An exact routing optimization and simulation model for bio-waste collection in the Brussels Capital Region

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Abstract

This paper presents a routing optimization and simulation model for a wide range of waste collection problems which allows for multiple depots with homogeneous, capacitated vehicles, intermediate stops at multiple processing facilities, and multiple pick-ups per waste collection location. By minimizing collection routing and vehicle investment costs, the model estimates the total transportation costs for a given network design and waste volumes to be collected at different demand points. The number of feasible routes is severely reduced by restricting the number of subsequent pick-up location visits. The model's use is illustrated through assessing four future, realistic bio-waste collection scenarios of the Brussels Capital Region (BCR). The scenarios differ with respect to assumptions on future collection rates, joint versus separate collection of food and green waste, and number and locations of processing facilities. The results show that the highest cost reduction can be achieved through joint collection of food and green waste combined with three composting locations. Moreover, we found that introducing multiple processing facilities significantly increases the complexity of the waste collection problem.

Keywords: waste collection; mixed integer linear programming optimization; simulation; multiple depots; intermediate facilities.

1. Introduction and problem statement

Smart cities consider waste collection as one of the more critical city logistics activities as it has a major impact on the quality of life, city attractiveness, congestion, urban environment, and municipal budgets (Gruler et al., 2017). Cities are continuously forced to review and re-optimize their waste collection systems due to new, stricter regulations to meet ever-rising ambitions related to separate collection. For instance, the latest amendment to the EU waste directive in 2018 obligates all member states to collect and treat bio-waste separately by December 2023. In light of these new requirements, the Brussels Capital Region (BCR) is investigating alternative bio-waste collection and treatment scenarios. Currently, garden waste is only collected in specific districts while food waste is collected throughout the BCR, but only on a voluntary basis. Of the estimated amount of bio-waste generated, only 9% is collected separately (2014 data). The remainder is collected jointly with residual waste and is incinerated with energy recovery.

To meet the new regulations, a limited number of future, realistic waste collection scenarios are investigated by the BCR's waste management authorities. These scenarios differ with respect to more or less ambitious collection rates, joint versus separate collection of food and green waste, and alternative locations of processing locations. To be able to assess the financial feasibility of these scenarios, an optimization model is needed to estimate the resulting transportation costs. To this aim, this paper presents a mixed integer linear programming model for developing optimized waste collection routes with multiple depots and homogeneous, capacitated vehicles requiring intermediate stops at multiple processing facilities, and multiple pick-ups per collection node.

The main contributions of this research are as follows. First, we present a new, exact optimization model to optimize and evaluate a selected number of waste collection scenarios. Second, using real-life data we show how this model can be used to assist in the decision-making process of a large urban area faced with the challenge of meeting growing demands on separated waste collection with limited financial means. Third, this paper provides an optimization model for cases with multiple capacitated depots, multiple capacitated processing facilities combined with intermediate stops, and multiple pick-ups at collection locations. To the best of our knowledge, such a general waste collection optimization model has never been presented before. Fourth, we show how the number of feasible routes can be reduced severely by introducing trips in which the number of subsequent pick-up location visits is limited.

This paper proceeds as follows. Section 2 situates this work in the relevant literature on waste collection routing. Section 3 describes four different collection trips that are used as key decision variables in the mixed integer linear programming model. Section 4 presents the results of applying the model on four bio-waste collection scenarios in the Brussels Capital Region. Finally, Section 5 concludes this paper and gives some directions for future research.

2. Literature review

A recent overview of the literature of strategic network design in waste reverse supply chains is given in Van Engeland et al. (2020). Beliën et al. (2014) provide a structured review of the operational municipal solid waste collection problem. In the 5-category classification of the literature on waste collection systems presented by Lu et al. (2017) this work falls in the simultaneous node and arc routing problems category, which takes as input the higher-level facility location decisions (see, e.g., Adeleke and Ali, 2020 or Caramia and Giordani, 2020).

Operational household waste collection problems are either modeled as arc routing problems, which entails the construction and assignment of routes to collection vehicles such that all streets in a given area are visited over a given time period, or as node routing problems, in which waste needs to be collected at specific collection sites or nodes. Some studies integrate the higher-level decision of designing the service area with the operational decision of developing collection trips (e.g., Teixeira et al., 2004, Kim et al., 2006, or Ramos and Oliveira, 2011 for node routing models, and Cortinhal et al., 2016, Mourão et al., 2009, Constantino et al., 2015 or Zbib and Laporte, 2020 for arc routing models).

The real-life problem studied in this paper also integrates aspects of operational waste collection (routing) and tactical decisions. However, as our model is developed for waste collection in one city (or urban region), partitioning of the area into sectors is not relevant. Instead, our tactical decisions relate to the midterm investments in capacity, i.e., the number of collection vehicles to be purchased.

The specific problem studied in this paper requires to aggregate the waste generation at the level of districts which leads to a node routing problem with intermediate stops (or, equivalently, multiple trips) for disposing of waste. A comprehensive review on the multi-trip vehicle routing problem (MTVRP) is given by Cattaruzza et al. (2018). Hemmelmayr et al. (2013) use a node routing model for a real-world solid waste collection as a Periodic Vehicle Routing Problem with Intermediate Facilities (PVRP-IF) and develop a hybrid algorithm that combines a variable neighborhood search heuristic with an exact procedure for inserting the intermediate facilities. Markov et al. (2016) extend the waste collection problem with intermediate facilities by relaxing the assumptions of a fixed homogeneous fleet and fixed destination depots. By incorporating the decision on the number of vehicles to be used, we also relax the assumption of a fixed homogeneous fleet. Similar to Gruler et al. (2017) our problem involves multiple depots, but we do not consider stochastic waste volumes. Instead, we present a deterministic approach to evaluate a limited number of realistic scenarios that differ, among other things, on expected future waste generation.

Many recent contributions involve an illustration of the presented methodology to a real-life waste collection problem. For instance, Delgado-Antequera et al. (2020b) propose a semi-greedy construction heuristic and local search for constructing collection routes in a Spanish rural region to simultaneously minimize costs and balance routes. In a follow-up research, Delgado-Antequera et al. (2020a) extend this bi-objective setting to four objectives by incorporating the number of routes and distinguishing between route length balance and route time balance. Besides routing costs and route balancing, López-Sánchez et al. (2018) also minimize the number of vehicles used. They propose a Greedy Randomized Adaptive Search Procedure (GRASP) with a Variable Neighborhood Descent (VND) to a real-life waste collection problem of a Spanish city. Arango González et al. (2020) solve a bi-objective waste collection problem, minimizing both transportation costs and the environmental impact for islands in southern Chile. A Pareto frontier is constructed using an epsilon constraint and a weighted sum method.

Van Engeland and Beliën (2020) propose mixed integer programming (MIP) based heuristics as well as a column generation approach for solving a real-life tactical waste collection problem. The MIP heuristics start from the observation that, during preliminary testing, all solutions found were made up by routes of at most two trips. In contrast to our research, however, the setting studied in Van Engeland and Beliën (2020) is limited to one disposal facility and one depot. Their real-life application concerns collection of paper and carton, and plastic, metal and drink cartons (PMD) in a rural area.

Farrokhi-Asl et al. (2020) integrate the strategic facility location problem with the operational routing problem for a hazardous waste collection problem. Their model considers a multi-stage network in which hazardous waste is collected and transported to treatment centers after which waste residues are subsequently transported to recycle or disposal facilities. The proposed hybrid metaheuristic is capable of finding high quality solutions with respect to three objectives: minimizing costs, minimizing sites risk (measured by people living close to opened facilities), and minimizing fuel and CO_2 emissions. Considering multiple objectives, multiple depots and multiple treatment facilities, the model is very general, but in contrast to our model, it assumes that all waste generated at a specific node must be collected by only one vehicle. Yu et al. (2020) also study a multi-objective waste collection problem in a 2-echelon network integrating facility location and routing decisions, for which they propose an improved non-dominated sorting genetic algorithm. Similar to Farrokhi-Asl et al. (2020) split deliveries are not allowed, i.e., demand nodes must be served by one and only one vehicle, which is again the main difference with our work.

The previously described studies each include a specific set of constraints for a specific type of waste collection problem. However, a more general optimization model incorporating a large number of waste collection constraints is lacking in the literature. To the best of our knowledge, a general optimization model for cases with multiple capacitated depots, multiple capacitated processing facilities combined with intermediate stops, and multiple pick-ups at collection locations has never been presented before.

3. Methodology

This section presents a Mixed Integer Linear Programming (MILP) model for evaluating a particular waste collection scenario. As a scenario includes a particular set of locations for capacitated depots and capacitated processing facilities, we will assume these as input for the MILP model. Furthermore, we assume a set of demand points, i.e., districts, each characterized with a particular waste generation to be collected. The daily waste generation at the different demand points coincides with residents putting out their trash bags and bins. This depends on a cyclic collection calendar decided by the local authorities. As these collection calendars are often developed taking into account local preferences, we assume this schedule as given. Therefore, the waste generated on a day must be collected on that day. This makes the collection optimization over a cycle period much easier as the collection for each day is independent of the next day. Furthermore, our model allows for instances in which the volume or weight of the waste per pick-up point exceeds the capacity of a waste collection vehicle. Our task is thus to determine the number of homogeneous vehicles of a given capacity to be used at each depot and the collection routes for each vehicle on each day of the cycle period.

