Solving a real-life multi-period trailer-truck waste collection problem with time windows

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Declarations of interest: none

Abstract

By introducing local recovery networks, regional and local environmental authorities can play an important role in facilitating the circular economy. This paper studies a network design problem that encompasses the recovery of separately collected household waste streams, which are collected in containers at civic amenity sites. We formulate a generic tactical-operational container collection problem that will be solved using a mixed integer linear programming approach. This paper makes both a theoretical and practical contribution. We are the first to study a two container vehicle capacity restriction combined with collection site inventory capacities, time windows, shift break time, and shift duration constraints. The model is applied to a number of real-life test instances and scenarios. The results provide insight in how different combinations of scenarios exactly affect the fleet requirements. This not only includes the number of trucks or information under which circumstances an additional truck would (not) be needed, but also the 12-day collection schedule for the collection crews.

Keywords: container collection, waste management, mixed integer linear programming optimization, tactical-operational planning.

1. Introduction

In the light of the transition towards a more circular economy, recovery of products, parts or materials will gain in importance. Processes to close these loops include reuse, remanufacturing and recycling. Additionally, the EU proximity principle related to waste management and emissions generated by transporting large amounts of end-of-life products, shift attention to local recovery networks. As in many other countries and regions in the EU, in Flanders (Belgium) recovery of household waste and material is organised via a combination of different systems. Part of the material is collected through a door-to-door system and part is collected through centralized drop of sites (see infra). The practical organisation of the recovery network depends on the material under consideration, but for several flows the actual treatment of the separately material occurs outside of the country's borders. As a consequence, materials sometimes travel large distances before being used again as a resource.

Regional and local environmental authorities can play a vital role in developing local recovery networks, in particular when the practical organization of solid household waste and material collection, treatment and recovery is the competency of the regional or municipal authorities (which is the case in many regions in the EU). When setting up a new local recovery network, however competent environmental authorities are typically confronted with several practical constraints, often related to transport and storage conditions within the existing (public) infrastructure. This paper attempts to solve the particular case of waste and material collection via a network of household waste recycling centers or civic amenity (CA) sites and proposes a model to optimize such a collection problem for the specific case of the region "Meetjesland" (a region in the north-west of the province East Flanders in Belgium). However, the applicability of the model extends beyond this specific region and is applicable to other regions facing similar collection problems. In particular, due to the growing attention for local recovery networks, competent environmental authorities and decisions makers are often confronted with the request to collect additional flows separately. Ex-ante evaluation of the investment requirements remains often a difficult exercise in such cases, as it is for instance not always obvious if the optimal new collection schedule requires investments in new trucks.

The multi-municipal cooperation for domestic waste management Meetjesland (IVM) is currently investigating the set-up of a local recovery network. As in many regions in the EU, waste management in Belgium is generally a regional (i.e., Brussels, Flemish or Walloon) competency. Within the legal framework set out by regional authorities, municipalities can still decide on many practical details related to its Municipal Solid Waste (MSW) management. However, this competency comes with an important responsibility concerning minimal levels of public service provision in local MSW management. Most of the Flemish and Belgian municipalities cooperate with other, often geographically close municipalities when providing these public services.

An important part of selective collection of household waste is organised through waste recycling centres or civic amenity (CA) sites. In such sites residents can drop off many of their end-of-life (EOL) materials either for free or at a variable or fixed fee. Note that in practice different management models for CA sites co-exist. For instance a recycling center can be operated by the municipality or by a group of municipalities working together via multi-municipal cooperation (MMC), but in case the municipality is managing the recycling center, subsequent treatment of the collected flows is in many cases still organized via the MMC. The number of separately collected flows and the exact composition of those flows, tend to differ between CA sites, but flows such as bulky household refuse, garden waste, electric appliances, wood waste, demolition waste, scrap metal, hard plastics, oil, etc. are accepted in virtually all Flemish municipalities. Clearly the municipalities or MMCs will not process all of the above materials themselves. Therefore the municipality or MMC will outsource further sorting and processing (often via a request for tender) to other private or public players for a number of flows. The latter is important as in that case the municipality has no longer control over the remaining life cycle of the material. As MMCs and municipalities might have different objectives than private companies (i.e., welfare maximization versus profit maximization), transport decisions of private players might not always be welfare maximizing.

The above observation was one of the key drivers for IVM to assess the potential in terms of transport optimization of setting up a local recovery network for one of the flows collected at its CA sites. After observing that some materials which are part of the flow of hard plastics, are actually used as a resource in the manufacturing industry within Flanders, it became clear that the traditional recovery network is probably not welfare maximizing if all transport costs, including externalities (such as emissions, congestion and noise hindrance) are taken into account. In the traditional recovery network hard plastics are shipped to various locations in Belgium and abroad for sorting once they have been collected at the CA sites affiliated to IVM. After sorting, the different sub-flows are either (shredded and) treated in recycling centers (often abroad) or shipped directly to a client where the material is used as a raw material in the production process.

An initial assessment by IVM revealed that end-of-life polyvinyl chloride (PVC) is used in considerable quantities as a resource by a firm located less than 100 km from the center of IVM's operational area. However, establishing a local recovery network for PVC involving the CA sites and nearby firm revealed several transport-related problems. As PVC is a sub-flow of hard plastics and hard plastics are generally collected as a single flow, starting with the new local recovery network for PVC requires either centralized sorting of hard plastics or separate collection of PVC at the CA sites. As the existing contracts with the processors state that hard plastics (in this case the remaining hard plastics after separating PVC) are collected at each CA site, only the latter option is feasible in reality. Additional constraints on the available space at the CA sites prevent the possibility of on-site stockpiling of large quantities of PVC.

Given the above constraints IVM decided to start with small $12\,m^3$ containers for PVC collection on a selection of its CA sites. In order to ensure a minimum degree of purity in the separately collected PVC flow, only a limited number of easily identifiable products -such as window and door frames, roll-down shutters and planks - are allowed in the designated PVC container. A first assessment within a pilot project revealed that in this way about 10 % (by weight) of hard plastics is collected separately as PVC. Before the pilot project can be extended to all 18 CA-sites within the MMC, IVM would like to know how the PVC can be collected and transported efficiently to the client.

The containers with PVC must be collected regularly, but given the limited scale of the project (i.e., currently only 18 CA sites), investing in a new vehicle exclusively dedicated to transport in the new local recovery network, would probably result in too much vehicle idle time. Therefore IVM would also like to know if the same vehicle fleet can be used additionally for transport of another larger flow. In particular, transport of the so-called bulky household refuse flow from the CA sites to the processing or transfer station seems to be a valid candidate. Bulky household refuse can be described as all waste generated by the normal operation of a private household which, because of its size, nature and/or weight, cannot be stored in the curbside receptacle for household waste collection[2]. Note that this flow is thus different from the residual household waste flow which is mainly collected at the curbside via bags or containers. Bulky household refuse is in all Flemish municipalities collected via the CA sites. The flow is also at least twice a year collected at the curbside via an on-demand system. Note that in our case we only focus on the bulky household refuse flow which is collected via the CA sites.

Combining transport of this flow with a local recovery network for PVC via the CA sites has the potential to yield an efficient solution for IVM for two reasons. First, for many CA sites, included the sites within the operating area of IVM, bulky household refuse is an important flow in terms of volume and weight. Combining such a bigger flow which needs to be transported separately anyway with a new, but much smaller flow can result in benefits of scope for the MMC. The number of additional trucks required to transport the PVC flow might for instance be limited when the same fleet of trucks used to transport both flows. Secondly, transport of bulky household refuse from the CA sites to the treatment facility is currently done via an external firm. Organising transport of both bulky household refuse and PVC internally, might result in a more efficient solution for the MMC in terms total expenses. Before the MMC can assess if the latter indeed holds, detailed information is needed on the number of trucks and the exact collection schedule. Both can be estimated with the model.

More specifically, the required fleet and appropriate collection schedule can be obtained by solving the following cost minimization problem. Containers, dedicated for either bulky waste or PVC, gradually fill up as residents drop off their waste at multiple civil amenity sites. Collection trucks, stationed at a depot, can collect up to two full containers simultaneously if the truck is equipped with a detachable trailer. Containers are not allowed to overflow. Thus, deciding on which day in the planning horizon to replace them with empty containers is crucial. Crews, working in shifts, are assigned to trucks and replace (partly) full containers with empty ones. Full containers are dropped off at the client processors (clients, henceforth) for the respective flows and empty ones are picked up. Furthermore, crews must adhere to

[2]For a more detailed definition, see OVAM (2022)

rules regarding breaks, the maximum working time and site opening hours. The goal of the model is to find a schedule that minimizes total cost, consisting of route and vehicle costs. This schedule describes which crew should visit which CA site on which day of the planning horizon and can be interpreted as the steady-state regime that can be performed over and over again.

Within the waste collection optimization literature one can distinguish between arc routing (e.g., Tirkolaee et al., 2018, 2019, 2022) or node routing, which is the approach adopted in this paper. Our problem setting has a unique combination of features not studied so far in the related literature. Collection is done by homogeneous vehicles having a discrete capacity of two containers that must be (un)loaded as a whole, which is rarely studied. Interesting exceptions include Bogh et al. (2014), Hauge et al. (2014), le Blanc et al. (2006), Raucq et al. (2019), and Wøhlk and Laporte (2022). This setting combined with a rich variety of operational constraints including shift durations, time windows, rest breaks, and collection site inventory capacity restrictions makes our problem setting unique.

In Section 2, an overview of the relevant literature is given. Section 3 provides a clear description of the optimization problem, explains the applied methodology by defining the concept of trips and offering an example of a feasible collection schedule and describes the full mixed integer linear programming model. Next, we explain some simplifications in Section 3.5. The test instances are presented in Section 4, and results are given in Section 5. Section 6 concludes the paper.

2. Literature

The design and optimization of recovery networks falls in the broad domain of reverse logistics related to waste management. Recent reviews on this topic can be found in, e.g., Beliën et al. (2014), Ghiani et al. (2014), Govindan and Soleimani (2017), Bing et al. (2016) and Van Engeland et al. (2018). Fleischmann et al. (2000) distinguish five activities (collection, inspection and separation, re-processing, disposal and re-distribution) in recovery network design. This paper focuses on collection.

Table 1: Overview of related literature on waste collection.

Study	Planning horizon	Decisions	Objective	Constraints					Solution methodology
				Vehicle capacity	Max. daily working time	Site time windows	Break (rest) time	Site inventory capacity	
Archetti & Speranza (2004)	One period (day)	Routing	Minimize total cost (drivers, extra time, penalty cost)	1 container	x	x			Improvement heuristic
Archetti & Speranza (2005)	One period (day)	Routing	Minimize total cost (drivers, extra time, penalty cost)	1 container	x	x			Improvement heuristic
Aringhieri et al. (2018)	One period (day)	Routing	Minimize vehicles used and minimize total duration	1 container	x				Neighborhood-based metaheuristic and MILP
Benjamin & Beasley (2010)	One period (day)	Routing	Minimize vehicles used and minimize total traveling time	Continuous capacity constraint	x	x	x		Tabu search and variable neighborhood search
Benjamin & Beasley (2013)	One period (day)	Routing	Minimize vehicles used and minimize total traveling time	Continuous capacity constraint	x	x	x		Neighborhood heuristic improved with a dynamic programming procedure
Bogh et al. (2014)	Multiple days (rolling horizon)	Routing	Minimize routing costs and minimize service costs at treatment facilities	2 containers				x	Simulated annealing
De Bruecker et al. (2018)	Multiple days	Routing	Minimize labor costs	Continuous capacity constraint	x		Shift succ.	Minimal one collection per week	Model enhancement, tabu search and simulation
Elbek & Wøhlk (2016)	Multiple days (rolling horizon)	Routing	Minimize routing costs and minimize service costs at treatment facilities	2 container types of fixed continuous capacity				x	Construction heuristic and variable neighborhood search
Fadda et al. (2018)	Multiple days	Routing	Minimize vehicle and routing costs	Continuous capacity constraint	x			x	Three-phased heuristic
Hauge et al. (2014)	One period (day)	Routing	Minimize total travel time	2 containers					Column Generation
Kim et al. (2006)	One period (day)	Routing	Minimize vehicles used and minimize total traveling time, maximize route compactness, balance workload	Continuous capacity constraint	x	x	x		Insertion heuristic
Lavigne et al. (2021)	One period (day)	Routing	Minimize vehicle and routing costs	Continuous capacity constraint	x			Process facility capacity	MILP
le Blanc et al. (2006)	Multiple days	Routing	Minimize routing costs	2 containers	x				Route construction heuristic followed by MILP for route selection
Marseglia et al. (2022)	One period (day)	Routing, configuration of multiple bin containers	Minimize containers used, minimize distance travelled	1 container				Capacity restriction with discrete intervals	Two-phase heuristic, MILP
Parth et al. (2018)	One period	Waste to depots and depots to recovery centers	Minimize collection cost, maximize recycling profit	Continuous capacity constraint				x	Chance constrained linear programming model
Rabbani et al. (2016)	One period (day)	Routing	Minimize total travel time	1 container	x				Local search and simulated annealing
Ramos et al. (2018)	Multiple days	Routing	Minimize routing costs, maximize recycling profit	Continuous capacity constraint				x	MIP and heuristic
Raucq et al. (2019)	One period (day)	Truck type, routing	Minimize total active time	2 containers	x	x			Column generation
Son et al. (2016)	One period (day)	Routing	Maximize collected waste quantitities, minimize environmental emissions	Heterogeneous vehicles with continuous capacity constraint	x	x (not in the case)		Minimal one visit for each site	ArcGis model
Teixeira et al. (2004)	Multiple days	Routing	Minimize total distance traveled	Continuous capacity constraint	x			Maximal time interval between collections	Construction heuristic
Tirkolaee et al. (2018)	Multiple days	Routing	Minimize vehicle and routing costs	Continuous capacity constraint	x				Construction heuristic and simulated annealing, MILP for evaluation
Tirkolaee et al. (2019)	Multiple periods	Routing	Minimize vehicle and routing costs, minimize longest tour distance	Continuous capacity constraint					ε-constraint method and evolutionary based heuristic
Tirkolaee et al. (2021)	Multiple periods	Routing	Minimize distance travelled, minimize time window violation, minimize the number of people around the disposal site	Continuous capacity constraint	x			x	MILP and a fuzzy chance-constrained programming approach
Tirkolaee et al. (2022)	Multiple periods	Routing	Minimize vehicle and routing costs, minimize vehicles emission, maximize hired labor, minimize workload deviation	Continuous capacity constraint	x				multi-objective simulated annealing and invasive weed optimization algorithm
Van Engeland and Beliën (2021)	Multiple days	Routing	Minimize vehicle and routing costs	Continuous capacity constraint	x				MILP heuristic, column generation
Vargas et al. (2022)	Multiple days	Routes to vehicles, truck allocation and routing, waste transfer station internal operation	Minimize number of vehicles and level daily waste collection		x				MILP, metaheuristic and discrete event simulation
Wøhlk and Laporte (2022)	One period (day)	Routing	Minimize vehicle and routing costs	2 containers	x				Variable neighborhood search
Wy et al. (2013)	One period (day)	Routing	Minimize vehicle and routing costs	1 container	x	x	x		Local neighborhood search
This paper	Multiple days	Routing	Minimize vehicle and routing costs	2 containers	x	x	x	x	MILP

