in Operational Research.* 2005, Vol. 12, pp. 135-144.

51. **Kim, B.-I.; Kim, S.; Sahoo, S.** Waste collection vehicle routing problem with time windows. *Computers & Operations Research.* 2005, Vol. 33, pp. 3624-3642.

52. **Simonetto, E. O.; Borenstein, D.** A decision support system for the operational planning of solid waste collection. *Waste Management.* 2006, Vol. 27, pp. 1286-1297.

53. **Wu, X. Y.; Huang, G. H.; Liu, L.; Li, J. B.** An interval nonlinear program for the planning of waste management systems with economies-of-scale effects - A case study for the region of Hamilton, Ontario, Canada. 2006, Vol. 171, pp. 349-372.

54. **Nuortio, T.; Kytöjoki, J.; Niska, H.; Bräysy, O.** Improved route planning and scheduling of waste collection and transport. *Expert systems with applications.* 2006, Vol. 30, pp. 223-232.

55. **Johansson, O. M.** The effect of dynamic scheduling and routing in a solid waste management system. *Waste Management.* 2006, Vol. 26, pp. 875-885.

56. **Sniezek, J.; Bodin, L.** Using mixed integer programming for solving the capacitated arc routing problem with vehicle/site dependencies with an application to the routing of residential sanitation collection vehicles. *Annals of Operations Research.* 2006, Vol. 144, pp. 33-58.

57. **Karadimas, N. V.; Kolokathi, M.; Defteraiou, G.; Loumos, V.** Ant Colony system vs ArcGIS Network Analyst: The Case of Municipal Solid Waste Collection. *5th WSEAS International Conference on Environment, Ecosystems and Development, Tenerife, Spain.* 2007.

58. **Karadimas, N. V.; Kolokathi, M.; Defteraiou, G.; Loumos, V.** Municipal Waste Collection of Large Items optimized with arc GIS network analyst. *Proceedings 21st European Conference on Modelling and Simulation.* 2007.

59. **McLeod, F.; Cherrett, T.** Quantifying the transport impacts of domestic waste collection strategies. *Waste Management.* 2007, Vol. 28, pp. 2271-2278.

60. **Apaydin, O.; Gonullu, M. T.** Route optimization for solid waste collection: Trabzon (Turkey) Case study. *Global NEST Journal.* 2007, Vol. 9, Issue 1, pp. 6-11.

61. **Yeomans, J. S.** Solid waste planning under uncertainty using evolutionary simulation-optmization. *Socio-economic Planning Sciences.* 2007, Vol. 41, pp. 38-60.

62. **Bautista, J.; Fernandez, E.; Pereira, J.** Solving an urban waste collection problem using ants heuristics. *Computers & Operations Research.* 2007, Vol. 35, pp. 3020-3033.

63. **Ombuki-Berman, B. M.; Runka, A.; Hanshar, F. T.** Waste collection vehicle routing problem with time windows using multi-objective genetic algorithms. *International Association of Science and Technology for Development Proceedings of the Third IASTED International Conference on Comutational Intelligence. Evolutionary computation.* 2007, pp. 91-97.

64. **Tavares, G.; Zsigraiova, Z.; Semiao, V.; Carvalho, M. da G.** A case study of fuel savings through optimasation of MSW transportation routes. *Management of Environmental Quality: An international Journal.* 2008, Vol. 19, Issue 4, pp. 444-454.

65. **Li, J.-Q.; Borenstein, D.; Mirchandani, P. B.** Truck scheduling for solid waste collection in the City of Porto Alegre, Brazil. *Omega.* 2008, Vol. 36, pp. 1133-1149.

66. **Ustundag, A.; Cevikcan, E.** Vehicle route optimization for RFID integrated waste collection system. *International Journal of Information Technology & Decision Making.* 2008, Vol. 7, Issue 4, pp. 611-625.

67. **Hansmann, R. S.; Zimmerman, U. T.** Integrated Vehicle Routing and Crew Scheduling (IVRCS) in Waste Management -Part 1-. *Dagstuhl Seminar Proceedings 09261 Models and Algorithms for Optimization in Logistics.* 2009, http://drops.dagstuhl.de/opus/volltexte/2009/2185.

68. **Tavares, G.; Zsigraiova, Z.; Semiao, V.; Carvalho, M. da G.** Optimisation of MSW collection routes for minimum fuel consumption using 3D GIS modelling. *Waste Management.* 2009, Vol. 29, pp. 1176-1185.

69. **Arribas, C. A.; Blazquez, C. A.; Lamas, A.** Urban solid waste collection system using mathematical modelling and tools of geographic information systems. *Waste Management & Research.* 2009, Vol. 28, pp. 355-363.

70. **De Meulemeester, L.; Laporte, G.; Louveaux, F. V.; Semet, F.** Optimal Sequencing of skip collections and deliveries. *Journal of the operational research society.* 1997, Vol. 48, pp. 57-64.

71. **Aringhieri, R.; Bruglieri, M.; Malucelli, F.; Nonato, M.** A particular vehicle routing problem in the collection and disposal of special waste. *Presented at Tristan 2004, Guadeloupe, French West Indies.* 2004.

72. **Aringhieri, R.; Bruglieri, M.; Malucelli, F.; Nonato, M.** An asymmetric vehicle routing problem arising in the collection and disposal of special waste. *Electronic Notes in Discrete Mathematics.* 2004, Vol. 17, pp. 41-47.

73. **Dell'Amico, M.; Righini, G.; Salani, M.** A branch-and-price approach to the vehicle routing problem with simultaneous distribution and collection. *Transportation Science.* 2005, Vol. 40, pp. 235-273.

74. **Archetti, C.; Speranza, M. G.** Collection of waste with single load trucks: A real case. [book auth.] B. Fleischmann and A. Klose. *Distribution Logistics: advanced solutions to practical problems.* 2005, pp. 105-121.

75. **Bianchessi, N.; Righini, G.** Heuristic Algorithms for the vehicle routing problem with simultaneous pick-up and delivery. *Computers & Operational Research.* 2005, Vol. 34, pp. 578-594.

76. **Bommisetty, D.; Dessouky, M.; Jacobs, L.** Scheduling collection of recyclable material at Northern Illinois University campus using a two-phase algorithm. *Computers Industrial Engineering.* 1998, Vol. 35, pp. 435-438.

77. **Salhofer, S.; Schneider, F.; Obersteiner, G.** The ecological relevance of transport in waste disposal systems in Western Europe. *Waste Management.* 2007, Vol. 27, pp. S47-S57.

78. **Taillard, E.; Badeau, P.; Gendreau, M.; Guertin, F.; Potvin, J.-Y.** A tabu search heuristic for the vehicle routing problem with soft time windows. *Transportation Science.* 1997, Vol. 31, pp. 170–186.

79. **Hokkanen, J.; Salminen, P.** Choosing a solid waste management system using multicriteria decision analysis. *European Journal of Operational Research.* 1997, Vol. 98, pp. 19-36.

80. **Teixeira, J.; Antunes, A. P.; Pinho de Sousa, J.** Recyclable waste collection planning - a case study. *European Journal of Operational Research.* 2003, Vol. 158, pp. 543-554.

81. **Sumathi, V.R.; Natesan, U.; Sarkar, C.** GIS-based approach for optimized siting of municipal solid waste landfill. *Waste Management.* 2008, Vol. 28, pp. 2146-2160.