The required number of trucks for a waste stream will differ over the weekdays as collection calendars are often not balanced per waste stream. One could argue that the true investment cost for waste collection vehicles for a particular waste stream would then be the cost of the maximum number of vehicles required per week. However, the waste collection calendar which considers all types of separately collected waste streams is in most cases balanced. I.e., the workload for waste collectors is assumed to be spread in a balanced way over the days of the week. Furthermore, waste collection vehicles can be used for multiple waste streams. For example, a waste collection vehicle that is not used for bio-waste collection on Monday could be used for the waste collection of paper and cardboard. Thus, we consider the vehicle investment cost as an opportunity cost. If a vehicle is used for a particular waste stream on a specific day, this vehicle cannot be used for other waste streams, which in its turn will create additional vehicle investment requirements for these waste streams. This enables us to model the waste collection problem per day instead of over the entire week.

We assume that vehicles must always return to the depot they came from as this allows the truck drivers to go to work by car/bicycle and pick up their vehicle in the evening without having to move between depots. We also assume that trucks do not have to be completely full before going to a processing facility, but are allowed to only visit at most two districts before going to a processing facility. The motivation for the latter assumption is given by the experience, gained from current practice, of the waste collection authorities who provided the case study for this research. Allowing collection at a second district (when there is remaining truck capacity after collecting at the first district) before unloading at a processing facility often leads to important savings in driven distance. Allowing the collection of smaller quantities at several districts is discouraged by the authorities as this is not perceived to be beneficial in terms of saved driving distance. We, therefore, restrict the number of districts per trip to two districts. Nevertheless, our model could be extended to include three or more district visits per drop-off. When gradually increasing the maximum number of district visits, the model increasingly resembles a general version of the well-known vehicle routing problem (with multiple depots and homogeneous, capacitated vehicles requiring intermediate stops at multiple processing facilities). Introducing a limitation on the number of consecutive visits reduces the complexity of this complex general waste collection problem. As will be shown in Section 4.2, this allows current state-of-the-art MILP-solvers to solve relatively small instances to (near) optimality. In summary, the following assumptions were made:

Assumption 1	Vehicles can leave from multiple depots with depot-specific capacity restrictions.
Assumption 2	Waste can be dropped off at multiple intermediate processing facilities with facility-specific capacity restrictions.
Assumption 3	Vehicles must return to the depot they left from.
Assumption 4	The fleet is homogeneous.
Assumption 5	All waste put on the curb on a day must be collected on the same day.
Assumption 6	A vehicle can visit up to two consecutive districts before visiting a processing facility.

Before we state the MILP model, we illustrate the concept of daily collection routes, in which we distinguish between four types of trips. They will constitute the key decision variables in the MILP.

3.1. Collection routes

Examples of feasible collection routes for two vehicles on a particular day are provided in Figure 1. Vehicle 1 leaves depot 2, visits district 1, and drops off the waste at processing facility 2. It then

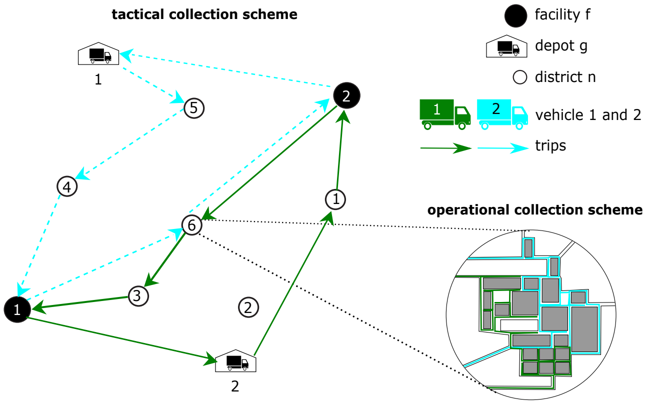

Figure 1: Example of feasible waste collection routes.

resumes its route by collecting part of the waste of district 6. As there is still vehicle capacity left, it continues collecting waste at district 3, after which it goes to processing facility 1. Vehicle 2 leaves depot 1 and visits districts 5 and 4. It drops off its waste at processing facility 1. The truck then visits district 6 for collecting a fraction of this district's waste, goes to processing facility 2, and returns to its depot.

A collection route of a vehicle on a day is constructed using trips. Each trip is a building block that represents a visit to one or two districts. We distinguish four different types of trips which are displayed in Figure 2. When more than two visits per trip are allowed, the number of trip types increases to twice the number of allowed consecutive visits.

type 1	starting at a vehicle depot (g), visiting a district (district 1) and visiting a processing facility (f);
type 2	starting at a processing facility (f), visiting a district (district 1), and returning to a processing facility (f);
type 3	starting at a vehicle depot (g), visiting a district (district 1), visiting a second district (district 2), and visiting a processing facility (f);
type 4	starting at a processing facility (f), visiting a district (district 1), visiting a second district (district 2), and visiting a processing facility (f).

If $|G|$ is the number of depots, $|F|$ the number of processing facilities and $|N|$ the number of districts, there will be $|G|\text{x}|N|\text{x}|F|$ type 1 trips, $|F|\text{x}|N|\text{x}|F|$ type 2 trips, $|G|\text{x}|N|\text{x}|N|\text{x}|F|$ type 3 trips and $|F|\text{x}|N|\text{x}|N|\text{x}|F|$ type 4 trips.

3.2. Mixed Integer Linear Programming model

In what follows, we provide a MILP formulation of the problem. First, we present indices and sets.

$n \in N$	Districts
$v \in V$	Vehicles
$y \in Y$	Trips
$g \in G$	Garages or depots
$f \in F$	Processing facilities

The following parameters are used. Units of measurement are given between brackets:

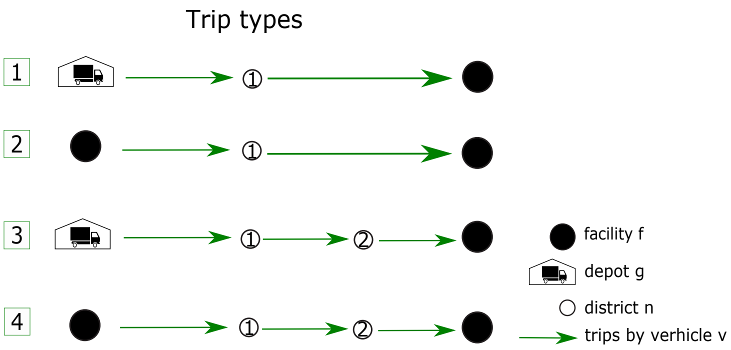

Figure 2: Four trip types to construct a collection route.

Q_n	Amount of waste to be collected in district n. (tonne)
S_n	Collection speed in district n. (hour/tonne)
C^h	Hourly cost of transportation (fuel, wages). (euro/hour)
C^v	Vehicle cost per day (depreciation). (euro/vehicle)
H	Maximum number of hours a truck can drive on a day. (hours)
L	Capacity of a truck. (tonne)
M	A large number.
B_g	Maximum number of vehicles that can leave depot g on a day.
A_f	Maximum amount of waste that can be dropped off at processing facility f on a day. (tonne)
T_{nf}^{toproc}	Travel time from district n to processing facility f. (hours)
$T_{fn}^{fromproc}$	Travel time from processing facility f to district n. (hours)
T_{gn}^{dep}	Travel time from depot g to district n. (hours)
$T_{fg}^{procdep}$	Travel time from processing facility f to depot g. (hours)
$T_{nn'}^{nb}$	Travel time from district n to district n'. (hours)
T_f^{drop}	Time it takes to drop off waste at processing facility f. (hours)
$T_{ngf}^1 = T_{gn}^{dep} + T_{nf}^{toproc} + T_f^{drop}$	Travel time to perform a type 1 trip in which a truck travels from depot g to district n and then to processing facility f. (hours)
$T_{nff'}^2 = T_{fn}^{fromproc} + T_{nf'}^{toproc} + T_{f'}^{drop}$	Travel time to perform a type 2 trip in which a truck travels from processing facility f to district n and then to processing facility f'. (hours)
$T_{nn'gf}^3 = T_{gn}^{dep} + T_{nn'}^{nb} + T_{n'f}^{toproc} + T_f^{drop}$	Travel time to perform a type 3 trip in which a truck travels from depot g to district n, then to district n' and then to processing facility f. (hours)
$T_{nn'ff'}^4 = T_{fn}^{fromproc} + T_{nn'}^{nb} + T_{n'f'}^{toproc} + T_{f'}^{drop}$	Travel time to perform a type 4 trip in which a truck travels from processing facility f to district n, then to district n' and then to processing facility f'. (hours)