Table 1 gives an overview of the related literature on optimization studies applied to operational waste collection. The container collection problem studied in this problem has four distinctive characteristics: (1) the truck-trailer setting with complete (un)loading leading to a discrete vehicle capacity constraint of two containers and hence trips of maximum 2 stops, (2) the tactical aspect of scheduling trips in a multiple days time horizon (i.e., the timetabling aspect), (3) the incorporation of time-related constraints as time windows and break rest time, and (4) the incorporation of site inventory capacity constraints.

The most distinguishing feature of this paper's problem setting is the discrete vehicle capacity constraint of two containers which leads to trips of at most two stops. Table 1 shows that most settings studied in the literature entail a continuous capacity constraint in which materials can be collected until a fixed amount is reached. A minority of studies considers a discrete capacity constraint in which containers must be (un)loaded as a whole. Moreover, half of these studies assume a capacity of only one container (e.g., Archetti and Speranza, 2004, 2005; Aringhieri et al., 2018; Marseglia et al., 2022; Rabbani et al., 2016; Wy et al., 2013), which leaves only 5 studies with a two-container vehicle capacity: Bogh et al. (2014), Hauge et al. (2014), le Blanc et al. (2006), Raucq et al. (2019), and Wøhlk and Laporte (2022). Elbek and Wøhlk (2016) also study a setting with two containers per vehicle, but these have continuous capacities (of different material types) and do not have to be loaded as a whole. None of those papers, however, incorporates the rich variety of time-related and site inventory capacity constraints of the problem setting studied in this paper, even not if we include the papers with a different vehicle capacity setting. Similar to this research, Van Engeland and Beliën (2021) also consider trips of at most two stops (albeit considering a continuous vehicle capacity constraint), but their problem setting does not include collection site related constraints as time windows and storage capacity nor breaks (rest time) for staff. In terms of constraints, the problem settings addressed by Kim et al. (2006) and Benjamin and Beasley (2010, 2013) are most closely related to our problem setting. The main differences with our setting include the continuous vehicle capacity constraint and the disregard of site inventory capacity constraints. Only a minority of studies do incorporate site inventory capacity constrictions: Bogh et al. (2014); Elbek and Wøhlk (2016); Fadda et al. (2018); Jatinkumar Shah et al. (2018); Ramos et al. (2018); Tirkolaee et al. (2021). Marseglia et al. (2022) address a special type of site capacity constraint as their setting allows to decide on the configuration of multiple bin containers at collection sites. This gives rise to a site capacity restriction with discrete intervals. Overflow of waste at collection sites is often avoided by an indirect capacity restriction by requiring a minimal number of collections per time period (e.g., De Bruecker et al., 2018; Son and Louati, 2016), or equivalently a maximal time interval between collections (e.g., Teixeira et al., 2004). Lavigne et al. (2021) and Lavigne et al. (2023) only consider a (process) capacity constraint at the process facilities and not for the material inventories at the collection sites.

Few papers address planning horizons of multiple days in the context of waste collection. le Blanc et al. (2006) examine a multi-depot collection problem of recyclable waste in which a vehicle can collect, as is the case in our setting, two containers in one trip. Although mainly a tactical study, the model also incorporates operational decisions. The solution process consists of a route generation step followed by a set partitioning step in which routes are combined to satisfy all requirements. Other papers that involve two-container vehicles and a multiple-day planning horizon are presented by Elbek and Wøhlk (2016) and Bogh et al. (2014). Unlike our study, both papers employ a rolling horizon approach in which routes are re-optimized when new information on fill levels becomes available.

Although there are shared characteristics between our problem and the ones described above, none of them incorporates all the aspects of our problem:

- A planning horizon of several days, in which the containers gradually fill up.
- A tactical scheduling problem deciding on the assignment of sites to days, crews to sites and vehicles to crews.
- The use of a truck-trailer combination which can load up to two containers.
- The shared use of vehicles by different crews.
- The incorporation of operational constraints on maximal working time, time windows, and break (rest) time.

To the author's best knowledge and as can be seen in Table 1, no prior research on the two-container problem combined with the aspects described above has been conducted. We therefore propose a tactical-operational two-container collection problem with site inventories, site time windows and shift constraints that will be solved using a Mixed Integer Linear Programming (MILP) approach that is built on the concept of trips.

3. Methodology

3.1. Problem Description

In this section, we provide a description of the multi-period trailer-truck waste collection problem with time windows. More detailed elements of the case, such as loading times, client locations and container capacities are presented in Section 4.

Residents dispose of waste in containers located at Civic Amenity sites (sites, henceforth). These containers must be collected and transported to a client. Each site i in the set of sites I can accommodate one or more containers with a container capacity CAP_i^{cont} and a total site capacity CAP_i^{tot}. As residents drop off their waste, the containers gradually fill up during the planning horizon D. We assume that first a container should be entirely filled up, before the next one can be used for dropping off waste. If a certain container is (almost) full, it has to be collected and replaced by an empty container.

Vehicles $v \in V$ are stationed at the vehicle depot where crews $c \in C$ also start and end their shift. Crews cannot start earlier than the earliest start time ST and need to return to the deport before the latest end time ET. Their shift should not exceed the maximum working time of DUR^{max}. Crews can share vehicles, but evidently, a crew cannot use a vehicle when another already occupies it. However, a crew that works a later shift might use the same vehicle as an "earlier" crew as long as the early crew is already back at the depot. A vehicle consists of a roll-off type truck with hook lift and a trailer. A truck can load exactly one container. If a trailer is attached to the truck, it can load exactly two containers: one on the truck and one on the trailer. Loading and unloading times can depend on the number of containers loaded and may differ when a trailer is attached to the truck. Before returning to the depot, crews must pay one last visit to the client to return to the depot with one or two empty containers. Sites can have multiple containers for the same waste fraction. Therefore, it might occur that, on a single day, multiple containers of the same waste fraction should be collected at a site. To avoid a situation in which different crews are collecting simultaneously at the same site, it is imposed that multiple site visits on a particular day should be performed by only one and the same crew.

All along the collection process described above, certain timing restrictions are to be respected. The crew has to adhere to the time windows $k \in K$ of the sites. In order to allow for some flexibility, a crew is allowed to wait a certain amount of time at the gate of a site until it opens. Within a certain day, a crew is allowed to work for a limited number of hours, but a break of DUR^b hours should be scheduled approximately in the middle of the shift.

The objective is to determine a collection schedule and a fleet size with a minimum cost. This collection cost is calculated as the sum of the operational cost, the total hours worked multiplied by the variable cost C^h and the investment cost, the required fleet multiplied by the vehicle cost C^v.

3.2. Defining trips

As discussed above, a vehicle can load at most two containers; hence at most two subsequent site visits are possible before a visit to the client is necessary. Additionally, collection and unloading times depend on the number of containers loaded. Based on these considerations, we propose a solution method based on "trips". These trips are constructed a priori such that the trip set could contain all feasible site combinations. Four types of trips are identified:

type 1	starting at the vehicle depot (D), visiting a site (site A) and visiting the client (C);
type 2	starting at the client (C), visiting a site (site A) and returning to the client (C);
type 3	starting at the vehicle depot (D), visiting a site (site A), visiting a second site (site B) and visiting the client (C);
type 4	starting at the client (C), visiting a site (site A), visiting a second site (site B) and visiting the client (C).

On double-visit trips (i.e., type 3 or 4), it is possible to either visit two different sites or to visit the same site twice. In the latter case, the travel time between the two sites is equal to zero. Note that we do not explicitly mention a return trip, i.e., a trip from the client (C) back to the depot (D). Since we only consider a single depot and single client, every active crew on a day will face the travel time from client to depot. Hence, this travel time is subtracted from the maximal working time of a crew and a the cost of this return trip is added to the objective function for each crew leaving the depot on a certain day. The trips will be the main building block of the MILP model. They can be combined in order to make a feasible schedule for a crew on a day.

3.3. Example feasible schedule

A simplified example of a feasible schedule without break times for a single day, 5 sites and 2 crews is given in Figure 1 and Table 2. The time windows of the sites are given in Table 3. Crew 1 starts at the vehicle depot at 10:00 and drives 30 minutes to site 1. Container collection takes 30 minutes. Crew 1 leaves site 1 at 11:00, exactly when the first time window of site 1 ends. Travel time to site 2 takes 15 minutes. Since site 2 opens at 11:30, the crew will have to wait 15 minutes at the gates. The crew ends this (type 3) trip at 14:05 after which it can make a new trip. It will again visit site 1 (type 2 trip). After unloading this container, it is 15:30. Since driving back to the depot takes 0:35, the crew will arrive back at the depot at 16:05. Its shift had a duration of 6:05 hours. On the same day, crew 2 drives from the depot to site 5 (type 1 trip). Afterwards, the crew will visit sites 4 and 3 (type 4 trip). Since site 4 only opens at 10:00, the crew will have to wait 35 minutes. The crew ends its trips at 13:40 and there are still 35 minutes left to go back to the depot and end the shift at 14:15. Since both schedules overlap, two vehicles will be needed.

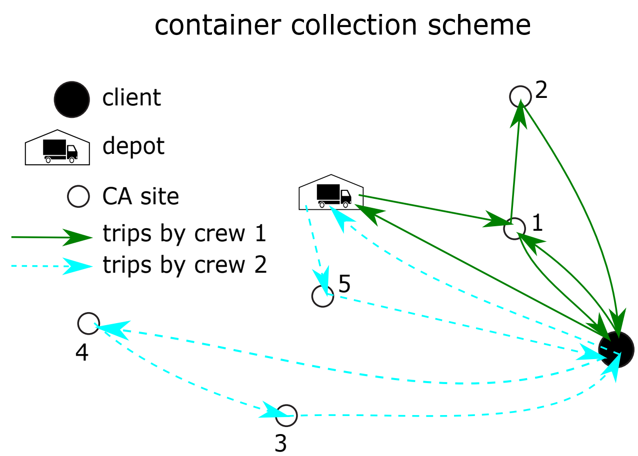


Figure 1: Example of a feasible container collection scheme.