The following decision variables are used:

y^1_{vngf}	=1 if vehicle v performs a type 1 trip leaving depot g, visiting district n, and dropping off waste at processing facility f, 0 otherwise;
$y^2_{vnff'}$	Number of type 2 trips vehicle v performs leaving processing facility f, visiting district n, and dropping off waste at processing facility f';
$y^3_{vnn'gf}$	=1 if vehicle v performs a type 3 trip leaving depot g, visiting district n, and n' and dropping off waste at processing facility f, 0 otherwise;
$y^4_{vnn'ff'}$	Number of type 4 trips vehicle v performs leaving processing facility f, visiting district n and n', and dropping off waste at processing facility f';

x^1_{vngf}	The amount of waste collected in district n by vehicle v performing type 1 trips leaving depot g, visiting district n, and dropping off waste at processing facility f. (tonne);
$x^2_{vnff'}$	The amount of waste collected in district n by vehicle v performing type 2 trips leaving processing facility f, visiting district n, and dropping off waste at processing facility f'. (tonne);
$x^{31}_{vnn'gf}$	The amount of waste collected in district n by vehicle v performing type 3 trips leaving depot g, visiting district n and n', and dropping off waste at processing facility f. (tonne);
$x^{32}_{vnn'gf}$	The amount of waste collected in district n' by vehicle v performing type 3 trips leaving depot g, visiting district n and n', and dropping off waste at processing facility f. (tonne);
$x^{41}_{vnn'ff'}$	The amount of waste collected in district n by vehicle v performing type 4 trips leaving processing facility f, visiting district n and n', and dropping off waste at processing facility f'. (tonne);
$x^{42}_{vnn'ff'}$	The amount of waste collected in district n' by vehicle v performing type 4 trips leaving processing facility f, visiting district n and n', and dropping off waste at processing facility f'. (tonne);
p_{vgf}	=1 if vehicle v leaves depot g, collects waste, drops off its last load of waste at processing facility f, and returns to the same depot, 0 otherwise.
z	The number of vehicles needed for performing the waste collection on a day.

The Mixed Integer Linear Programming (MILP) formulation of this Waste Collection Problem (WCP) is:

$$
\text{(F1)} \qquad \min_{x,y,p,z} \quad \begin{aligned}[t] & C^v \cdot z + \sum_{v \in V} C^h \cdot \\ & [\sum_{n \in N} \sum_{n' \in N} \sum_{g \in G} \sum_{f \in F} \sum_{f' \in F} (T^1_{ngf} \cdot y^1_{vngf} + T^2_{nff'} \cdot y^2_{vnff'} + \\ & T^3_{nn'gf} \cdot y^3_{vnn'gf} + T^4_{nn'ff'} \cdot y^4_{vnn'ff'} + \\ & T^{procdep}_{fg} \cdot p_{vfg} + \\ & S_n \cdot x^1_{vngf} + S_n \cdot x^2_{vnff'} + S_n \cdot x^{31}_{vnn'gf} + \\ & S_{n'} \cdot x^{32}_{vnn'gf} + S_n \cdot x^{41}_{vnn'ff'} + S_{n'} \cdot x^{42}_{vnn'ff'})] \end{aligned} \tag{1}
$$

Waste collection transportation costs consist of operational costs (fuel, personnel) costs and investment costs (the cost of acquiring and maintaining a vehicle). The former is calculated by multiplying an hourly operational cost by the total driving time of all vehicles. The latter is the number of vehicles required to perform the waste collection multiplied by a depreciation cost per

day. Although researchers often must resort to estimations of these cost parameters, it is of vital importance that the relative difference between operational and investment costs is properly thought out. Otherwise, the model will make wrong assumptions on the trade-off of the level of importance between the two cost elements.
Subject to:

Vehicle capacity block

$$x^1_{vngf} \leq L \cdot y^1_{vngf} \qquad v \in V, n \in N, g \in G, f \in F \tag{2}$$

$$x^2_{vnff'} \leq L \cdot y^2_{vnff'} \qquad v \in V, n \in N, f \in F, f' \in F \tag{3}$$

$$x^{31}_{vnn'gf} + x^{32}_{vnn'gf} \leq L \cdot y^3_{vnn'gf} \qquad v \in V, n \in N, n' \in N, g \in G, f \in F \tag{4}$$

$$x^{41}_{vnn'ff'} + x^{42}_{vnn'ff'} \leq L \cdot y^4_{vnn'ff'} \qquad v \in V, n \in N, n' \in N, f \in F, f' \in F \tag{5}$$

The maximum amount of waste that can be picked up during one trip cannot exceed a vehicle's capacity. The amounts on the left hand side are the total waste collected on one specific trip. This trip can however be performed multiple times a day. Note that how the waste is divided over the repetitions of this trip for a vehicle does not influence the results of the optimization. We therefore do not need a constraint for each repetition.

Demand block

$$\sum_{v \in V} \sum_{g \in G} \sum_{n' \in N} \sum_{f \in F} \sum_{f' \in F} [x^1_{vngf} + x^2_{vnff'} + x^{31}_{vnn'gf} + x^{32}_{vn'ngf} + x^{41}_{vnn'ff'} + x^{42}_{vn'nff'}] = Q_n \qquad n \in N \tag{6}$$

All waste put out on the streets must be picked up; i.e., the demand of every district must be met.

Maximal shift duration

$$\sum_{n \in N} \sum_{n' \in N} \sum_{g \in G} \sum_{f \in F} \sum_{f' \in F} [S_n \cdot x^1_{vngf} + S_n \cdot x^2_{vnff'} + S_n \cdot x^{31}_{vnn'gf} + S_{n'} \cdot x^{32}_{vnn'gf} + S_n \cdot x^{41}_{vnn'ff'} + S_{n'} \cdot x^{42}_{vnn'ff'} + T^1_{ngf} \cdot y^1_{vngf} + T^2_{npp'} \cdot y^2_{vnff'} + T^3_{nn'gf} \cdot y^3_{vnn'gf} + T^4_{nn'ff'} \cdot y^4_{vnn'ff'} + T^{procdep}_{fg} \cdot p_{vfg}] \leq H \qquad v \in V \tag{7}$$

Each vehicle can drive around and collect waste for up to H hours per day.

Vehicle logic block

$$\sum_{n \in N} \sum_{n' \in N} \sum_{g \in G} \sum_{f \in F} (y^1_{vngf} + y^3_{vnn'gf}) \leq 1 \qquad v \in V \tag{8}$$

$$\sum_{n \in N} \sum_{n' \in N} \sum_{f \in F} (y^1_{vngf} + y^3_{vnn'gf}) = \sum_{f \in F} p_{vfg} \qquad v \in V, g \in G \tag{9}$$

$$M \cdot \sum_{n' \in N} \sum_{n' \in N} \sum_{g \in G} \sum_{f \in F} (y^1_{vngf} + y^3_{vnn'gf}) \geq \sum_{n \in N} \sum_{f \in F} \sum_{f' \in F} (y^2_{vnff'} + \sum_{n' \in N} y^4_{vnn'ff'}) \qquad v \in V \tag{10}$$

$$\sum_{v \in V} \sum_{n \in N} \sum_{n' \in N} \sum_{g \in G} \sum_{f \in F} (y^1_{vngf} + y^3_{vnn'gf}) \leq z \tag{11}$$

Constraint set (8) ensures that a vehicle can only leave the depot once a day. Therefore, it can only perform one type 1 or type 3 trip per day. Moreover, a vehicle must return to the same depot where it started, imposed by constraint set (9). A vehicle can only perform type 2 and type 4 trips if it performs a type 1 or a type 3 trip on the same day. This is ensured by constraint set (10). As described in the parameters list, M represents a large number. Only if a vehicle leaves a depot, trips between processing facilities are allowed. In constraint set (10), only one of the two y-variables on the left-hand side could potentially become 1 (as opposed to zero). They represent the trips leaving a depot and this can only be done once by a vehicle. Only when one of the left-hand side variables equals 1, the y-variables on the right-hand side are allowed to be larger than 0. The latter variables (right-hand side) represent trips between processing facilities. They can be any integer larger than or equal to zero. If one of the y-variables on the left-hand side equals 1, then the vehicle leaves a depot, which means that trips between processing facilities on the right-hand side are allowed to become larger than one. But because the left-hand side can be maximum 1 and we want to allow the right-hand side values to be higher than one (multiple trips between processing facilities are allowed to be performed by a vehicle), we multiply the left-hand side by a large number M. If the variables on the left-hand side remain zero (i.e. the vehicle does not leave any depot), the left-hand side will be zero. Due to the $\geq$ sign, no variable on the right can be larger than zero, therefore making sure that no trips between processing facilities are performed by the vehicle. If one of the variables on the left-hand side turns to one, the left-hand side will become a large number (M). Due to the $\geq$ sign, the right-hand side can now become any number, thus allowing multiple trips between processing facilities. Finally, constraint set (11) makes sure that the number of vehicles to be purchased must be larger or equal than the required number of vehicles.

Processing facility and depot capacity

$$\sum_{v\in V}\sum_{n\in N}\sum_{n'\in N}\sum_{g\in G}\sum_{f'\in F}(x^{1}_{vngf}+x^{2}_{vnn'f'f}+x^{31}_{vnn'gf}+x^{32}_{vnn'gf}+x^{41}_{vnn'f'f}+x^{42}_{vnn'f'f})\leq A_f \qquad f\in F \qquad (12)$$

$$\sum_{v\in V}\sum_{n\in N}\sum_{n'\in N}\sum_{f\in F}(y^{1}_{vngf}+y^{3}_{vnn'gf})\leq B_g \qquad g\in G \qquad (13)$$

Constraint set (12) makes sure that the daily capacity of each processing facility is not exceeded, while constraint set (13) limits the number of vehicles assigned to a depot to the depot's capacity.

Processing facility balance constraints

$$\begin{aligned}&\sum_{n\in N}\sum_{n'\in N}\sum_{g\in G}\sum_{f'\in F}(y^{1}_{vngf}+y^{2}_{vnf'f}+y^{3}_{vnn'gf}+y^{4}_{vnn'f'f}) && (14)\\ &\quad=\sum_{g\in G}p_{vfg}+\sum_{n\in N}\sum_{n'\in N}\sum_{f'\in F}(y^{2}_{vnff'}+y^{4}_{vnn'ff'}) \qquad v\in V, f\in F\end{aligned}$$

Constraint set (14) ensures that the number of times a vehicle arrives at a processing facility equals the number of times it leaves from the facility.

Subtour elimination block

A solution feasible with respect to all previously described constraints still allows for the creation of subtours, i.e. multiple closed sequences of nodes within a route that are not connected to one another. In Figure 4, vehicle 2 (dashed lines) has two subtours. The subtours start and end at the same location, but they are not connected to one another, which makes it impossible for the truck to execute this collection scheme. Note that subtours cannot occur within a trip, as the four trip types described above include at most 2 districts. Nevertheless, subtours of trips can still occur. Although constraint set (14) ensures that each vehicle leaves from the same processing facility as the one it arrived at, it does not guarantee that each trip is connected to the other trips and hence to the depot. To efficiently model trip subtour elimination constraints, we translate the resulting vehicle routes into a new graph, called the subtour graph, with a node for each depot and for each processing facility, and a directed arc for each trip connecting the start and end node of that trip. Figure 3 depicts the subtour graph corresponding to the collection routes presented in Figure 1. The trip performed by vehicle 1, starting from depot 2, collecting waste at district 1, and ending at processing facility 2, is translated into a directed arc from depot 2 to processing facility 2. The trip performed by vehicle 2, starting from depot 1, collecting waste at districts 5 and 4, and ending at processing facility 1, is translated into a directed arc from depot 1 to processing facility 1. The two directed arcs between processing facilities 1 and 2 represent the second trips for both vehicle

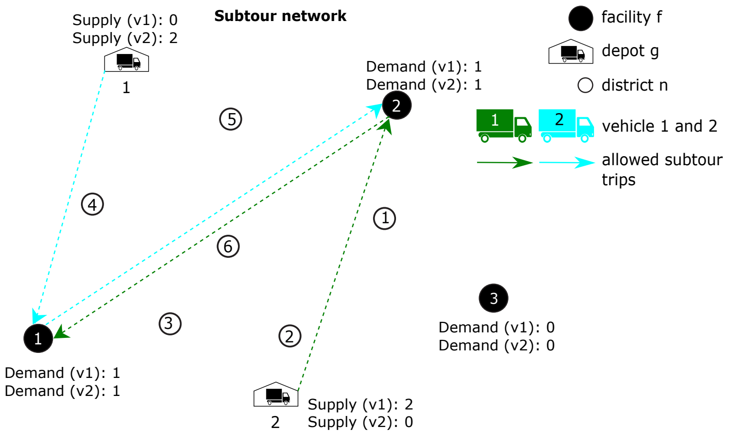

Figure 3: The subtour network corresponding to the collection routes in Figure 1.

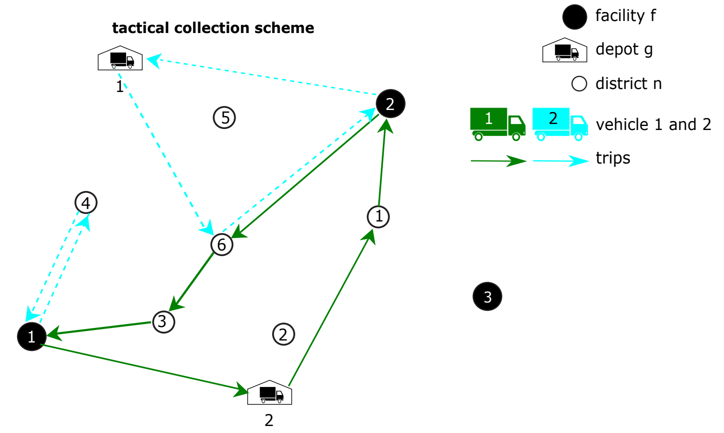

Figure 4: Collection routes with a subtour for the route of vehicle 2.

routes.
Figure 4 and Figure 5 respectively depict the collection routes and its corresponding subtour graph when subtours occur. Vehicle 2 drives from depot 1 to district 6, processing facility 2, and, finally, back to depot 1. It also drives from processing facility 1 to district 4 and back to processing facility 1. The collection route for vehicle 2 therefore contains 2 subtours, but still is a feasible solution to formulation (1)-(14). The corresponding subtour graph only contains one directed arc for vehicle 2 moving from depot 1 to processing facility 2.
We assign each processing facility that is visited by the vehicle on that day (according to the y-variables) a demand of 1 dummy product. If the processing facility is not visited, its demand is set to 0. The depot the vehicle leaves from receives a supply of dummy products equal to the number of visited processing facilities. To check whether a solution of the y-variables creates subtours, we check in the subtour network if all demand can be satisfied. If a subtour exists, the demand of a processing facility that is not connected to the supplying depot cannot be met.

To add these subtour elimination constraints to the model, we need additional variables which are derived from the y-variables leaving out the district indices:

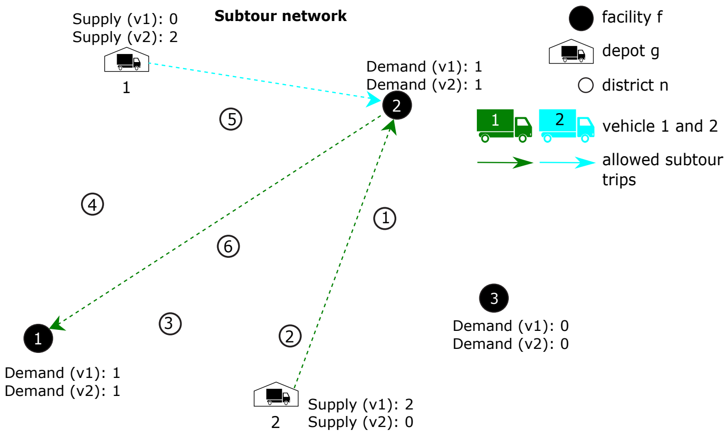

Figure 5: The subtour graph corresponding to the collection routes in Figure 4.

k_{vf} =1 if vehicle v visits processing facility f, 0 otherwise;
$a^{proc,proc}_{vff'}$ =1 if vehicle v performs at least one trip starting at processing facility f and ending at processing facility f', 0 otherwise;
$a^{dep,proc}_{vgf}$ =1 if vehicle v performs a trip starting at depot g and ending at processor p, 0 otherwise;
$\alpha^{proc,proc}_{vff'}$ =the flow between processing facility f and processing facility f'. (integer);
$\alpha^{dep,proc}_{vgf}$ =the flow between depot g and processing facility f (integer);

The demand for dummy products for a certain collection route is captured by k_{vf}. Transporting the dummy products from one node to another in the subtour graph is only allowed if the corresponding arc exists, i.e., if the vehicle performs a trip starting and ending at the corresponding nodes. Whether this is the case is captured in the decision variables $a^{proc,proc}_{vff'}$ and $a^{dep,proc}_{vgf}$. The number of transported dummy products over the arcs of the subtour network is captured in the alpha decision variables. Using these variables, the subtour elimination constraints can be formulated as follows:

$$\sum_{n\in N}\sum_{n'\in N}\sum_{g\in G}\sum_{f'\in F}(y^1_{vngf}+y^2_{vnff'}+y^2_{vnf'f}+y^3_{vnn'gf}+y^4_{vnn'ff'}+y^4_{vnn'f'f})\geq k_{vf} \qquad v\in V, f\in F \qquad (15)$$

$$\sum_{n\in N}\sum_{n'\in N}\sum_{g\in G}\sum_{f'\in F}(y^1_{vngf}+y^2_{vnff'}+y^2_{vnf'f}+y^3_{vnn'gf}+y^4_{vnn'ff'}+y^4_{vnn'f'f})\leq 100k_{vf} \qquad v\in V, f\in F \qquad (16)$$

$$\sum_{n\in N} y^{2}_{vnff'} + \sum_{n\in N}\sum_{n'\in N} y^{4}_{vnn'ff'} \geq a^{proc,proc}_{vff'} \qquad v\in V, f\in F, f'\in F \tag{17}$$

$$\sum_{n\in N} y^{2}_{vnff'} + \sum_{n\in N}\sum_{n'\in N} y^{4}_{vnn'ff'} \leq 100\cdot a^{proc,proc}_{vff'} \qquad v\in V, f\in F, f'\in F \tag{18}$$