Table 2: Feasible schedule of the container collection scheme depicted in Figure 1.

crew	l	st_l	T_t^A	wt_{dcl1}	$siteA$	$COLLT_t^A$	T_t^{AB}	wt_{dcl2}	$siteB$	$COLLT_t^B$	T_t^C	$UNLT^C$	et_l
1	1	10:00	0:30	0:00	1	0:30	0:15	0:15	2	1:00	0:35	1:00	14:05
	2	14:05	0:20	14:25	1	0:30	0:00	0:00	-	0:00	0:20	0:15	15:30
2	1	6:20	0:10	0:00	5	0:25					0:50	0:15	8:00
	2	8:00	1:25	0:35	4	0:25	0:50	0:00	3	1:00	0:35	0:50	13:40

l = the sequence number of the trip, st_l = the start time of the trip, T_t^A = the time for driving towards the first site of the trip, wt_{dcl1} = the waiting time before entering the first site of the trip, $siteA$ = the first site of the trip, $COLLT_t^A$ = collection time at the first site of the trip, T_t^{AB} = the time for driving towards the second site of the trip, wt_{dcl2} the waiting time before entering the second site of the trip, $siteB$ = the second site of the trip, $COLLT_t^B$ = collection time at the second site of the trip, T_t^C = the time for driving towards the client, $UNLT^C$ = the unloading time at the client, et_l = the end time of the trip.

Table 3: Example of time windows. For a description of the used symbols, see Section 3.4.

site	Open (OT_{id1})	Closed (CT_{id1})	Open (OT_{id2})	Closed (CT_{id2})
1	9:00	11:00	14:00	17:00
2	11:30	17:00		
3	9:00	12:30	14:00	16:30
4	10:00	12:00		
5	6:30	7:30	16:00	17:00

3.4. Mixed Integer Linear Programming model

In what follows, we give the MILP formulation of the problem under study. First, we present the symbols we will use, starting with the indices and sets.

$i \in I$	Civic Amenity site (CA Site), further on called (container) site;
$d \in D$	Days in the planning horizon;
$c \in C$	Crews;
$v \in V$	Vehicles;
$t \in T$	Trips;
$l \in L$	Sequence numbers, order of trips by a crew c on a day d;
$p \in P$	Site visits within a certain trip, $P = \{1, 2\}$;
$k \in K$	Time windows of sites i.

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

A_{tp}	Parameter indicating whether trip t visits a p'th site [0/1];
C^v	Cost of a vehicle for the entire planning horizon (depreciation, taxes, insurance,...) [euro];
C^h	Variable cost per hour [euro];
C^w	Penalty cost for waiting per hour [euro];
CAP_i^{tot}	Total container capacity of site i [tonnes];
CAP_i^{cont}	Single container capacity of site i [tonnes];
$COLLT_t^A$	Collection time of the first (A) site of trip t [hour];
$COLLT_t^B$	Collection time of the second (B) site of trip t [hour];
FR_{id}	Fill rate of site i on day d [tonnes];
$UNLT^{C1}$	Time of unloading one container at the client [hour];
$UNLT^{C2}$	Time of unloading two containers at the client [hour];
ST	Earliest start time of crew shift at vehicle depot [hour];
ET	Latest end time of crew shift at client [hour];

T_t^A	Travel time towards first (A) of p sites of trip t [hour];
T_t^{AB}	Travel time between first (A) and second (B) site of trip t [hour];
T_t^C	Travel time between last site of trip t and client (C) [hour];
T_{tp}^{pro}	Fixed amount of time needed prior to collection at the p-th site of trip t [hour]: $T_{t1}^{pro} = T_t^A$, $T_{t2}^{pro} = T_t^A + COLLT_t^A + T_t^{AB}$;
T_{tp}^{prc}	Fixed amount of time needed prior to leaving the p-th site of trip t [hour]: $T_{t1}^{prc} = T_t^A + COLLT_t^A$, $T_{t2}^{prc} = T_t^A + COLLT_t^A + T_t^{AB} + COLLT_t^B$;
T^{CD}	Travel time between client and depot [hour];
DUR^{max}	Maximal working time per day, incl. time to travel back to depot, excl. breaks;
DUR^c	Maximal crew working time per day to be spent on trips and waiting (excl. break) [hour]: $DUR^c = DUR^{max} - T^{CD}$;
DUR^v	Maximal time a vehicle is available [hour]: $DUR^v = ET - ST + T^{CD}$;
DUR^b	Duration of a break [hour];
DUR_t	Duration of trip t, including driving, collection and unloading times, excluding waiting times and travel time between client and depot. [hour]: $DUR_t = T_t^A + COLLT_t^A + T_t^C + UNLT^{C1}$ (for trips with one visit), $DUR_t = T_t^A + COLLT_t^A + T_t^{AB} + COLLT_t^B + T_t^C + UNLT^{C2}$ (for trips with two visits);
REQ_i	Parameter indicating how many times a site i should be visited during the entire planning horizon [-]: $REQ_i = \lceil \sum_{d \in D} FR_i / CAP_i^{tot} \rceil$;
$VISIT_{ti}$	Parameter indicating how many times a site i is visited on trip t [0/1/2]. By convention, if two containers are collected on the same trip, we consider it as two visits;
$VISIT_{tip}$	Parameter indicating whether site i is visited on trip t as the p-th site in this trip [0/1];

$START_t^D$ Parameter indicating whether trip t starts at the vehicle depot (type 1 or 3 trip) [0/1];
$OPEN_{id}$ Parameter indicating whether site i is open during at least one time window on day d;
OT_{idk} Time on which site i opens on day d in its k-th time window [hour];
CT_{idk} Time on which site i closes on day d in its k-th time window [hour];
$MWHB$ Minimal amount of working hours for which a break is mandatory [hour];
M^t Maximal number of trips a crew can perform on a certain day;
M^i Maximal number of times a site i can be visited on a single day;
M^w Maximal time a crew is allowed to wait [hours];
M "Big M", used in constraints regarding time windows and break hours, equals 24 [-].

The decision variables are:

$amcoll_{id}$ Amount of waste collected at site i on day d [tonnes];
b_{dclp} =1 if crew c takes its break on day d after collection at the p-th site of the trip, at sequence number l, 0 otherwise [-];
et_{dcl} End time of the trip scheduled at sequence number l of crew c on day d [hour];
g_{tdcl} =1 if trip t is performed as the l-th trip by crew c on day d, 0 otherwise [-];
$ifvisit_{idc}$ =1 if crew c visits site i on day d, 0 otherwise [-];
inv_{id} Inventory of site i at the end of day d [tonnes];
y_{dc} =1 if crew c is scheduled on day d, 0 otherwise [-];
si_i Start inventory of site i at the beginning of day 1 [tonnes];
st_{dcl} Start time of the trip scheduled at sequence number l of crew c on day d [hour];
st_{dc}^b Start time of break of crew c on day d [hour];
u_{dclpk} =1 if site p of the trip at sequence number l performed by crew c on day d will; arrive in the k-th time windows interval, 0 otherwise [-];
w_{dcv} =1 if crew c is assigned to vehicle v on day d, 0 otherwise [-];
wt_{dclp} Time period during which crew c waits before entering the p-th site of the trip scheduled; at sequence number l on day d [hour];
x_{dv} =1 if vehicle v is used on day d, 0 otherwise [-];
z =Total number of vehicles needed [-].

The MILP formulation of this two Container Collection Problem (2CCP) is:

$$
\text{(F1)} \quad \textsf{minimize} \quad C^v z + \sum_{t\in T}\sum_{d\in D}\sum_{c\in C}\sum_{l\in L} C^h \cdot DUR_t \cdot g_{tdcl} + \sum_{t\in T}\sum_{d\in D}\sum_{c\in C} C^h \cdot T^{CD} \cdot g_{tdc1} + \sum_{d\in D}\sum_{c\in C}\sum_{l\in L}\sum_{p\in P} C^w \cdot wt_{dclp} \tag{1}
$$

subject to
Vehicle block

$$
\sum_{v\in V} x_{dv} \leq z \qquad d \in D, \tag{2}
$$

$$
w_{dcv} \leq x_{dv} \qquad d \in D, c \in C, v \in V, \tag{3}
$$

$$
g_{tdcl} \leq \sum_{v\in V} w_{dcv} \qquad t \in T, d \in D, c \in C, l \in L, \tag{4}
$$

$$
\sum_{v\in V} w_{dcv} \leq 1 \qquad d \in D, c \in C, \tag{5}
$$

$$
\sum_{c\in C} w_{dcv} \leq 1 \qquad d \in D, v \in V, \tag{6}
$$

$$
M \cdot (2 - w_{dcv} - w_{dc'v}) + st_{dc1} \geq et_{dc'L} + T^{CD} \qquad d \in D, c \in C, c' \in C : c' > c, v \in V. \tag{7}
$$

Inventory block

$$
\sum_{t\in T}\sum_{d\in D}\sum_{c\in C}\sum_{l\in L} g_{tdcl} \cdot VISIT_{ti} \geq REQ_i \qquad i \in I, \tag{8}
$$

$$
inv_{i(d-1)} + FR_{id} - amcoll_{id} = inv_{id} \qquad d \in 2, ..., |D|, i \in I, \tag{9}
$$

$$
si_i + FR_{i1} - amcoll_{i1} = inv_{i1} \qquad i \in I, \tag{10}
$$

$$
inv_{i|D|} \leq si_i \qquad i \in I, \tag{11}
$$

$$
inv_{i(d-1)} + FR_{id} \leq CAP_i^{tot} \qquad d \in 2, ..., |D|, i \in I, \tag{12}
$$

$$
inv_{i|D|} + FR_{i1} \leq CAP_i^{tot} \qquad i \in I, \tag{13}
$$

$$amcoll_{id} \leq CAP_i^{con} \cdot \sum_{t\in T}\sum_{c\in C}\sum_{l\in L} VISIT_{ti} \cdot g_{tdcl} \qquad d \in D, i \in I, \qquad (14)$$

$$amcoll_{id} \geq CAP_i^{con} \cdot \left(\sum_{t\in T}\sum_{c\in C}\sum_{l\in L} VISIT_{ti} \cdot g_{tdcl} - 1\right) \qquad d \in D, i \in I, \qquad (15)$$

$$M^i \geq \sum_{t\in T}\sum_{c\in C}\sum_{l\in L} g_{tdcl} \cdot VISIT_{ti} \qquad d \in D, i \in I. \qquad (16)$$

Trip and sequence block

$$\sum_{t\in T} g_{tdc(l-1)} \geq \sum_{t\in T} g_{tdcl} \qquad d \in D, c \in C, l \in 2, ..., |L|, \qquad (17)$$

$$\sum_{t\in T} g_{tdcl} \leq 1 \qquad d \in D, c \in C, l \in L, \qquad (18)$$

$$2 \cdot ifvisit_{idc} \geq \sum_{t} g_{tdcl} \cdot VISIT_{ti} \qquad i \in I, d \in D, c \in C, l \in L, \qquad (19)$$

$$\sum_{c\in C} ifvisit_{idc} \leq 1 \qquad i \in I, d \in D. \qquad (20)$$

Trip and sequence block (if Depot $\neq$ Client)

$$\sum_{t\in T}\sum_{l\in L} START_t^D \cdot g_{tdcl} \leq 1 \qquad d \in D, c \in C, \qquad (21)$$

$$(M^t - 1) \cdot \sum_{t\in T} START_t^D \cdot g_{tdc1} \geq \sum_{t\in T}\sum_{l\in 2..|L|} (1 - START_t^D) \cdot g_{tdcl} \qquad d \in D, c \in C, \qquad (22)$$

$$g_{tdc1} \leq START_t^D \qquad t \in T, d \in D, c \in C, \qquad (23)$$

$$g_{tdcl} \leq 1 - START_t^D \qquad t \in T, d \in D, c \in C, l \in 2, ..., |L|. \qquad (24)$$