$$\sum_{n\in N} y^{1}_{vngf} + \sum_{n\in N}\sum_{n'\in N} y^{3}_{vnn'gf} \geq a^{dep,proc}_{vgf} \qquad v\in V, g\in G, f\in F \tag{19}$$

$$\sum_{n\in N} y^{1}_{vngf} + \sum_{n\in N}\sum_{n'\in N} y^{3}_{vnn'gf} \leq 100\cdot a^{dep,proc}_{vgf} \qquad v\in V, g\in G, f\in F \tag{20}$$

$$\alpha^{proc,proc}_{vff'} \leq M\cdot a^{proc,proc}_{vff'} \qquad v\in V, f\in F, f'\in F \tag{21}$$

$$\alpha^{dep,proc}_{vgf} \leq M\cdot a^{dep,proc}_{vgf} \qquad v\in V, f\in F, g\in G \tag{22}$$

$$\sum_{f'\in F}(\alpha^{proc,proc}_{vf'f} - \alpha^{proc,proc}_{vff'}) + \sum_{g\in G}\alpha^{dep,proc}_{vgf} - k_{vf} = 0 \qquad v\in V, f\in F \tag{23}$$

$$M\cdot(1-\sum_{f\in F} p_{vfg}) + \sum_{f\in F}(\alpha^{dep,proc}_{vgf} - k_{vf}) \geq 0 \qquad v\in V, g\in G \tag{24}$$

$$\sum_{f\in F}(\alpha^{dep,proc}_{vgf} - k_{vf}) \leq 0 \qquad v\in V, g\in G \tag{25}$$

Constraint sets (15) and (16) determine which processing facilities are visited by vehicle v. Constraint sets (17)-(20) translate the y-variables into the subtour graph's a-variables. Constraint sets (21)-(22) ensure that transporting dummy products is only allowed between depots and processing facilities when the vehicle performs trips with the corresponding arcs' start and end points. Constraint set (23) ensures that the number of dummy products arriving at a processing facility equals the number of products leaving, minus the facility's demand. Finally, constraint sets (24)-(25) make sure that all demand is met by transporting the dummy products to the processors. When a vehicle leaves a depot (tested by $\sum_{f\in F} p_{vfg}$), the number of dummy products leaving this depot must equal the number of processing facilities it visits.

Note that formulation (1)-(25) allows for many symmetric solutions. To avoid unnecessary explorations of symmetric solutions in the branch-and-cut process of the MILP solver, we add the following symmetry breaking constraints:

$$\sum_{n\in N}\sum_{n'\in N}\sum_{g\in G}\sum_{f\in F}(y^{1}_{vngf} + y^{3}_{vnn'gf}) \leq \sum_{n\in N}\sum_{n'\in N}\sum_{g\in G}\sum_{f\in F}(y^{1}_{v-1ngf} + y^{3}_{v-1nn'gf}) \qquad v\in\{2,\ldots,|V|\} \tag{26}$$

We assume a homogeneous fleet. Formulation (1)-(25) however regards a solution in which vehicle 1 performs a particular sequence of trips different from a solution in which vehicle 10 performs the same sequence of trips (all other route-vehicle combinations being equal). These two solutions are however in reality the same. Therefore, constraints (26) force the model to first create a route for vehicle 1, then for vehicle 2, etc.

Secondly, for trips that visit two districts, there are for each depot-facility and facility-facility combination two options: one trip in which district n is visited first and one in which district n' is visited first. Of those two options, the option taking the least amount of time should be selected. Thus, to further break symmetry we only include the $y^{3}_{vnn'gf}$ and $y^{4}_{vnn'ff'}$ variables corresponding to this option.

4. Results

4.1. Case study

This research was motivated by the challenge of the Brussels Capital Region to reform the municipal bio-waste collection and treatment system, managed by the Brussels' waste collection authorities, to meet the new EU regulations for 2023. Bio-waste treatment scenarios were developed by Bortolotti et al. (2019) for which appropriate collection systems are proposed and evaluated in this case study.

First, in close collaboration with the Brussels' waste collection authorities the actual bio-waste collection has been analysed. Data was gathered on the historical collection rates of bio-waste and residual waste. One observation is that currently only 9% of the total bio-waste is collected separately and treated appropriately, whereas the remainder is collected together with residual waste and incinerated with energy recovery. The historical data was extrapolated to provide estimations for 2025, which is the reference year of this study. The objective is to considerably increase the fraction of bio-waste collected separately and to encourage bio-waste prevention at the source by 2025.

Bio-waste consists of food waste on the one hand and green waste on the other hand. Both waste types differ concerning processing options and could therefore benefit from a separate collection. However, separate collection brings challenges in terms of transportation and supplying sufficient capacity in processing facilities.

Four factors complicate the decision process for setting up a new collection system for bio-waste that meets the future EU standards. First, there is a limited budget, which excludes several expensive alternatives and requires an accurate forecast of the future operational transportation costs of the selected alternatives. Second, future waste levels are uncertain. Although future population size growth suggests an increase in bio-waste, it is far from clear how much of this bio-waste can be recovered separately from the residual waste. Two waste collection scenarios regarding annual separately collected food waste amounts (17 kt and 30 kt) are simulated. The annual amount of separately collected green waste is assumed to remain at 14.5 kt. Furthermore, the BCR aims to prevent food waste at the source, further reducing the food waste currently residing in the residual waste bag. Two waste prevention scenarios are simulated, one without food waste prevention and one with 20 kt food waste prevention at the source, reducing the food waste content in the residual waste fraction with 20 kt.

Third, different treatment options exist for processing food and green waste. Food waste can be treated separately in a bio-gas installation while green waste is typically composted. Currently, the BCR's separately collected food waste is collected door-to-door, transported to a transfer station in the BCR (SUEZ NOH), and then hauled to a bio-gas plant in Ypres, 130 km away from the BCR, managed by an external partner. Green waste is composted in a local composting facility, managed by the Brussels waste collection authorities. The two waste streams could potentially be treated together using a state-of-the-art composting facility (split up in three physical locations in the BCR with identical capacities) or a bio-gas co-composting processing facility in the North-East of the BCR. Figure 6 provides an overview of the potential treatment locations and the transfer station in the BCR. The latter two treatment options, however, involve new treatment facility investments in the BCR and require a minimum waste volume to run efficiently. Thus, the two new treatment options are only considered in combination with the waste collection scenarios in which 30 kt food waste is collected separately. The locations of the (potential) treatment sites are shown as green dots in Figure 6.

Fourth, when food and green waste are treated together, joint collection is possible. Food and green waste are collected at the same time by the same waste collection vehicle. This allows the waste collection authorities to considerably cut the hours driven and reduce the required number of waste collection vehicles for bio-waste collection. We, therefore, expect a considerable reduction in both

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[1] Map exported from OpenStreetMap contributors (2019)

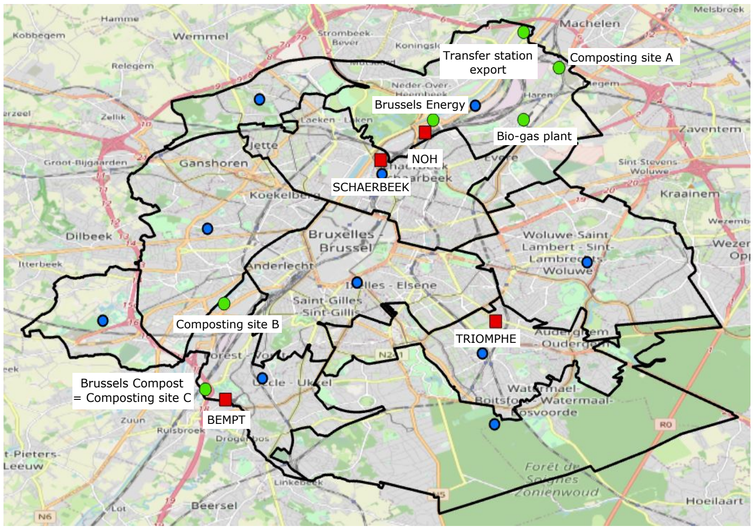

Figure 6: Regions, treatment locations, and depots in the Brussels Capital Region.[1]

operational and investment costs. Municipal residual waste and municipal food waste are collected both in bags (70%) and in bins (30%). Waste is collected in bins in apartment buildings, offices, and other large establishments. This distinction must be made as the driving speed for the two collection modes differs, resulting in different collection speeds (variable S_n). We also remark that residual waste is collected twice a week, while bio-waste is collected once a week. Waste collection vehicles collecting residual waste must therefore drive twice through all streets in the BCR, while vehicles collecting bio-waste, must do so only once. Also, green waste is only collected in specific areas of the BCR. For example, in the densely populated areas in the center of the BCR, green waste is not collected separately but can be deposited in the waste bags or bins dedicated to food waste.