Timing block

$$\sum_{t\in T}\sum_{l\in L} DUR_t \cdot g_{tdcl} + \sum_{l\in L}\sum_{p\in P} wt_{dclp} \leq DUR^c \qquad d \in D, c \in C, \qquad (25)$$

$$et_{dc|L|} \leq ET \qquad d \in D, c \in C, \qquad (26)$$

$$st_{dc1} \geq ST \qquad d \in D, c \in C, \qquad (27)$$

$$M^w \cdot \sum_{t\in T} A_{tp} \cdot g_{tdcl} \geq wt_{dclp} \qquad d \in D, c \in C, l \in L, p \in P. \qquad (28)$$

$$st_{dc(l-1)} + \sum_{p \in P} wt_{dc(l-1)p} + \sum_{t \in T} DUR_t \cdot g_{tdc(l-1)} + \sum_{p \in P} b_{dc(l-1)p} \cdot DUR^b = st_{dcl}$$

$$d \in D, c \in C, l \in 2, ..., |L|, \tag{29}$$

$$st_{dcl} + \sum_{p \in P} wt_{dclp} + \sum_{t \in T} DUR_t \cdot g_{tdcl} + \sum_{p \in P} b_{dclp} \cdot DUR^b = et_{dcl}$$

$$d \in D, c \in C, l \in L. \tag{30}$$

Time windows block

$$g_{tdcl} \cdot VISIT_{ti} \leq 2 \cdot OPEN_{id} \qquad i \in I, t \in T, d \in D, c \in C, l \in L, \tag{31}$$

$$A_{tp} \cdot g_{tdcl} \leq \sum_{k \in K} u_{dclpk} \qquad t \in T, d \in D, c \in C, l \in L, p \in P, \tag{32}$$

$$\sum_{k \in K} u_{dclpk} \leq \sum_{t \in T} A_{tp} \cdot g_{tdcl} \qquad d \in D, c \in C, l \in L, p \in P, \tag{33}$$

$$st_{dcl} + \sum_{t \in T} T^{pro}_{tp} \cdot g_{tdcl} + \sum_{p' \in P: p' \leq p} wt_{dclp'} + \sum_{p' \in P: p' < p} DUR^b \cdot b_{dclp'} \geq$$

$$\sum_{t \in T} \sum_{i \in I} VISIT_{tip} \cdot OT_{idk} \cdot g_{tdcl} - M \cdot (2 - \sum_{t \in T} A_{tp} \cdot g_{tdcl} - u_{dclpk})$$

$$d \in D, c \in C, l \in L, p \in P, k \in K, \tag{34}$$

$$st_{dcl} + \sum_{t \in T} T^{prc}_{tp} \cdot g_{tdcl} + \sum_{p' \in P: p' \leq p} wt_{dclp'} + \sum_{p' \in P: p' < p} DUR^b \cdot b_{dclp'} \leq$$

$$\sum_{t \in T} \sum_{i \in I} VISIT_{tip} \cdot CT_{idk} \cdot g_{tdcl} + M \cdot (2 - \sum_{t \in T} A_{tp} \cdot g_{tdcl} - u_{dclpk})$$

$$d \in D, c \in C, l \in L, p \in P, k \in K. \tag{35}$$

Break block

$$\sum_{l \in L} \sum_{p \in P} b_{dclp} \geq \sum_{v \in V} w_{dcv} \qquad d \in D, c \in C, \tag{36}$$

$$M \cdot \sum_{l \in L} \sum_{p \in P} b_{dclp} \geq et_{dc|L|} + T^{CD} - st_{dc1} - MWHB \qquad d \in D, c \in C, \tag{37}$$

$$st^b_{dc} \leq st_{dcl} + \sum_{t \in T}(g_{tdcl} \cdot T^{prc}_{tp}) + \sum_{p' \in P: p' \leq p} wt_{dclp} + M \cdot (1 - b_{dclp}) \quad d \in D, c \in C, l \in L, p \in P, \tag{38}$$

$$st^b_{dc} \geq st_{dcl} + \sum_{t \in T}(g_{tdcl} \cdot T^{prc}_{tp}) + \sum_{p' \in P: p' \leq p} wt_{dclp} - M \cdot (1 - b_{dclp}) \quad d \in D, c \in C, l \in L, p \in P, \tag{39}$$

$$st^b_{dc} \leq st_{dc1} + (DUR^{max}/2 + 1) \qquad d \in D, c \in C, \tag{40}$$

$$st^b_{dc} \geq st_{dc1} + (DUR^{max}/2 - 1) \qquad d \in D, c \in C, \tag{41}$$

$$b_{dclp} \leq \sum_{t \in T} g_{tdcl} \cdot A_{tp} \qquad d \in D, c \in C, l \in L, p \in P. \tag{42}$$

Domain block

$$z \in 0, ..., |V|, \tag{43}$$

$$b_{dclp} \in \{0, 1\} \qquad d \in D, c \in C, \tag{44}$$

$$g_{tdcl} \in \{0, 1\} \qquad t \in T, d \in D, c \in C, l \in L, \tag{45}$$

$$ifvisit_{idc} \in \{0, 1\} \qquad in \in I, d \in D, c \in C, \tag{46}$$

$$u_{dclpk} \in \{0, 1\} \qquad d \in D, c \in C, l \in L, p \in P, k \in K, \tag{47}$$

$$x_{dv} \in \{0, 1\} \qquad d \in D, v \in V, \tag{48}$$

$$w_{dcv} \in \{0, 1\} \qquad d \in D, c \in C, v \in V, \tag{49}$$

$$0 \leq amcoll_{id} \qquad i \in I, d \in D, \tag{50}$$

$$0 \leq inv_{id} \qquad i \in I, d \in D, \tag{51}$$

$$0 \leq si_i \qquad i \in I, \tag{52}$$

$$0 \leq et_{dcl} \leq 24 \qquad d \in D, c \in C, l \in L, \tag{53}$$

$$0 \leq st_{dcl} \leq 24 \qquad d \in D, c \in C, l \in L, \tag{54}$$

$$0 \leq st^b_{dc} \leq 24 \qquad d \in D, c \in C, \tag{55}$$

$$0 \leq wt_{dclp} \leq 24 \qquad d \in D, c \in C, l \in L, p \in P. \tag{56}$$

The objective function (1) minimizes the total cost. This cost is composed of the vehicle cost (first term) and a cost for performing the trips (second term). Recall that each crew leaving the depot, should return to the depot and we did not explicitly include these trips in the model. Instead, we account for their cost by noticing that each crew performing a trip that starts at the depot ($l = 1$), will have to return to the depot as well. This is represented by the third term in the objective function. The fourth term represents the small penalty cost imposed to discourage waiting.

Vehicle block

Constraints (2) calculate the minimal number of vehicles needed. Constraints (3) ensure that the x_{dv}-variable is 1 if a crew c uses vehicle v on day d. Constraints (4) assign a crew c that is active on day d to a vehicle v. Constraints (5) state that a crew c can use at most one vehicle v on day d. Constraints (6) on the other hand state that a vehicle v can only be occupied by at most one crew c on day d. Constraints (7) make sure that a crew c can only use vehicle v if another crew c' using the same vehicle v on the same day d has already returned to the depot. Therefore, the start time of crew c must be higher than the end time of the last trip of crew c' augmented with the time to drive back to the depot T^{CD}. Note that the variable $et_{dc'|L|}$ contains the end time of the last trip of crew c' on day d, no matter the number of trips that are actually performed.

Inventory block

Constraints (8) ensure that the minimal required number of trips to a site i are performed over the entire planning horizon. Note that this constraint is in fact redundant, since constraints (9)-(11) will ensure that the necessary number of site visits are performed as well. However, constraints (8) are left in since they proved to be (strong) valid inequalities. Constraints (9) set the inventory of site i at the end of day d equal to the inventory of the previous day $d-1$, augmented with today's fill rate FR_{id} and subtracted with the amount of waste which was collected today $amcoll_{id}$. Constraints (10) do the same, but for the first day. At the beginning of this first day, the inventory level is given as si_i. Constraints (11) make sure that all inventory levels at the end of the planning horizon are lower than the start levels. In that way, all waste is collected. Constraints (12) and (13) limit the inventory levels of each site i to their upper bound. Constraints (14) state that the collected amounts at site i on day d cannot exceed the container capacity CAP_i^{con} multiplied by the number of containers collected on that day. Constraints (15) state that the collected amounts at site i on day d should at least equal the number of visits minus 1, multiplied by a full container capacity CAP_i^{con}. For example, if site i is visited twice on day d, the collected amounts should at least equal a full container capacity. If this is not the case, it would mean that one of these two visits is redundant. Constraints (16) limit the number of visits to site i on day d to at most M^i.

Trip and sequence block

For this block of constraints, we have two versions depending on the location of the client relative to the vehicle depot. If the depot and client are situated at the same location, it does not matter whether a trip starts at the client or at the depot. The distinction between type 1 and type 2 or type 3 and type 4 trips disappears and only type 1 and type 3 trips are generated a priori. Therefore, constraints (17)-(18) suffice. Constraints (17) make sure that the next trip l of a crew c on day d is only used if a trip is performed on the previous sequence number $l-1$. Constraints (18) restrict the number of trips that a crew c performs on day d per sequence number l to 1.

It is possible to have more than one container installed per site. To avoid that different crews are working at the same site at the same moment, we add constraints (19) and (20) to the model. Constraints (19) set $ifvisit_{idc}$ to 1 if a certain crew c visits site i on day d. The factor 2 on the left hand side refers to the maximal number of visits within a trip. Constraints (20) consequently prevent more than one crew from visiting site i on day d.

If the depot and client are situated at different locations, the trip set will contain type 1 and type 3 trips that start at the depot ($START_t^D = 1$) and type 2 and type 4 trips ($START_t^D = 0$) that start at the client. Consequently, constraints (21)-(24) are added to the model. Constraints (21) ensure there is at most one trip t that starts at the vehicle depot per crew c per day d. Consequentially, constraints (22) allow for $M^t - 1$ trips that start at the client per day d if the crew c has left the depot (i.e., $g_{tdc1} = 1$, for at least one t). Hence, a total of M^t trips can be performed per crew per day: one leaving the depot and $M^t - 1$ starting at the client. Constraints (23) prevent the first ($l = 1$) trip t of a crew c on day d to start at the client. Note that for a trip starting at the client, $START_t^D = 0$. Constraints (24) on the other hand prevent the other trips t of a crew c on day d to start at the depot. Note that for a trip starting at the depot, $START_t^D = 1$.

Timing block

Constraints (25) restrict the total crew working time, consisting of the fixed trip durations (DUR_t) and the variable waiting times (wt_{dclp}), of a crew c on day d to be lower than or equal to the maximal working time per day minus the time the crew will need to drive back to the depot at the end of the shift (T^{CD}). Constraints (26) ensure that the end time of the last trip of crew c on day d is lower than or equal to the end time at the client. Constraints (27) make sure a crew c cannot start before its shift on day d has started. Constraints (28) restrict the amount of time during which crew c waits before entering the p-th site to at most M^w for each sequence number l and day d. Constraints (29) calculate the start time of the l-th trip of a crew c on day d, based on the start time, waiting times, break and duration of the trip at the previous sequence number $l-1$. Constraints (30) calculate the end time of the l-th trip of a crew c on day d, based on the start time, waiting times, break and duration of the performed trip.

Time windows block

Constraints (31) allow only visits on day d to sites i that are open. The factor 2 on the right hand side refers to the maximal number of visits within a trip. Constraints (32) enforce that at least one time interval k for the visit to the p-th site should be chosen if a trip t is performed by crew c on day d on a certain sequence number l. Constraints (33) on the other hand prevent the model from choosing a time window k if there is no p-th site in the l-th trip by c on day d. Constraints (34) make sure that if a p-th site is visited on day d by crew c on sequence number l within time windows time window k, the time of arrival at the site is larger than or equal to the opening time OT_{idk} of that site i on d of time window k. Constraints (35) state that collection at the p-th site at the l-th sequence number, performed by crew c on day d should be terminated before the closing time of this site i in this time window, if this time window k is selected. Note that the correct prior durations T^{pro} are considered in each of these constraints: the time to reach site A (T_t^A) and waiting time before entering this site (wt_{dcl1}) in the case when $p = 1$, and T_t^A, wt_{dcl1}, $COLLT_t^A$, a potential break time of DUR^b and the time to drive from site A to site B (T_t^{AB}) when $p = 2$. Analogously for the time prior to closing time T^{prc}: T_t^A, wt_{dcl1} and time for collection at site A ($COLLT_t^A$) if $p = 1$, and T_t^A, wt_{dcl1}, $COLLT_t^A$, a potential break time of DUR^b, T_t^{AB} and time for collection at site B ($COLLT_t^B$) in case of $p = 2$.

Break block

To ensure a break is taken by each crew on each day, we propose two sets of constraints. Constraints (36) ensure that every active crew should take a break. Since breaks should be taken approximately halfway a shift, these constraints will additionally make sure that each crew is working for at least $DUR^{max}/2 - 1$ hours. However, if collection tasks are limited these constraints would result in artificially long shifts (e.g., by augmenting the waiting time). Therefore, we propose constraints (37) which ensure that only crews working longer than $MWHB$ hours should schedule a break. This variant allows for shorter shift durations. If the working time of crew c on day d exceeds $MWHB$, a break should be scheduled. Furthermore, we assume that a break can be taken immediately after collection at a site. Note that only one version of these constraints (36) or (37) is to be included in the model. Constraints (38) and (39) calculate the start time of the break of crew c on the day d at the p-th site of trip sequence number l to the correct value. Indeed, if $b_{dclp} = 1$, then the last terms of the right hand side will disappear, and st_{dc}^b will equal the time at which collection is completed and the crew can take its break. The timing of the breaks is imposed in constraints (40) and (41). The former ensures the break starts earlier than one hour after the middle of a shift. The latter guarantees the break does not start more than one hour earlier than the middle of a shift. For example, if a crew works 8 hours per day, the crew will be scheduled somewhere after 3 hours, but before 5 hours of working. Additionally, constraints (42) allow breaks only to be scheduled after collection at the p-th site for a day-crew-sequence number combination dcl on which a trip is performed.

Domain block

Finally, constraints (43)-(56) define the domains of the decision variables.

3.5. Reduced trip set heuristic

The 2CCP is difficult to solve. In general, a commercial solver will not be able to find the optimal solution within a reasonable amount of computation time. This is among other things due to the complexity status of the problem. Another reason is the large amount of trips that are generated before solving the MILP (see Section 3.4), which results in a large number of decision variables. By reducing the number of trips, the solution process can be simplified. The following reasoning is made to reduce the size of the trip set:

1. In case the client is at the same location as the depot (the case of bulky waste, see Section 4), the distinction between type 1 vs. type 2 and type 3 vs. type 4 trips disappears. Hence, all type 2 and type 4 trips are redundant in the trip set.
2. Loading and unloading two containers in a double-visit trip (i.e., type 3 and type 4 trips) can be relatively expensive due to long loading and unloading times. In such cases, it would only be worthwhile to visit two sites on such a double-visit trip if this additional (un)loading cost does not outweigh the extra transportation cost of visiting the two sites on two separate trips. Based on the loading, unloading and all traveling times, the double-visit trip will only be retained in the trip set if this option is cheaper than visiting the sites separately with type 1 or type 2 trips. Note that this operation might eliminate trips that could appear in an optimal solution. For example, imagine a solution in which on a certain day d two containers should be collected at a certain site i. It might very well be the case that this site is only open during a single limited time window, making two separate trips to i infeasible. Since the double-visit trip was eliminated a priori, a solution scheduling this double-visit trip can not be found.
3. When studying the double-visit trips (i.e., type 3 and type 4 trips), we see that each time two versions are made: first visiting site A and afterwards B, and first visiting B and then A. This distinction could be useful in case of different time windows. However, the distinction also increases the number of trips considerably. Therefore, in the reduced trip set, we only retain the cheapest of both options. Note that, due to differences in time windows, this operation might eliminate trips that could appear in an optimal solution.

The size of the resulting trip set will depend on the instances. These are discussed in the next sections.

4. Application

We applied the MILP formulation described in Section 3.4 with the reduced trip set (see Section 3.5) to real life scenarios for IVM. The geographic locations of the 18 container sites affiliated to IVM are given in Figure 2. General parameters that apply to all case studies and scenarios are given in Table 4. No exact cost figures were known, but in the objective function, only the ratio of operational costs and vehicle costs is of importance. In consultation with IVM, a value of 10 per working hour and 100 per vehicle for a two week period was deemed reasonable. Additionally, a small penalty cost of 5 per waiting hour was imposed to discourage waiting. As planning horizon, a two week period in June was selected[3]. Fill rates were moderate over these 12 days and estimated to be representative for most weeks of the year (see Table A.1 and Table A.2). Within a certain day of the planning horizon, a crew is allowed to work for 8 hours in total. Each crew can start at the depot as early as 7:00 a.m., but should finish unloading at the client by 17:00 p.m. Data concerning the travel times is displayed in A.3.

Two material flows are considered: bulky waste and PVC. Since PVC volumes are small (see below), only one day of the week (Wednesday) will be reserved for PVC collection. The other days will serve for collection of bulky waste. In this way, we separate both collection schemes and two schedules, one for bulky waste and one for PVC, will be obtained from two independent optimization runs. Since the schedules are designed for other days of the planning horizon, they can both be performed using the same vehicle fleet. Characteristics of bulky waste and PVC collection are given in Table A.4.

4.1. Bulky waste

The first flow is bulky waste. Containers containing bulky waste should be transported to the processor located next to the vehicle depot. Consequently, the time to drive from client to depot T^{CD} will be 0. As can be seen in Table A.4, most sites accommodate more than one container. To keep the number of visits to a site limited, a maximum of 2 container collections per site per day is allowed (i.e., $M^i = 2$). Bulky waste is collected in containers of $30\,\mathrm{m}^3$ or $40\,\mathrm{m}^3$, depending on the site. Every site corresponds to only one size of container. These container sizes are important: a truck with trailer can load two $30\,\mathrm{m}^3$ containers or one $40\,\mathrm{m}^3$

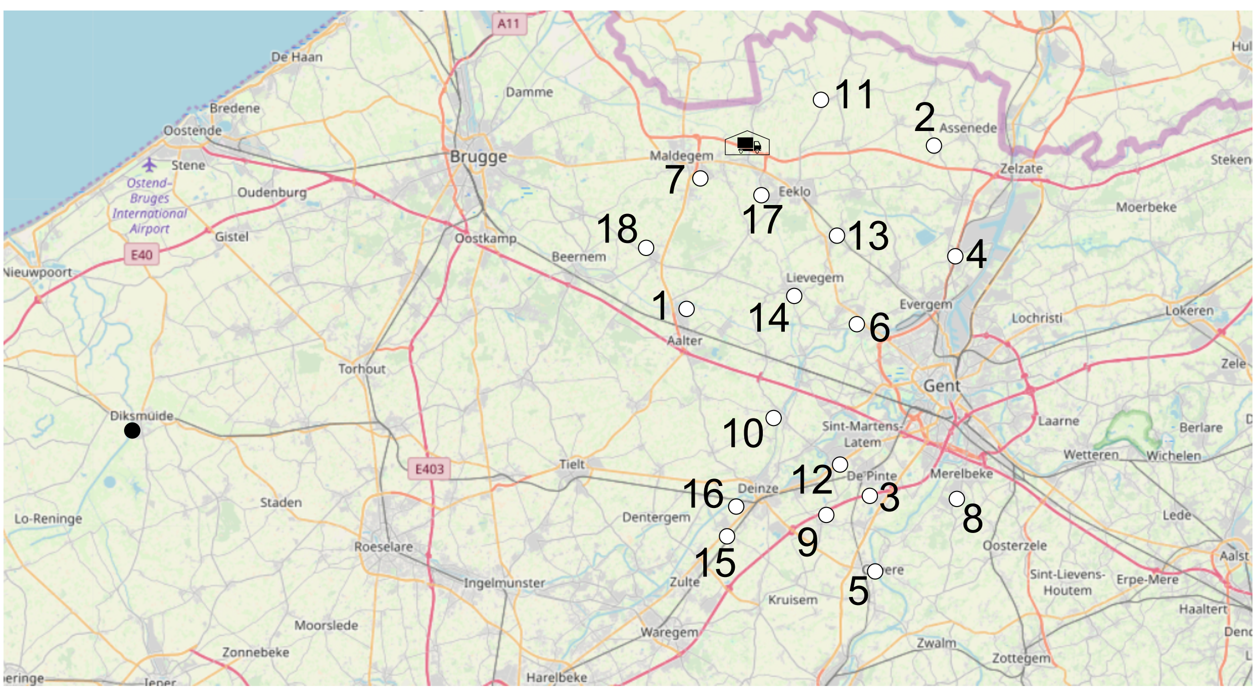
[3] On the one hand, the planning horizon should be sufficiently long to ensure that most sites have full containers. On the other hand, the problem size should remain limited to make sure the solver can find a solution. A two week planning horizon was a good compromise.

Table 4: General parameters and specifications of the test cases

parameter	value
number of days in planning horizon	12
number of crews available	3
time to load first container	0.5 [h]
time to load two containers at same site	0.83 [h]
time to load second container at different site	1 [h]
time to unload one container $UNLT^{C1}$	0.25 [h]
time to unload two containers $UNLT^{C2}$	1 [h]
break time DUR^b	0.5 [h]
maximum wait time per site M^w	1 [h]
working time per day DUR^{max}	8 [h]
vehicle time per day DUR^v	10 [h]
vehicle cost per two weeks C^v	100 [-]
working cost per hour C^h	10 [-]
penalty cost for waiting per hour C^w	5 [-]
earliest start time ST	7:00 am
latest stop time ET	17:00 pm
maximum waiting time M^w	1 [h]

A crew can start at the *depot* at 7:00 am, and should stop at the *client* at 17:00 pm. If the client is not located at the depot, a crew could arrive well after 17:00 at the depot.

Figure 2: Geographic locations of the case study



vehicle depot (truck symbol), container sites (white numbered dots), PVC client (black dot) and bulky waste client (truck symbol).

and one $30\,\mathrm{m}^3$ container. It is impossible to load two $40\,\mathrm{m}^3$ containers. When constructing the trips, this condition was checked and only feasible trips were generated a priori. Note that the site set I contains 17 sites, since no data on the fill rates for bulky waste were available for site 18 (see Table A.1). A crew can at most perform 4 trips per day ($M^t = 4$). In the case of bulky waste, this is not a constraint. Client and depot are on the same location, and hence another crew can continue the trip sequence without additional cost. Since the number of collection tasks is extensive, every crew should schedule a 30 minute break (constraints 37 are removed and only constraints 36 are retained). The planning horizon spans two weeks, on which collection is possible on every Monday, Tuesday, Thursday, Friday and Saturday. Since no collection of bulky waste can take place on Wednesday, the fill rates of this day are added to the fill rates of the subsequent Thursday.

4.2. PVC

The second flow is PVC. The client for PVC is located at a different location than the depot. The travel time from the client to the depot T^{CD} is 1:03. Only one container of $12\,\mathrm{m}^3$ for PVC collection is installed per site, hence $M^i = 1$. No data were available for the PVC fill rates of site 3, hence the size of the site set I is 17. An overview of all container sites and their specifications is given in Table A.4. A crew can at most perform 4 trips per day ($M^t = 4$). In the case of PVC, the client is located rather far from the depot. Consequently, trip durations are long and the maximal working time DUR^c would be reached before exceeding the maximum number of trips M^t. Since the number of collection tasks is limited, only crews with shifts over 6 hours ($MWHB = 6$), should schedule a 30 minute break (constraints 36 are removed and only constraints 37 are retained). The planning horizon spans two weeks, on which collection is possible. Currently, the fill rates for PVC are not exactly known. Therefore, we will use a constant fraction of the fill rates for hard plastics (see Table A.2). Preliminary data indicates that PVC volume accounts for roughly 10 % of the hard plastics volume. In the light of the optimization model, these volumes are too low. Even with a currently exceptional PVC fraction of 13 %, only one container out of 18 would be full after 18 days (3 weeks). Hence, one could easily design a collection scheme in which one site per day is visited. Additionally, the only site with a full container would have to be visited twice in this 18 day period. One vehicle would suffice to perform the collection.

However, as explained above, one could combine the collection of PVC and bulky waste, using the same vehicle fleet. Since the PVC volume is rather low, we consider a variant in which it is assumed that there is only one day per week on which PVC is collected. Since Wednesday is the only day on which each site is open, we consider this day as "PVC collection day". We assume a 12 week collection scheme.

5. Results and discussion

The following sections describe the results obtained by solving the MILP programming model using CPLEX Optimization Studio version 12.6 on a 64-bit operating system with Intel i7-4600U processor and 16 GB RAM. If no optimal solutions were found, the optimization routine was stopped after 17 hours. For some instances, the solver ran out of memory before this time. All results are summarized at the end of this section in Table 9.

5.1. Bulky waste base case

In the case of bulky waste, the client is situated at the same location as the vehicle depot. Consequently, the amount of trips could be reduced according to the first approach described in Section 3.5. Additionally, since the unloading location is rather close to the collection locations (container sites), the second approach to reduce the trip set described in Section 3.5 will prove to be important. A total of 46 trips is generated, listed in Table A.5. Using this set of trips, the model found a solution for the base case of 1434.47 using 2 vehicles.
When comparing the solution of 1434.47 to the LB of 1373.71, reported by CPLEX, the optimality gap is 4.24 %. The schedule for the two week period is given in Tables 5 and 6. In the solution, there was no need for waiting before entering a site.

5.2. Bulky waste additional periods

To investigate the effect of different fill rates, this subsection optimizes the collection of bulky waste for other weeks than the two weeks in June. We optimize for two weeks in July, with considerable higher fill rates and two weeks in December with lower fill rates.
In July, total costs amount to 1698.47 (gap of 5.89 % with respect to a LB of 1598.43) for a two week period. For this collection process, three vehicles were needed.
For the two weeks in December, total costs were 1273.89 (gap of 7.85 % with respect to lower bound of 1173.89). Two vehicles were needed.

5.3. Bulky waste alternative travel times

The travel times used in the base case of Section 5.1 were based on real-time transportation by car on a Monday morning around 10:00 am (see Table A.3). However, a Heavy Goods Vehicle (HGV), has a maximum speed which is lower than that of a car. Therefore, additional simulations are run to investigate the effect of these reduced speeds. However, since mostly secondary roads are traveled and highways are not often used, we expect the effect of the maximum speed to be limited. In the first scenario, we simulate a HGV with a maximum speed of 85 km/h, but without real-time transportation, i.e. no delays of traffic congestion, road construction works and detours. Naturally, the legal speed limit could not be exceeded.