Waste collection vehicles are stationed at specific depots. Upon close inspection of the historical data provided to us by the BCR's waste collection authorities, we found that specific depots are used for specific waste streams and collection mode (bag or bin) combinations. Three depots are used for the collection of residual waste bags (NOH, BEMPT, and TRIOMPHE). Residual waste bins are all emptied by vehicles from one depot: SCHAERBEEK. Food and green waste bags are collected by vehicles leaving from BEMPT and food waste bins are emptied by trucks from SCHAERBEEK. The locations of the depots are shown as red squares in Figure 6. For the capacity of the three depots for residual waste bag collection vehicles, we use the same distribution as currently used by the BCR's waste collection authorities. For the latter, we determined how many vehicles leave each of the three depots on an average week for the collection of residual waste bags. These numbers were then transformed into a distribution stating what percentage of the vehicles leave from which depot. We estimated the maximum number of vehicles that would be required for each day based on the data provided to us by the BCR's authorities and divided this number over the depots using this distribution. The BCR's waste collection authorities informed us that this division will probably remain constant in the near future. We, therefore, keep this distribution for the simulated scenarios. In a future study, this restriction will be removed to determine an optimal assignment of depots to waste streams (food, green, bio-, and residual waste) and collection modes (bags/bins).

Taking into account all these factors, four scenarios were defined, each with their own specific waste collection alternatives (treatment option and jointly/separate collection of bio-waste). These scenarios and their respective waste collection alternatives differ with respect to (1) the assumption on how much of the future bio-waste generation will be separated and how much will end up in the residual waste fraction, (2) the number, types, and locations of the processing facilities, and (3) which waste streams are collected together and which separately. The resulting waste scenarios and their waste collection alternatives are presented in Table 1.

Scenario		Residual waste	Food waste	Green waste	Joint bio-waste
BAU	Treatment option	Brussels Energy	Export to Ypres	Brussels Compost	n.a.
	Weight (kt)	328	17	14.5	n.a.
	Depots bags	NOH, BEMPT, TRIOMPHE	BEMPT	BEMPT	n.a.
	Depots bins	SCHAERBEEK	SCHAERBEEK	SCHAERBEEK	n.a.
	Collection modes	bag & bin	bag & bin	bag	n.a.
Scenario 1	Treatment option	Brussels Energy	3 composting sites, bio-gas, export to Ypres	3 composting sites bio-gas, Brussels compost	3 composting sites, bio-gas, export to Ypres
	Weight (kt)	315	30	14.5	44.5
	Depots bags	NOH, BEMPT, TRIOMPHE	BEMPT	BEMPT	BEMPT
	Depots bins	SCHAERBEEK	SCHAERBEEK	SCHAERBEEK	SCHAERBEEK
	Collection modes	bag & bin	bag & bin	bag	bag & bin (only food)
Scenario 2	Treatment option	Brussels Energy	Export to Ypres	Brussels Compost	n.a.
	Weight (kt)	308	17	14.5	n.a.
	Depots bags	NOH, BEMPT, TRIOMPHE	BEMPT	BEMPT	n.a.
	Depots bins	SCHAERBEEK	SCHAERBEEK	SCHAERBEEK	n.a.
	Collection modes	bag & bin	bag & bin	bag	n.a.
Scenario 3	Treatment option	Brussels Energy	3 composting sites, bio-gas, export to Ypres	3 composting sites, bio-gas, Brussels compost	3 composting sites, bio-gas, export to Ypres
	Weight (kt)	295	30	14.5	44.5
	Depots bags	NOH, BEMPT, TRIOMPHE	BEMPT	BEMPT	BEMPT
	Depots bins	SCHAERBEEK	SCHAERBEEK	SCHAERBEEK	SCHAERBEEK
	Collection modes	bag & bin	bag & bin	bag	bag & bin (only food)

Table 1: Scenarios and collection alternatives for the BCR case

In the business as usual (hereafter BAU) case, 17 kt food waste is collected separately from residual waste. No additional food waste is prevented at the source, resulting in a residual waste quantity of 328 kt. Food and green waste are always collected separately as the current treatment option (food waste exported to Ypres and green waste treated at Brussels Compost) is not altered. The alternative treatment options would require higher levels of separate food waste collection to operate efficiently. Table 1 also provides an overview of the different collection modes per waste stream (bag/bin) and the depots from which the waste collection vehicles can leave.

In scenario 1, 30 kt food waste is collected separately. No additional food waste is prevented at the source. Therefore, residual waste quantities are reduced to 315 kt. The two new alternative treatment options (three composting sites and a bio-gas installation) can run efficiently with this higher level of collected bio-waste. They are therefore added to the treatment options of separately collected bio-waste fractions. Under scenario 1, food and green waste could potentially be collected jointly and transported to either the transfer station for export to Ypres, to three new composting sites, or to a new bio-gas plant.

Scenario 2 is the waste prevention scenario: 17 kt food waste collection combined with 20 kt food waste prevention. The only difference between scenario 2 and the BAU case is a reduction of the residual waste quantity. The additional food waste collection of scenario 1 and the food waste prevention of 20 kt of scenario 2 are combined in scenario 3.

Optimizing each combination of scenario and collection alternative allows us to answer five specific questions from policy makers. First, the impact of collecting additional food waste separately from the residual waste fraction on costs can be determined. Will costs rise if the BCR's residents can be convinced to improve their food waste separation rate? Second, we can determine how the fleet would need to be reallocated from residual waste to bio-waste and whether additional vehicle investments should be made. Third, the cost impact of the waste prevention scenarios shows us how sensitization of the BCR's residents can have a direct effect on the costs incurred by the waste collection authorities. Fourth, the three bio-waste treatment options can be evaluated to derive the preferred option with regards to collection costs. Last, we will derive how significant the cost reduction would be if bio-waste is collected jointly.

Parameter	Value
C_h: Hourly cost of transportation (fuel, wages). (euro/hour)	55[a]
C_v: Vehicle cost per day (depreciation). (euro/vehicle)	15.28[a]
H: Maximum number of hours a truck can drive on a day. (hours)	6.7
L: Capacity of a truck. (tonne)	6
M: A large number.	99999

[a] The cost parameters represent the trade-off between the daily investment cost of a vehicle and the hourly operational cost of collecting waste. This trade-off was provided to us by the Brussels' waste collection authorities as no real cost parameters could be disclosed.

Table 2: Parameter values for the BCR case study

Table 2 provides the values of the parameters for this waste collection problem. Note that the cost parameters for the operational and investment costs do not reflect the actual costs. They merely represent the trade-off between the daily investment cost of a vehicle and the hourly operational cost of collecting waste. This trade-off was provided to us by the Brussels' waste collection authorities as no real cost parameters could be disclosed. Multiplying these two cost parameters by the same number to create the real monetary costs will result in the same solutions to the different problem instances, i.e., the same routes will be created. Furthermore, comparing the different scenarios using these costs remains valid as long as all scenarios are run with the same cost parameters. Waste generation data is gathered on a district level. The Brussels Capital Region contains 145 districts. However, to provide solutions within reasonable computation time, the districts were aggregated to ten regions, presented in Figure 6. The center of gravity coordinate of a region (blue dots) represents the location to which a vehicle will have to drive and leave from for waste collection in that region.

The data provided to us by the Brussels' waste collection authorities comprised 3 months in the summer and 2 months in autumn. As generally more waste is generated in autumn than in the summer an average week in the summer and an average week in autumn was constructed, which are both simulated. The annual results presented in Section 4.2 are the average results of these two weeks, multiplied by 52 weeks. The results of one week per season can be found in Appendix B.

The driving distance within a district was calculated using the GIS-software Arcgis Pro (ESRI, 2019), road maps by OpenStreetMap (OpenStreetMap contributors, 2019), and UrbIS-Adm GIS-data provided by the Brussels Regional Informatics Centre (2019). The driving time per region is then derived by dividing the driving distance by a driving speed, which varies between 5 km/h and 30 km/h depending on the population density of the region and the collection mode. Bin collection in the BCR generally can be done faster than bag collection, which is why a fixed speed of 30 km/h is used for this collection mode. The collection speed (S_n) per region (in hour/ton) is derived by dividing the regions' collection time by the daily waste generated in this district.

For each scenario, an optimization will be executed to find the daily collection routes for the waste vehicles with a minimum transportation cost. Vehicles can be assigned to one of the available depots (depending on the waste stream) and transport the collected waste to different processing facilities (e.g., the three composting sites in scenario 1).

4.2. Case study results

For each combination of scenario, collection alternative, season, collection mode, and weekday (234 instances) an optimization was run for 8 hours using IBM ILOG CPLEX Optimization Studio, Version 12.10 with the default settings and optimization strategies. CPLEX applies a branch-and-cut algorithm with a depth-first strategy. It periodically uses heuristics to compute integer solutions at a current node. Note that no cut-off value for the optimization gap was introduced. The model was run on the Genius cluster of the Flemish Supercomputer infrastructure which uses Intel Skylake processors (Intel(R) Xeon(R) Gold 6140 CPU, 2.30GHz). We restricted the optimization of each instance to the use of 6 cores. The aggregated results per week for each combination of scenario, collection alternative, season, and collection mode can be found in Appendix B. Each line presents the aggregated vehicle requirements and costs for an entire week. The minimum and maximum gaps over the days of the week are shown in the last two columns. For 94 of the instances, an optimal solution was found. Of the remaining instances, most reached a gap lower than 1% (105), others (20) obtained a gap varying between 1% and 5%. For 15 of the 234 instances, the resulting gap exceeded 5% after 8 hours, but remained below 10%. Appendix B presents for each combination the total number of truckdays (i.e. the use of one truck on one day), working hours, and costs for the simulated week, and the minimum and maximum gap over the simulated days. The instances with higher gaps are the instances of the composting treatment option with three treatment locations. Instances with multiple depot locations however have low gaps. We can therefore conclude that introducing multiple intermediate drop-off locations makes this waste collection problem significantly more difficult to solve.

BAU, scenario 2	Separate collection bio-waste	
Waste stream	Green	Food
Processor	Composting	Bio-gas (Ypres)
Weight (kt)	14.5	17
Collection duration (h)	18,573	38,841
Truckdays	2,886	6,032
Investment cost[a]	44,098	92,169
Operational cost[a]	1,021,489	2,181,989
Total cost[a]	1,065,587	2,274,158

[a] The cost parameters represent the trade-off between the daily investment cost of a vehicle and the hourly operational cost of collecting waste. This trade-off was provided to us by the Brussels' waste collection authorities as no real cost parameters could be disclosed.

Table 3: Results for bio-waste collection for the BAU case and scenario 2 for the BCR case.

Table 3, Table 4, and Table 5 show the results for respectively bio-waste collection under the BAU case and scenario 2, bio-waste collection under scenario 1 and scenario 3, and residual waste collection under all scenarios. When more food waste is collected separately from the residual waste fraction, collection costs for bio-waste will increase if the same collection option (separate versus joint) and treatment option (food waste export to Ypres for bio-gas treatment & green waste composting by Brussels Compost) are maintained. However, bio-waste collection costs are expected to increase by less than 1%. This is due to the low collection efficiency of food waste collection. Most routes executed by a vehicle on a day only include one drop-off due to the still relatively the low collection rate compared to residual waste. Vehicles collecting bio-waste are more constrained by their maximum shift duration than their load capacity and need to drive through all the streets

Scenario 1 & 3	Joint collection bio-waste			Separate collection bio-waste		
Processor	Composting	Bio-gas	Export to Ypres	Composting	Bio-gas	Export to Ypres & Brussels Compost
Weight (kt)	44.5	44.5	44.5	44.5	44.5	44.5
Collection duration (h)	40,814	42,163	41,763	57,207	60,933	58,644
# Truckdays	6,448	6,630	6,578	8,918	9,594	9,100
Investment cost[a]	98,525	101,306	100,512	136,267	146,596	139,048
Operational cost[a]	2,244,781	2,318,967	2,296,960	3,146,372	3,351,302	3,225,436
Total cost[a]	2,343,307	2,420,273	2,397,472	3,282,640	3,497,899	3,364,484

[a] The cost parameters represent the trade-off between the daily investment cost of a vehicle and the hourly operational cost of collecting waste. This trade-off was provided to us by the Brussels' waste collection authorities as no real cost parameters could be disclosed.

Table 4: Results for bio-waste collection for scenario 1 and scenario 3 for the BCR case.

All scenarios	Residual waste			
	BAU	Scenario 1	Scenario 2	Scenario 3
Processor	Brussels Energy	Brussels Energy	Brussels Energy	Brussels Energy
Weight (kt)	328	315	308	295
Collection duration (h)	103,829	102,226	101,474	99,874
Truckdays	16,978	16,640	16,328	16,016
Investment cost[a]	259,424	254,259	249,492	244,724
Operational cost[a]	5,710,585	5,622,431	5,581,088	5,493,045
Total cost[a]	5,970,009	5,876,691	5,830,579	5,737,770

[a] The cost parameters represent the trade-off between the daily investment cost of a vehicle and the hourly operational cost of collecting waste. This trade-off was provided to us by the Brussels' waste collection authorities as no real cost parameters could be disclosed.

Table 5: Results for residual waste collection for the BCR case.

Collection type	Treatment option bio-waste	BAU	Scenario 1	Scenario 2	Scenario 3
Separate	3 composting sites	n.a.	9,159,330	n.a.	9,020,409
	Bio-gas	n.a.	9,374,589	n.a.	9,235,669
	Export to Ypres & Brussels Compost	9,309,754	9,241,175	9,170,324	9,102,254
Joint	3 composting sites	n.a.	8,219,997	n.a.	8,081,076
	Bio-gas	n.a.	8,296,964	n.a.	8,158,043
	Export to Ypres & Brussels Compost	n.a.	8,274,162	n.a.	8,135,242

Table 6: Total costs per scenario and collection alternative.

of the BCR regardless of the waste put on the curb.

The additional food waste collection requires 3% more truckdays (6214 in scenario 1 vs. 6032 in BAU). From Table 5 we derive that 2% less truckdays (16,640 in scenario 1 vs. 16,978 in BAU) are needed for residual waste collection. From Table 7 and Table 8 in Appendix B we can derive that under scenario 1, on an average week in the summer, a waste collection vehicle needs to leave a depot 317 (237+80) times for collecting the residual waste generated in the BCR and 323 times in autumn (242+81). Under the BAU scenario, however, a waste collection vehicle needs to leave a depot 324 (243+81) times in the summer and 329 (247+82) times in autumn for collecting residual waste. Therefore, reducing the residual waste in scenario 1 requires 7 truckdays less in summer and 6 truckdays less in autumn for the weekly residual waste collection. Increasing the food waste collection, while maintaining the current treatment strategy (Export to Ypres) requires 120 truckdays (93+27) for collecting the weekly generated food waste in summer and 119 (93+26) in autumn. This is 5 truckdays more than the BAU scenario (120–(92+23)) in summer and 2 truckdays more in autumn (119–(93+24)). Thus, the collection vehicles freed up thanks to the reduced residual waste can be employed for the collection of the increased food waste.

Joint collection of food and green waste is, as can be expected, always significantly less expensive than separate collection (between 29% and 31% less expensive). If food and green waste are collected jointly under scenario 1 and if both are treated in Ypres, the number of truckdays can be reduced further by 75 (55+93+27-100) on a weekly basis in summer and by 75 (56+93+26-100) in autumn (see Table 7 and Table 8 in Appendix B). Considering this large reduction in required truckdays, the fleet size could potentially be reduced if food and green waste are collected jointly. Of the three treatment options, the composting option results in the lowest costs. Note that the instances of this treatment option have higher gaps compared to the instances of the other two options. Therefore, there is a probability that the cost of this option would even be smaller, making this option even more suitable. This is because the locations of the three identical composting facilities are more dispersed over the geographical area of the BCR, which reduces the distance of each region in the BCR to its closest treatment location. Furthermore, the additionally collected food waste will create additional costs for transporting the waste to the treatment facility in Ypres, which is not included in this analysis. The waste collection costs of the three options need to be compared to the respective investment and exploitation costs to determine the best course of action. This is however considered outside the scope of this paper, but instead, part of the report presented to the Brussels' waste collection authorities.

Table 5 presents the impact of the different scenarios on residual waste collection. As the waste collected in the residual waste bags and bins is reduced in scenarios 1, 2, and 3, the number of trucks required and the hours worked, and, therefore, also the costs, drop. An annual food waste prevention of 20 kt can reduce residual waste collection costs by 2.3% (comparing scenario 2 with BAU), while on an average day, residual waste collection would require 2 trucks less.

A summary of the costs for both residual and bio-waste collection is presented in Table 6. Although we expected a rise in collection costs under scenario 1, if additional food waste is collected separately a cost reduction can be achieved: -0.7% under the same treatment option and -1.6% under the composting scenario. If 20 kt food waste could be prevented at the source, a cost reduction of 1.5% can be achieved. Combining both prevention and additional food waste collection in Scenario 3 reduces total costs by 3.1% under the composting scenario. If, however, bio-waste would be collected jointly, the costs of collecting bio-waste can be reduced with 29% to 31%, depending on the treatment option. Joint bio-waste collection can, thus, lead to a total cost reduction of 11.7% and 13.2% under respectively scenario 1 and scenario 3 (under the composting treatment option).

5. Conclusion and future research

This paper provides a mixed integer linear programming model for developing optimized waste collection routes with multiple depots, homogeneous, capacitated vehicles requiring intermediate stops at multiple processing facilities, and multiple pick-ups per collection location. The model can be used by policy makers to simulate waste collection scenarios and evaluate the impact of policy decisions on costs and the required waste collection fleet.

The model's use was illustrated through four future, realistic bio-waste collection scenarios of the Brussels Capital Region (BCR). The results show that if the current treatment option and collection mode (separate collection of food and green waste) remains, the additional separate collection of food waste would decrease collection costs. Moreover, joint collection of food and green waste can significantly reduce bio-waste collection costs by up to 31%. Furthermore, a cost reduction can be achieved if the composting treatment option would be implemented in which bio-waste is composted in three locations spread over the BCR.