Table 5: Bulky waste collection schedule of volumes for a 2 week period

day	crew	site A	volume A [m3]	site B	volume B [m3]
Monday(1)	1	Merelbeke(8)	30		
		Aalter(1)	40		
Tuesday(2)	1	Deinze(16)	30	Zulte(15)	40
		Sint-Laureins(11)	37.6		
	2	Assenede(2)	40		
		Eeklo(17)	39.2		
		Evergem(4)	55.2	Evergem(4)	55.2
		Lovendegem(6)	21.2		
Thursday(4)	1	Aalter(1)	40		
		Maldegem(7)	40		
		Nazareth(9)	40	De Pinte(3)	29.4
	2	Evergem(4)	60	Evergem(4)	60
		Deinze(16)	29.4	Nevele(10)	29.4
		Eeklo(17)	38.8		
Friday(5)	1	Waarschoot(13)	16.3		
		Sint-Martens-Latem(12)	5.7		
		Assenede(2)	40		
	2	Merelbeke(8)	30		
		Aalter(1)	40		
		Deinze(16)	30	Zulte(15)	40
Saturday(6)	1	Zomergem(14)	25.3		
		Gavere(5)	42.6	Gavere(5)	42.6
		Eeklo(17)	78.8		
		Eeklo(17)	78.8		
	2	Evergem(4)	57.6	Evergem(4)	57.6
		Aalter(1)	40		
		Zulte(15)	37.6		
		Sint-Laureins(11)	40		
Monday(7)	1	Maldegem(7)	6.24		
		Nazareth(9)	40		
		Aalter(1)	40		
		Merelbeke(8)	30		
Tuesday(8)	1	Evergem(4)	60	Evergem(4)	60
		Deinze(16)	57	Deinze(16)	57
	2	Eeklo(17)	39.2		
		Nevele(10)	29.4		
		Zulte(15)	38.4	De Pinte(3)	30
		Assenede(2)	36.8		
Thursday(10)	1	Maldegem(7)	40		
		Assenede(2)	40		
		Aalter(1)	40		
		Deinze(16)	30	Nevele(10)	28.8
	2	Evergem(4)	60	Evergem(4)	60
		Eeklo(17)	40		
		Nazareth(9)	27	De Pinte(3)	28.2
Friday(11)	1	Merelbeke(8)	27.6		
		Aalter(1)	40		
		Waarschoot(13)	36		
		Zomergem(14)	40		
	2	Zulte(15)	40		
		Gavere(5)	48.5	Gavere(5)	48.51
		Eeklo(17)	40		
		Sint-Laureins(11)	40		
Saturday(12)	1	De Pinte(3)	30	Sint-Martens-Latem(12)	76
		Aalter(1)	33.6		
		Sint-Martens-Latem(12)	76		
	2	Evergem(4)	60	Evergem(4)	60
		Nazareth(9)	40	Nevele(10)	30
		Eeklo(17)	37.6		

Table 6: Bulky waste collection time schedule

day	crew	site A	start trip	break A	site B	break B	end trip	shift duration (incl. break)
Monday(1)	1	Merelbeke(8)	12:51				15:00	
		Aalter(1)	15:00	0:30			17:00	4:09
Tuesday(2)	1	Deinze(16)	8:47		Zulte(15)		12:49	
		Sint-Laureins(11)	12:49	0:30			14:26	5:39
	2	Assenede(2)	9:44				11:01	
		Eeklo(17)	11:01				12:01	
		Evergem(4)	12:01	0:30	Evergem(4)		15:15	
		Lovendegem(6)	15:15				16:46	7:02
Thursday(4)	1	Aalter(1)	9:44				11:15	
		Maldegem(7)	11:15				12:15	
		Nazareth(9)	12:15	0:30	De Pinte(3)		16:54	7:10
	2	Evergem(4)	7:00		Evergem(4)		9:45	
		Deinze(16)	9:45	0:30	Nevele(10)		14:12	
		Eeklo(17)	14:12				15:12	8:12
Friday(5)	1	Waarschoot(13)	11:46				13:06	
		Sint-Martens-Latem(12)	13:06				15:13	
		Assenede(2)	15:13	0:30			17:00	5:14
	2	Merelbeke(8)	8:44				10:52	
		Aalter(1)	10:52	0:30			12:53	
		Deinze(16)	12:53		Zulte(15)		16:55	8:11
Saturday(6)	1	Zomergem(14)	8:51				10:22	
		Gavere(5)	10:22		Gavere(5)	0:30	14:18	
		Eeklo(17)	14:18				15:17	
		Eeklo(17)	15:17				16:17	7:26
	2	Evergem(4)	7:33		Evergem(4)		10:17	
		Aalter(1)	10:17	0:30			12:18	
		Zulte(15)	12:18				14:31	
		Sint-Laureins(11)	14:31				15:38	8:05
Monday(7)	1	Maldegem(7)	9:30				10:30	
		Nazareth(9)	10:30				12:47	
		Aalter(1)	12:47	0:30			14:48	
		Merelbeke(8)	14:48				16:56	7:26
Tuesday(8)	1	Evergem(4)	7:00		Evergem(4)		9:45	
		Deinze(16)	9:45		Deinze(16)	0:30	13:29	
		Eeklo(17)	13:29				14:28	7:28
	2	Nevele(10)	7:41				9:35	
		Zulte(15)	9:35	0:30	De Pinte(3)		14:24	
		Assenede(2)	14:24				15:41	8:00
Thursday(10)	1	Maldegem(7)	8:35				9:35	
		Assenede(2)	9:35				10:52	
		Aalter(1)	10:52	0:30			12:53	
		Deinze(16)	12:53		Nevele(10)		16:50	8:15
	2	Evergem(4)	8:23		Evergem(4)		11:08	
		Eeklo(17)	11:08	0:30			12:38	
		Nazareth(9)	12:38		De Pinte(3)		16:47	8:24
Friday(11)	1	Merelbeke(8)	8:33				10:42	
		Aalter(1)	10:42	0:30			12:42	
		Waarschoot(13)	12:42				14:02	
		Zomergem(14)	14:02				15:34	7:01
	2	Zulte(15)	7:18				9:31	
		Gavere(5)	9:31	0:30	Gavere(5)		13:26	
		Eeklo(17)	13:26				14:26	
		Sint-Laureins(11)	14:26				15:33	8:15
Saturday(12)	1	De Pinte(3)	8:39		Sint-Martens-Latem(12)		12:42	
		Aalter(1)	12:42	0:30			14:42	
		Sint-Martens-Latem(12)	14:42				16:49	8:10
	2	Evergem(4)	7:15		Evergem(4)		10:00	
		Nazareth(9)	10:00	0:30	Nevele(10)		14:35	
		Eeklo(17)	14:35				15:34	8:19

Crews must take a 30 minutes break.

These travel times can be found in Table A.6. This scenario resulted in a total cost of 1350.54 (gap of 7.40 % with respect to a LB of 1250.53) and used 2 vehicles. In a second scenario, we estimated real-time travel times for an HGV to be 15 % higher than the ones calculated in the first scenario. This (more robust) scenario resulted in a total cost of 1428.12 (gap of 0.01 % with respect to a LB of 1427.98) and used 2 vehicles as well.

5.4. *Smaller containers at a distant site*

This subsection investigates the effect of a change of container size at site 9 (Nazareth). The 40 m^3 containers are replaced by containers with a maximum volume of 30 m^3. This is motivated by the fact that site 9 is a rather distant site. To save on working hours, it might be worthwhile to combine this site on a double-visit trip. Since a small container can not only be combined with another small container, but also with a large container, the change in container size in Nazareth will lead to more trips in the set. More specifically, the set will be extended with the following trips:

1. Nazareth(9) - Nazareth(9)
2. Nazareth(9) - Sint-Martens-Latem(12)
3. Zulte(15) - Nazareth(9)

The solver ran out of memory after circa 2 hours. A solution of 1369.13 (gap of 7.30 % with respect to a LB of 1269.13) was found, using two vehicles.

5.5. *PVC base case*

In the case of PVC, considerably more trips are generated. This is due to two reasons. First, PVC is collected in containers of 12 m^3. Consequently no container size combinations can be eliminated and every site can be combined with every other site. Second, the client is situated at another location than the vehicle depot. As a consequence, the first approach to reduce the size of the trip set (see Section 3.5) cannot be applied and two versions of each route will exist: one starting at the depot and one starting at the client. The second approach to reduce the number of trips, will also have a small effect. Since the client is rather distant, the time disadvantage of double-visit trips is somewhat countered. The third trip reducing approach can be applied. A total of 342 trips is generated. Since this is a fairly large number of trips, we decided not to show them in a table.

Each crew is again allowed to work 8 hours per day, but since the travel time from client to depot at the end of each day equals 1.05 hours (63 minutes), we set $DUR^c = 8 - 1.05 = 6.95$ =6:57 h. Only crews working longer than 5 hours are allowed to take a break.

For this 12 week period, and a PVC fraction of 10 %, total costs amount to 1289.01 (gap of 12.63 % with respect to LB of 1126.17). The schedule is given in Table 7 and 8 and can be performed using 2 vehicles.

Table 7: PVC collection schedule of volumes for a 12 week period

day	crew	site A	volume A [m^3]	site B	volume B [m^3]
1	1	Evergem(4)	9.65	Sint-Martens-Latem(12)	9.74
2	1	Eeklo(17)	12.00	Lovendegem(6)	12.00
	2	Maldegem(7)	12.00		
		Nazareth(9)	4.49	Nevele(10)	8.19
3	1	Deinze(16)	0.90	Zulte(15)	6.01
	2	Evergem(4)	12.00	Merelbeke(8)	12.00
4	1	Zomergem(14)	12.00	Aalter(1)	12.00
	2	Assenede(2)	9.32	Knesselare(18)	12.00
5	1	Eeklo(17)	9.17	Evergem(4)	10.82
6	1	Lovendegem(6)	9.09	Nevele(10)	10.10
	2	Maldegem(7)	10.92	Deinze(16)	12.00
7	1	Waarschoot(13)	12.00	Zomergem(14)	1.55
	2	Evergem(4)	9.65	Zulte(15)	6.04
8	1	Sint-Laureins(11)	11.95	Assenede(2)	9.32
	2	Eeklo(17)	9.17	Aalter(1)	11.21
9	1	Evergem(4)	10.82	Merelbeke(8)	8.91
10	1	Maldegem(7)	10.92		
		Nazareth(9)	12.00	Gavere(5)	9.02
	2	Lovendegem(6)	12.00	Nevele(10)	12.00
11	1	Eeklo(17)	9.17	Evergem(4)	12.00
12	1	Assenede(2)	9.32	Knesselare(18)	1.57
	2	Aalter(1)	10.42	Zulte(15)	12.00

The volume of PVC is 10 % vol. of hard plastics. Collection on every Wednesday.

Table 8: PVC collection time schedule for a 12 week period (every Wednesday)

day	crew	site A	start trip	break A	site B	break B	end trip	shift duration (incl. break)
1	1	Evergem(4)	11:37		Sint-Martens-Latem(12)		16:00	4:23
2	1	Eeklo(17)	10:04		Lovendegem(6)		14:01	3:57
	2	Maldegem(7)	7:57				9:45	
		Nazareth(9)	9:45	0:30	Nevele(10)		14:52	6:55
3	1	Deinze(16)	12:45		Zulte(15)		17:00	4:15
	2	Evergem(4)	11:05		Merelbeke(8)		15:35	4:30
4	1	Zomergem(14)	12:37		Aalter(1)		16:37	4:00
	2	Assenede(2)	13:01		Knesselare(18)		17:00	3:59
5	1	Eeklo(17)	9:53		Evergem(4)		14:05	4:12
6	1	Lovendegem(6)	10:51		Nevele(10)		14:52	4:01
	2	Maldegem(7)	7:00		Deinze(16)		11:12	4:12
7	1	Waarschoot(13)	12:01		Zomergem(14)		16:00	3:59
	2	Evergem(4)	12:27		Zulte(15)		17:00	4:33
8	1	Sint-Laureins(11)	12:49		Assenede(2)		16:55	4:06
	2	Eeklo(17)	13:08		Aalter(1)		16:56	3:48
9	1	Evergem(4)	11:05		Merelbeke(8)		15:35	4:30
10	1	Maldegem(7)	7:00				8:48	
		Nazareth(9)	8:48		Gavere(5)	0:30	14:05	7:05
	2	Lovendegem(6)	10:51		Nevele(10)		14:52	4:01
11	1	Eeklo(17)	9:53		Evergem(4)		14:05	4:12
12	1	Assenede(2)	13:01		Knesselare(18)		17:00	3:59
	2	Aalter(1)	12:40		Zulte(15)		16:59	4:19

Crews working longer than 5 hours should take a 30 minute break.

5.6. *PVC additional fill rates*

Since the pilot project (see Section 1) was conducted for a limited period of time, we do not have additional fill rate data at our disposal. Therefore, we investigate the effect of a lower and upper bound on the volumes of PVC collected. In case of a volume percentage of 7 % of hard plastics, the costs decrease to 951.36 (gap of 11.43 % with respect to LB of 842.65). Still two vehicles would be needed. If the volumes of PVC would be 13 %, the model could not find a solution.

5.7. *PVC alternative travel times*

Analogously to Section 5.3, we simulate the PVC collection on two other travel time matrices. We assume a PVC fraction of 10 % of the volume of hard plastics. The first scenario (heavy goods vehicle without reduced driving speed) resulted in a total cost of 1375.80 (gap of 11.48 % with respect to a LB of 1217.83) and used two vehicles. For the second (more robust) scenario (real-time travel time estimation of 15 % excess travel time), a total cost of 1464.12 was attained (gap of 9.39 % with respect to a LB of 1326.71). In this scenario, also two vehicles are required.

Table 9: Overview of results of all optimized scenarios

scenario	number of vehicles	working hours	total objective	LB (solver)	gap [%]
Bulky base	2	123.44	1434.47	1373.71	4.24
Bulky December	2	107.39	1273.89	1173.89	7.85
Bulky July	3	139.84	1698.47	1598.43	5.89
Bulky HGV	2	115.05	1350.53	1250.53	7.40
Bulky HGV + 15%	2	122.81	1428.12	1427.98	0.01
Bulky smaller cont. at distant site (9)	2	116.91	1369.13	1269.13	7.30
PVC base	2	108.90	1289.01	1126.17	12.63
PVC 70% vol.	2	75.14	951.36	842.65	11.43
PVC 130% vol.					
PVC HGV	2	117.58	1375.80	1217.83	11.48
PVC HGV + 15%	2	126.41	1464.12	1326.71	9.39

In the scenario "PVC 130 % vol." the optimization model could not find a feasible solution within the time limit of 17 hours.

5.8. *Discussion*

Most analysed scenarios show that 2 trucks are sufficient to transfer bulky household refuse from the CA sites to the treatment facility. More importantly, our results suggest that initiating a local recovery network for PVC requires no additional trucks once the MMC uses its own fleet for the transportation of bulky household refuse. For the MMC such insight can be crucial as investing in a fleet for collection of bulky household refuse would enable them to start the of PVC transfer without additional investments in the fleet. However, a glance at the sensitivity analysis of our results shows that the picture is more complex. Not unexpectedly, a higher fill rate of the main flow in volume and weight (bulky household refuse) results in the requirement for an additional truck. Although this result might seem trivial, for the MMC it is crucial to understand under which circumstance a third truck is needed. Here, using real historical fill rates (i.e., 2 weeks in July), shows that during a busier period 2 trucks are indeed insufficient to transfer all the bulky household refuse in time. Our data suggest that investing in three trucks would avoid any overflows or any inconveniences related to the prevention of such overflows (such as residents who cannot drop off their bulky household refuse at their local CA site) during a busy period. However, during the quiet periods, the third truck would remain idle. Finally, the model also shows that small changes such as adjusting the container size for bulky household refuse at one of the CA sites can have an impact on overall performance, although the number of required trucks is not affected in this particular case. The above observations underline the need for the MMC to combine information on the likelihood at which the different scenarios might occur, with results of the MILP programming model when assessing the optimal investment in a new fleet.

6. Conclusion

In response to the growing ambition of many local environmental authorities to commit to a genuine circular economy transition, we developed a tailored version of a classical MILP model that accounts for some typical constraints which may emerge when a new local recovery network is introduced. The resulting generic MILP model proves to be an interesting tool when applied to a real-life example. For any MMC confronted with the dilemma whether to organize a local recovery network for an additional flow, it is imperative to understand how different scenarios will affect the need for investments in the existing or new fleet. The MILP programming model enables the MMC to gain insight in how different combinations of scenarios exactly affect the fleet requirements. This not only includes the number of trucks or information under which exact circumstances an additional truck would (not) be needed, but also the collection schedule (i.e., when and in which sequence the different CA-sites are visited) for the collection crews. By repeating the schedules of the planning horizon, a work routine that collects waste and materials over longer period can be obtained. However, care should be taken for day-to-day planning as fill rates and travel times are not deterministic but rather stochastic. Therefore, we mention the application of a simulation model as a future research direction. This model could check the robustness of the solutions in more detail.

As shown by the case, in some scenarios an optimal solution might entail the need for an additional collection truck. The exact impact of such an event depends to a large extent on the overall collection needs of the MMC. When a new, but limited flow in terms of volume is considered and no other flows are collected by the MMC (e.g., when the transfer of the other waste and material flows is outsourced to an external partner), understanding when exactly the threshold for an extra truck is reached, is indeed of prime importance for the MMC. In this case, the output of the MILP programming model will support the decision makers within the MMC in assessing the trade-off between idle time and overflows. Idle time is not uncommon for a truck, but when the threshold for a new truck is only just met, idle time might be excessively high. On the other hand, not investing in an additional truck might result in overflows. Although overflows can sometimes be temporarily prevented by placing an additional container (provided the CA site is large enough to accommodate for this), a systematic lack of transport capacity will ultimately result in a problematic situation for the MMC. Here, the model output will be relevant as it allows the decision makers within the MMC to deduce the required fleet size and the associated idle time under each scenario.

Overall, the MILP programming model shows that it is possible to account for several very case-specific constraints and scenarios. Case-specific elements, such as rules regarding breaks and shift durations can be removed or adjusted to apply the model to other cases. This is an interesting feature as different MMCs are likely to be confronted with very different constraints. However, many elements of the model remain quite general, such as the introduction of trips, and constraints regarding site capacities, trip sequences, and site opening hours. These elements can be retained for solving other trailer-truck waste collection problems with time-windows. Nevertheless, for some scenarios our approach did not succeed in finding a feasible solution. We therefore recommend the development of heuristic solution methods as a promising route for further research. These solution methods may be able to find feasible schedules for the problem instances for which the general-purpose solver failed to find a solution. Additionally, better solutions with smaller optimality gaps might be obtained using heuristics.

Furthermore, care should be taken for day-to-day planning as fill rates and travel times are not deterministic but rather stochastic. Therefore, we mention the application of a simulation model as a future research direction. This model could check the robustness of the solutions. Another potential future research direction is investigating the stability of the results, i.e. the range in which the parameters and coefficients of the model can change without affecting the results. Especially the range of fill rates that would still require the same vehicle investment or the range of site opening hours that would still allow a feasible schedule is an interesting avenue for further research.

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Appendix

Data

Table A.1: Fill rates per day for the bulky waste instance.

	site / day [m^3]	1 Monday	2 Tuesday	3 Wednesday	4 Thursday	5 Friday	6 Saturday	7 Monday	8 Tuesday	9 Wednesday	10 Thursday	11 Friday	12 Saturday
1	Aalter	26.13	-	26.13	26.13	39.20	39.20	26.13	-	26.13	26.13	39.20	39.20
2	Assenede	-	19.60	19.60	13.07	13.07	13.07	-	19.60	19.60	13.07	13.07	13.07
3	De Pinte	7.35	7.35	7.35	7.35	-	29.40	7.35	7.35	7.35	7.35	-	29.40
4	Evergem	29.40	29.40	29.40	29.40	29.40	29.40	29.40	29.40	29.40	29.40	29.40	29.40
5	Gavere	-	7.35	7.35	7.35	7.35	7.35	-	7.35	11.76	11.76	11.76	11.76
6	Lovendegem	-	1.84	1.84	1.84	1.84	1.84	-	1.84	1.84	1.84	3.27	3.27
7	Maldegem	-	7.84	9.80	9.80	9.80	9.80	-	7.84	7.84	7.84	7.84	7.84
8	Merelbeke	9.80	9.80	9.80	29.40	7.35	7.35	7.35	7.35	7.35	7.35	7.35	7.35
9	Nazareth	39.20	-	7.84	7.84	7.84	7.84	7.84	-	39.20	9.80	9.80	9.80
10	Nevele	9.80	-	29.40	-	9.80	9.80	9.80	-	29.40	-	9.80	9.80
11	Sint-Laureins	-	19.60	19.60	-	19.60	19.60	-	9.80	9.80	-	9.80	9.80
12	Sint-Martens-Latem	13.07	-	9.80	-	9.80	9.80	9.80	-	9.80	-	9.80	9.80
13	Waarschoot	-	6.53	6.53	-	6.53	6.53	-	6.53	6.53	-	6.53	6.53
14	Zomergem	-	6.53	6.53	6.53	6.53	6.53	-	6.53	6.53	6.53	6.53	6.53
15	Zulte	13.07	19.60	19.60	-	26.13	26.13	26.13	19.60	19.60	-	13.07	13.07
16	Deinze	-	9.80	9.80	9.80	29.40	29.40	-	14.70	14.70	29.40	14.70	14.70
17	Eeklo	-	39.20	39.20	39.20	19.60	19.60	-	39.20	39.20	39.20	19.60	19.60
18	Knesselare	-	-	-	-	-	-	-	-	-	-	-	-

All fill rates are in m^3. No fill rates available for site 18 (Knesselare).

Table A.2: Fill rates per day for hard plastics.

	site / day [m^3]	1 Monday	2 Tuesday	3 Wednesday	4 Thursday	5 Friday	6 Saturday	7 Monday	8 Tuesday	9 Wednesday	10 Thursday	11 Friday	12 Saturday
1	Aalter	4.67	-	9.34	4.67	4.67	4.67	4.67	-	9.34	4.67	4.67	4.67
2	Assenede	-	7.76	3.88	3.88	3.88	3.88	-	7.76	3.88	3.88	3.88	3.88
3	De Pinte	-	-	-	-	-	-	-	-	-	-	-	-
4	Evergem	9.02	9.02	9.02	9.02	9.02	9.02	9.02	9.02	9.02	9.02	9.02	9.02
5	Gavere	-	2.51	1.25	1.25	1.25	1.25	-	2.51	1.25	1.25	1.25	1.25
6	Lovendegem	-	8.79	4.39	4.39	4.39	4.39	-	8.79	4.39	4.39	4.39	4.39
7	Maldegem	-	9.10	4.55	4.55	4.55	4.55	-	9.10	4.55	4.55	4.55	4.55
8	Merelbeke	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90
9	Nazareth	2.29	-	4.58	2.29	2.29	2.29	2.29	-	4.58	2.29	2.29	2.29
10	Nevele	4.21	-	8.41	-	8.41	4.21	4.21	-	8.41	-	8.41	4.21
11	Sint-Laureins	-	3.32	1.66	-	3.32	1.66	-	3.32	1.66	-	3.32	1.66
12	Sint-Martens-Latem	1.35	-	2.71	-	2.71	1.35	1.35	-	2.71	-	2.71	1.35
13	Waarschoot	-	3.11	1.55	-	3.11	1.55	-	3.11	1.55	-	3.11	1.55
14	Zomergem	-	3.76	1.88	1.88	1.88	1.88	-	3.76	1.88	1.88	1.88	1.88
15	Zulte	3.34	3.34	3.34	-	6.68	3.34	3.34	3.34	3.34	-	6.68	3.34
16	Deinze	-	3.58	1.79	1.79	1.79	1.79	-	3.58	1.79	1.79	1.79	1.79
17	Eeklo	-	10.19	5.09	5.09	5.09	5.09	-	10.19	5.09	5.09	5.09	5.09
18	Knesselare	-	-	5.65	-	-	5.65	-	-	5.65	-	-	5.65

To convert to PVC, a ratio between e.g. 7 and 13 % could be applied. All fill rates are in m^3. No fill rates available for site 3 (De Pinte).