The instances of the case study were optimized using a state-of-the-art solver which attained reasonable gaps (between 0% and 10%). This shows that including a constraint on the maximum number of visits per trip (i.e. per visit to a processing facility) by using predefined trips as a decision variable reduces the complexity of this general waste collection problem. It, therefore, allows state-of-the-art solvers to find solutions with reasonable gaps within reasonable computation time for instances with up to ten districts, up to three processing facilities, and up to three depots. After optimizing the instances of the case study using a state-of-the-art solver we found that the solver could not reach optimality within reasonable computation time for instances with multiple processing facilities. For these instances, the solver attained reasonable gaps (between 1% and 10% for food waste and jointly collected bio-waste), but the gaps were significantly higher than the instances with a single processing facility. We, therefore, conclude that the introduction of multiple processing facilities (with intermediate stops) significantly increases the complexity of the waste collection problem. Thus, additional modelling efforts such as alternative formulations or pricing schemes are most likely best directed at handling the intermediate stops.

Combining the results of the case study on waste collection costs with treatment costs is left for a future study. Additionally, for larger instances or instances where a more detailed district level is considered, a heuristic seems most appropriate. Furthermore, allowing more than two subsequent pick-ups per trip will substantially increase the complexity of the waste collection problem. A heuristic is therefore deemed to be more appropriate when the allowed number of pick-ups per trip increases substantially.

The MILP-model presented in this study could be extended with the introduction of a heterogeneous fleet. This extension would require vehicle type-specific load capacity constraints and vehicle type-specific depot capacity constraints. Also, an interesting avenue for future research is to assume real-time information on the fill-levels of bins through the use of sensors giving rise to a smart waste collection system (see, e.g., Fadda et al., 2018; Ramos et al., 2018a, and Ramos et al., 2018b) and study the impact on collection costs and service levels in the different scenarios.

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Appendices

A. Proofs and bounds

Proposition 1. *The Waste Collection Problem (WCP) is strongly NP-hard*

Proof 1. *We prove that the WCP is strongly NP-hard by reduction of the bin packing problem, which is NP-hard. Consider an instance of the WCP with only one depot and only one processing facility. All vehicles and the processing facility have infinite capacity. The collection speed of every district is put to zero, which results in zero collection time at each district. Suppose that the depot and processing facility are located at the same location. Therefore the time it takes to perform a trip with a visit to district n will be the same regardless of the trip type (type 1 or type 2):* $T^1_n = T^2_n = T_n$ *for all n. Correspondingly, the duration of trips with a visit to district n, followed by a visit to district n' will be the same for trip type 3 and trip type 4:* $T^3_{nn'} = T^4_{nn'}$ *for all n and* n'*. Moreover, we assume that the duration of a trip type 3 or 4 with a visit to districts n and* n' *equals the sum of the durations of the two trips of type 1 or 2 to the two districts separately:* $T^3_{nn'} = T^4_{nn'} = T_n + T_{n'}$*. Consequently, the use of trip types 3 and 4 becomes redundant. In this reduced problem, the total duration of all trips performed together will be constant, regardless of the choice of trip types:*

$\sum_{n\in N} T_n = T^1_{ngf}\cdot y^1_{vngf} + T^2_{nff'}\cdot y^2_{vnff'} + T^3_{nn'gf}\cdot y^3_{vnn'gf} + T^4_{nn'ff'}\cdot y^4_{vnn'ff'} = Constant$. *As the collection time is constant, the objective function is reduced to minimizing the investment cost:* $C^v\cdot z$. *This equals minimizing the number of vehicles* z *required to collect all the waste if we assume an investment cost equal to one* ($C^v = 1$)*. Each vehicle has a maximum shift duration of* H*. Thus, the problem is reduced to creating a minimum number of subsets* (Z) *of* $T_n, n\in N$ *in which each subset has a duration* $\leq H$*. This is equivalent to the bin packing problem with a bin capacity of* H*. It can be shown that the minimum number of subsets in the bin packing problem equals* Z *if and only if the minimum cost of the WCP is* Z*. The bin packing problem is, therefore, a special case of the WCP. Thus, the WCP is strongly NP-hard.*

B. Detailed results of the bio-waste collection case study

Table 7, Table 8, Table 9 and Table 10 present for each combination of scenario, collection alternative, season and collection mode the total number of truckdays (i.e. the use of one truck on one day), working hours and costs for the simulated week and the minimum and maximum gap over the simulated days.
Note that bio-waste collection is not included in Table 9 (for scenario 2) and Table 10 (for scenario 3). Bio-waste collection in scenario 2 and the BAU case are the same, while it is also the same for scenario 1 and 3.

BAU								
Waste type	Processor	Season	bag/bin	Truck-days	Working hours	Total cost[a]	Min gap	Max gap
Residual waste	Brussels Energy	Summer	BAG	243	1515	87,056	0.01%	0.46%
			BIN	81	467	26,931	0.01%	0.47%
		Autumn	BAG	247	1532	88,023	0.17%	0.62%
			BIN	82	479	27,605	0.01%	0.22%
Food waste	Export to Ypres	Summer	BAG	92	614	35,153	0.01%	0.05%
			BIN	23	149	8,535	0.01%	0.01%
		Autumn	BAG	93	615	35,228	0.01%	0.06%
			BIN	24	149	8,551	0.01%	0.01%
Green waste	Brussels Compost	Summer	BAG	55	352	20,227	0.00%	0.01%
		Atumn	BAG	56	362	20,757	0.00%	0.05%

[a] The cost parameters represent the trade-off between the daily investment cost of a vehicle and the hourly operational cost of collecting waste. This trade-off was provided to us by the Brussels' waste collection authorities as no real cost parameters could be disclosed.

Table 7: Results for the business as usual scenario of the BCR case.

Scenario 1								
Waste type	Processor	Season	bag/bin	Truck-days	Working hours	Total cost[a]	Min gap	Max gap
Residual waste	Brussels Energy	Summer	BAG	237	1494	85,813	0.34%	0.51%
			BIN	80	458	26,419	0.01%	0.50%
		Autumn	BAG	242	1510	86,762	0.30%	0.53%
			BIN	81	469	27,033	0.01%	0.30%
Food waste	3 composting sites	Summer	BAG	91	586	33,621	1.35%	7.82%
			BIN	25	152	8,769	0.01%	2.07%
		Autumn	BAG	91	587	33,681	6.09%	9.16%
			BIN	24	153	8,808	0.01%	1.97%
	Bio-gas	Summer	BAG	95	626	35,892	0.01%	0.04%
			BIN	27	154	8,866	0.01%	0.01%
		Autumn	BAG	96	627	35,976	0.00%	0.29%
			BIN	26	155	8,919	0.01%	0.26%
	Export to Ypres	Summer	BAG	93	616	35,320	0.01%	0.10%
			BIN	27	155	8,945	0.01%	0.01%
		Autumn	BAG	93	617	35,369	0.01%	0.12%
			BIN	26	153	8,785	0.01%	0.01%
Joint bio-waste	3 composting sites	Summer	BAG	98	608	34,956	4.28%	9.04%
		Autumn	BAG	98	611	35,075	1.08%	8.93%
	Bio-gas	Summer	BAG	101	655	37,594	0.01%	1.14%
		Autumn	BAG	101	658	37,708	0.01%	1.58%
	Export to Ypres	Summer	BAG	100	648	37,170	0.01%	1.10%
		Autumn	BAG	100	651	37,310	0.01%	1.04%
Green waste	3 composting sites	Summer	BAG	55	356	20,414	0.01%	1.42%
		Autumn	BAG	57	365	20,961	0.01%	1.39%
	Bio-gas	Summer	BAG	62	385	22,147	0.00%	0.01%
		Autumn	BAG	63	396	22,735	0.00%	0.77%
	Brussels Compost	Summer	BAG	55	352	20,227	0.00%	0.01%
		Autumn	BAG	56	362	20,757	0.00%	0.05%

[a] The cost parameters represent the trade-off between the daily investment cost of a vehicle and the hourly operational cost of collecting waste. This trade-off was provided to us by the Brussels' waste collection authorities as no real cost parameters could be disclosed.

Table 8: Results for scenario 1 of the BCR case.

Scenario 2								
Waste type	Processor	Season	bag/bin	Truck-days	Working hours	Total cost[a]	Min gap	Max gap
Residual waste	Brussels Energy	Summer	BAG	234	1,484	85,197	0.26%	0.65%
			BIN	76	454	26,127	0.01%	0.48%
		Autumn	BAG	238	1,500	86,141	0.30%	0.63%
			BIN	80	465	26,789	0.01%	0.28%

[a] The cost parameters represent the trade-off between the daily investment cost of a vehicle and the hourly operational cost of collecting waste. This trade-off was provided to us by the Brussels' waste collection authorities as no real cost parameters could be disclosed.

Table 9: Results for scenario 2 of the BCR case, residual waste.

Scenario 3								
Waste type	Processor	Season	bag/bin	Truck-days	Working hours	Total cost[a]	Min gap	Max gap
Residual waste	Brussels Energy	Summer	BAG	232	1,465	84,135	0.45%	1.19%
			BIN	75	441	25,402	0.01%	0.18%
		Autumn	BAG	232	1,480	84,943	0.44%	1.03%
			BIN	77	454	26,204	0.01%	0.71%

[a] The cost parameters represent the trade-off between the daily investment cost of a vehicle and the hourly operational cost of collecting waste. This trade-off was provided to us by the Brussels' waste collection authorities as no real cost parameters could be disclosed.

Table 10: Results for scenario 3 of the BCR case, residual waste.