Table A.3: Travel time matrix

	from (row) / to (column)	1 Aalt.	2 Asse.	3 DePin.	4 Ever.	5 Gave.	6 Love.	7 Mald.	8 Mere.	9 Naza.	10 Neve.	11 StLau.	12 StML.	13 Waar.	14 Zome.	15 Zult.	16 Dein.	17 Eekl.	18 Knes.	Dpt	Clnt
1	Aalter	0	0.49	0.53	0.58	0.61	0.39	0.25	0.52	0.52	0.31	0.48	0.44	0.42	0.29	0.46	0.43	0.34	0.19	0.38	0.83
2	Assenede	0.50	0	0.63	0.25	0.70	0.41	0.30	0.61	0.66	0.64	0.23	0.58	0.27	0.48	0.76	0.75	0.25	0.42	0.27	1.18
3	De Pinte	0.53	0.63	0	0.47	0.21	0.39	0.71	0.32	0.16	0.30	0.81	0.14	0.55	0.51	0.37	0.37	0.70	0.65	0.75	1.09
4	Evergem	0.60	0.25	0.47	0	0.55	0.25	0.49	0.46	0.51	0.48	0.42	0.43	0.32	0.40	0.62	0.60	0.44	0.61	0.46	1.14
5	Gavere	0.56	0.69	0.22	0.52	0	0.44	0.74	0.23	0.19	0.40	0.86	0.28	0.60	0.59	0.32	0.32	0.75	0.69	0.80	1.07
6	Lovendegem	0.36	0.39	0.37	0.23	0.45	0	0.45	0.36	0.41	0.28	0.49	0.33	0.20	0.16	0.52	0.50	0.35	0.39	0.40	1.02
7	Maldegem	0.25	0.28	0.75	0.47	0.80	0.41	0	0.75	0.69	0.44	0.27	0.63	0.34	0.30	0.58	0.54	0.16	0.17	0.13	0.93
8	Merelbeke	0.53	0.58	0.32	0.42	0.25	0.34	0.71	0	0.32	0.42	0.76	0.37	0.49	0.49	0.47	0.47	0.65	0.65	0.70	1.09
9	Nazareth	0.50	0.67	0.15	0.51	0.20	0.43	0.68	0.33	0	0.25	0.85	0.12	0.58	0.46	0.27	0.27	0.70	0.63	0.79	1.03
10	Nevele	0.31	0.63	0.31	0.46	0.42	0.32	0.48	0.37	0.26	0	0.68	0.19	0.39	0.27	0.26	0.21	0.50	0.43	0.58	0.86
11	St-Laureins	0.49	0.24	0.79	0.43	0.86	0.48	0.28	0.77	0.82	0.68	0	0.74	0.30	0.50	0.82	0.78	0.26	0.41	0.18	1.16
12	St-M-Latem	0.44	0.58	0.15	0.42	0.30	0.34	0.62	0.31	0.13	0.19	0.76	0	0.49	0.40	0.30	0.26	0.64	0.57	0.69	1.00
13	Waarschoot	0.43	0.27	0.53	0.31	0.61	0.18	0.35	0.51	0.57	0.38	0.30	0.49	0	0.20	0.64	0.60	0.25	0.41	0.30	1.12
14	Zomergem	0.29	0.46	0.53	0.37	0.59	0.19	0.31	0.50	0.47	0.27	0.48	0.40	0.19	0	0.53	0.49	0.29	0.30	0.39	1.01
15	Zulte	0.49	0.81	0.36	0.65	0.42	0.57	0.64	0.46	0.27	0.26	0.87	0.28	0.65	0.54	0	0.10	0.71	0.58	0.77	0.98
16	Deinze	0.46	0.77	0.34	0.60	0.40	0.53	0.61	0.44	0.25	0.21	0.84	0.24	0.61	0.49	0.10	0	0.69	0.55	0.74	1.04
17	Eeklo	0.35	0.25	0.67	0.43	0.75	0.32	0.16	0.65	0.71	0.50	0.27	0.63	0.24	0.29	0.67	0.64	0	0.33	0.13	1.04
18	Knesselare	0.19	0.41	0.64	0.60	0.71	0.43	0.17	0.62	0.63	0.38	0.40	0.57	0.41	0.30	0.52	0.48	0.31	0	0.30	0.80
	Depot (IVM Eeklo)	0.38	0.27	0.72	0.45	0.79	0.37	0.12	0.70	0.75	0.56	0.19	0.67	0.29	0.39	0.70	0.67	0.11	0.29	0	1.05
	Client (Diksmuide)	0.87	1.16	1.04	1.14	1.12	1.06	0.93	1.03	1.00	0.84	1.15	0.98	1.12	1.01	0.97	1.03	1.06	0.79	1.05	0

Travel times between origin (row) and destination (column) points in hours. Calculated for cars at a Monday morning, around 10:00 am. Obtained using Google Maps.

Table A.4: Characteristics of the bulky waste and PVC instances.

		Instance 1: bulky waste					Instance 2: PVC						
id	name	$TDP =$ TCP [h]	$TPD =$ TPC [h]	CAP^{cont} [m^3]	nbCont [-]	CAP^{tot} [m^3]	TDP [h]	TPD [h]	TCP [h]	TPC [h]	CAP^{cont} [m^3]	nbCont [-]	CAP^{tot} [m^3]
1	Aalter	0.38	0.38	40	2	80	0.38	0.38	0.87	0.83	12	1	12
2	Assenede	0.27	0.27	40	2	80	0.27	0.27	1.16	1.18	12	1	12
3	De Pinte	0.72	0.75	30	2	60	0.72	0.75	1.04	1.09	-	-	-
4	Evergem	0.45	0.46	30	3	90	0.45	0.46	1.14	1.14	12	1	12
5	Gavere	0.79	0.80	30	2	60	0.79	0.80	1.12	1.07	12	1	12
6	Lovendegem	0.37	0.40	30	2	60	0.37	0.40	1.06	1.02	12	1	12
7	Maldegem	0.12	0.13	40	3	120	0.12	0.13	0.93	0.93	12	1	12
8	Merelbeke	0.70	0.70	30	2	60	0.70	0.70	1.03	1.09	12	1	12
9	Nazareth	0.75	0.79	40	2	80	0.75	0.79	1.00	1.03	12	1	12
10	Nevele	0.56	0.58	30	2	60	0.56	0.58	0.84	0.86	12	1	12
11	Sint-Laureins	0.19	0.18	40	2	80	0.19	0.18	1.15	1.16	12	1	12
12	Sint-M.-Latem	0.67	0.69	40	2	80	0.67	0.69	0.98	1.00	12	1	12
13	Waarschoot	0.29	0.30	40	1	40	0.29	0.30	1.12	1.12	12	1	12
14	Zomergem	0.39	0.39	40	2	80	0.39	0.39	1.01	1.01	12	1	12
15	Zulte	0.70	0.77	40	2	80	0.70	0.77	0.97	0.98	12	1	12
16	Deinze	0.67	0.74	30	2	60	0.67	0.74	1.03	1.04	12	1	12
17	Eeklo	0.11	0.13	40	2	80	0.11	0.13	1.06	1.04	12	1	12
18	Knesselare	0.29	0.30	-	-	-	0.29	0.30	0.79	0.80	12	1	12

TDP = time to drive from the depot to a site, TPD = time to drive from a site to the depot, TCP = time to drive from the client to a site, TPC = time to drive from a site to the client, CAP^{cont} = capacity of an individual container, nbCont = number of containers installed at a site, CAP^{tot} = total site capacity (equals $CAP^{cont} \cdot nbCont$).

Table A.5: Trips generated in the case of bulky waste.

trip id	site A	site B
1	Aalter(1)	
2	Assenede(2)	
3	De Pinte(3)	
4	De Pinte(3)	De Pinte(3)
5	De Pinte(3)	Gavere(5)
6	De Pinte(3)	Merelbeke(8)
7	De Pinte(3)	Nevele(10)
8	De Pinte(3)	Sint-Martens-Latem(12)
9	Evergem(4)	
10	Evergem(4)	Evergem(4)
11	Gavere(5)	
12	Gavere(5)	Gavere(5)
13	Gavere(5)	Merelbeke(8)
14	Gavere(5)	Sint-Martens-Latem(12)
15	Gavere(5)	Zulte(15)
16	Gavere(5)	Deinze(16)
17	Lovendegem(6)	
18	Lovendegem(6)	Lovendegem(6)
19	Maldegem(7)	
20	Merelbeke(8)	
21	Merelbeke(8)	Merelbeke(8)
22	Nazareth(9)	
23	Nazareth(9)	De Pinte(3)
24	Nazareth(9)	Gavere(5)
25	Nazareth(9)	Merelbeke(8)
26	Nazareth(9)	Nevele(10)
27	Nevele(10)	
28	Nevele(10)	Nevele(10)
29	Sint-Laureins(11)	
30	Sint-Martens-Latem(12)	
31	Sint-Martens-Latem(12)	Merelbeke(8)
32	Sint-Martens-Latem(12)	Nevele(10)
33	Waarschoot(13)	
34	Zomergem(14)	
35	Zulte(15)	
36	Zulte(15)	De Pinte(3)
37	Zulte(15)	Merelbeke(8)
38	Zulte(15)	Nevele(10)
39	Deinze(16)	
40	Deinze(16)	De Pinte(3)
41	Deinze(16)	Nazareth(9)
42	Deinze(16)	Nevele(10)
43	Deinze(16)	Sint-Martens-Latem(12)
44	Deinze(16)	Zulte(15)
45	Deinze(16)	Deinze(16)
46	Eeklo(17)	

Each trip starts and ends at the depot, which is at the same location as the client. 46 trips were generated a priori.

Table A.6: Travel time matrix (hgv)

	from (row) / to (column)	1 Aalt.	2 Asse.	3 DePin.	4 Ever.	5 Gave.	6 Love.	7 Mald.	8 Mere.	9 Naza.	10 Neve.	11 StLau.	12 StML.	13 Waar.	14 Zome.	15 Zult.	16 Dein.	17 Eekl.	18 Knes.	Dpt	Clnt
1	Aalter	0	0.60	0.61	0.61	0.68	0.37	0.29	0.55	0.53	0.30	0.47	0.49	0.44	0.32	0.48	0.46	0.34	0.20	0.39	1.04
2	Assenede	0.62	0	0.59	0.21	0.66	0.33	0.37	0.54	0.63	0.60	0.22	0.52	0.28	0.46	0.70	0.68	0.28	0.54	0.29	1.44
3	De Pinte	0.60	0.60	0	0.46	0.22	0.39	0.74	0.28	0.20	0.31	0.74	0.17	0.53	0.58	0.38	0.36	0.66	0.65	0.70	1.38
4	Evergem	0.58	0.21	0.45	0	0.53	0.19	0.53	0.40	0.49	0.47	0.38	0.38	0.33	0.35	0.56	0.55	0.44	0.63	0.45	1.36
5	Gavere	0.65	0.66	0.21	0.52	0	0.44	0.79	0.21	0.18	0.38	0.79	0.26	0.58	0.64	0.30	0.28	0.71	0.71	0.75	1.35
6	Lovendegem	0.37	0.33	0.37	0.19	0.45	0	0.39	0.32	0.42	0.27	0.36	0.31	0.15	0.17	0.46	0.44	0.28	0.41	0.32	1.25
7	Maldegem	0.29	0.35	0.75	0.51	0.82	0.39	0	0.69	0.67	0.44	0.33	0.63	0.29	0.38	0.62	0.60	0.16	0.21	0.12	1.11
8	Merelbeke	0.56	0.54	0.28	0.40	0.21	0.32	0.70	0	0.30	0.45	0.68	0.32	0.47	0.49	0.45	0.43	0.60	0.61	0.64	1.34
9	Nazareth	0.53	0.66	0.20	0.52	0.18	0.44	0.67	0.30	0	0.26	0.79	0.14	0.59	0.46	0.25	0.23	0.72	0.58	0.76	1.15
10	Nevele	0.30	0.61	0.31	0.47	0.38	0.27	0.44	0.41	0.26	0	0.58	0.18	0.37	0.27	0.24	0.23	0.49	0.35	0.54	1.09
11	St-Laureins	0.47	0.22	0.72	0.38	0.80	0.36	0.35	0.67	0.77	0.58	0	0.66	0.25	0.36	0.77	0.75	0.19	0.52	0.23	1.35
12	St-M-Latem	0.47	0.53	0.15	0.39	0.26	0.31	0.61	0.27	0.13	0.17	0.66	0	0.45	0.37	0.22	0.20	0.58	0.53	0.62	1.26
13	Waarschoot	0.44	0.29	0.52	0.33	0.60	0.15	0.29	0.47	0.56	0.37	0.25	0.45	0	0.16	0.56	0.54	0.18	0.41	0.22	1.32
14	Zomergem	0.32	0.46	0.51	0.35	0.59	0.17	0.38	0.46	0.46	0.27	0.36	0.38	0.16	0	0.46	0.44	0.25	0.29	0.32	1.19
15	Zulte	0.47	0.71	0.38	0.57	0.30	0.46	0.61	0.47	0.24	0.25	0.78	0.22	0.56	0.46	0	0.08	0.66	0.52	0.71	1.03
16	Deinze	0.45	0.69	0.36	0.56	0.28	0.44	0.59	0.45	0.23	0.23	0.77	0.20	0.54	0.44	0.08	0	0.64	0.50	0.69	1.04
17	Eeklo	0.34	0.27	0.65	0.43	0.72	0.28	0.16	0.59	0.69	0.49	0.19	0.58	0.18	0.27	0.67	0.65	0	0.31	0.09	1.23
18	Knesselare	0.20	0.52	0.66	0.68	0.74	0.41	0.21	0.60	0.58	0.36	0.50	0.54	0.41	0.29	0.53	0.52	0.37	0	0.31	0.97
	Depot (IVM Eeklo)	0.39	0.28	0.69	0.44	0.76	0.32	0.11	0.64	0.73	0.54	0.26	0.62	0.22	0.32	0.72	0.70	0.09	0.31	0	1.21
	Client (Diksmuide)	1.04	1.41	1.36	1.36	1.32	1.24	1.10	1.31	1.29	1.06	1.39	1.25	1.32	1.19	1.02	1.04	1.26	0.96	1.20	0

Travel times between origin (row) and destination (column) points in hours. Calculated for a heavy goods vehicle without real-time travel information. Obtained using OpenRouteService.