A decision-support tool for strategic waste collection in residential areas

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Abstract

In this paper, we present a decision-support tool that implements high level algorithms determining waste collection tours for municipal solid waste and the location of collection points. The application offers a high granularity in terms of data input, offering the possibility to run a large number of simulations for operational and strategic decision making. The decision-tool has already been used on the ground-field in the city of Köniz in Switzerland to reorganize their collection strategy. We present this reorganization through a case study is presented on the city of Fribourg in Switzerland to illustrate the decision possibilities.
Keywords: Decision-support tool, vehicle routing problems, facility location, waste management system.

1. Introduction

1.1. Location decisions in municipal solid waste management

Municipal solid waste (MSW) is the waste generated by households, offices, small-scale institutions, and commercial enterprises [1]. Its management can be divided into three main stages: waste generation, collection and transfer, and treatment and disposal. Effective MSW management requires careful consideration of numerous environmental, economic, technical, legislative, institutional, and political factors [2]. Hence, managing MSW is a multidisciplinary activity that involves multi-criteria decision-making at every stage of its process.

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The collection and transfer of MSW, hereafter referred to simply as collection, is the most costly aspect of the management cycle, accounting for approximately 70–80% of the total costs [3, 4]. The design of a MSW collection system involves medium- to long-term strategic decisions such as the location of collection points, vehicle depots, landfills and processing facilities, as well as short-term operational decisions to determine the collection frequency and the routing of collection vehicles [5]. Among other factors, location choices are interdependent with routing, which defines the sequence in which collection facilities are visited. This interdependence is explicitly captured by location–routing problems (LRPs), which integrate location and routing decisions within a single optimization framework [6].

From the users' point of view, collection systems are often divided into curbside (pick-up) systems, where the MSW is disposed outside their premises, and bring (drop-off) systems, where the MSW is brought to communal collection points [7]. These two systems lie at opposite ends of a spectrum, differing in required user effort and travel distance to collection points—zero distance representing a pure curbside system with door-to-door collection [8]). Although highly convenient for residents, curbside systems can have negative impacts, including increased fuel consumption, emissions, and noise, due to the heavy vehicles employed and the frequent stops performed.

The literature on MSW collection contains numerous examples of decision-support tools designed to assist short-term operational decisions, with a particular focus on the routing of collection vehicles transporting MSW to final disposal sites (e.g., [9], [10], [11], [12], [13], [14]). By contrast, decision-support tools addressing decisions at other planning levels are less common [15]. At the strategic level, decisions primarily concern the location of disposal and treatment facilities, such as collection points (e.g., [16], [17]), landfills (e.g., [18], [19]) and waste-to-energy facilities (e.g.,[20]), which represent more sustainable alternatives to landfills. At the tactical level, decision making involves several interrelated aspects, the most relevant being zoning, fleet sizing, and the assignment of collection days and frequencies. However, decision-support tools explicitly targeting this level remain scarce [21]. A notable exception is [15], which introduces a prescriptive analytics framework combining mathematical programming and discrete-event simulation to support tactical planning in MSW collection.

The site selection of major disposal facilities typically involves spatial problems, often addressed through GIS-based analyses and multi-criteria evaluation [22]. In contrast, the location of collection points (i.e., containers, bins, or other waste accumulation points) is usually modeled as location-allocation problems [23], which optimize facility placement while assigning users to them, and as LRPs [5]. For the latter, it is important to note that most studies do not question the underlying collection system. Notable exceptions include [24] and [25], where the authors compare a bring system—in which MSW is delivered to central collection sites—with either a door-to-door collection system [24] or an underground container system [25].

Although potentially valuable in practice, these optimization models are generally restricted to specific applications and have seldom been embedded within decision-support tools. When incorporated into such tools, routing decisions are typically treated as secondary; for instance, [17] does not consider them, while [16] determines vehicle routes only after location decisions have been made. Nevertheless, the overall system cost may become excessive if location and routing decisions are handled independently. In fact, jointly optimizing location and routing decisions through LRPs can reduce total costs over a long planning horizon, even when collection routes are subject to change [26].

1.2. Aim of this research

The project *Decision support for an efficient and sustainable waste collection*, funded by the Swiss Innovation Agency[1] (grant 36157.1 IP-EE), aimed to develop a prototype decision-support tool to help municipalities design the most suitable system for non-recoverable MSW collection. Conducted in collaboration with Schwendimann AG, a waste collection company (WCC) that services around thirty municipalities in the Greater Bern area (Switzerland), the project conceptualized alternative collection systems that integrate modern, ecological vehicle types and multi-stage collection processes. Its overarching objective was to support Swiss municipalities in transitioning from the predominantly used curbside systems for non-recoverable MSW to bring systems. The

[1] `https://www.innosuisse.admin.ch/en`

Swiss waste management market remains highly traditional and often skeptical of innovative approaches, as public tenders typically allow only minor, easily implementable adjustments to the status quo. In this context, decision-support tools are particularly valuable, providing evidence-based analyses that demonstrate the benefits of alternative collection strategies and facilitate municipal acceptance.

Given the heterogeneity of municipal contexts, no single collection system can be considered optimal for all. System performance is assessed through key indicators capturing municipality-specific ecological, economic, and social dimensions, derived from the optimization of the LRPs associated with the evaluated systems [27, 28]. Even with identically defined key indicators, comparing alternative collection systems for a given municipality remains a non-trivial task. To facilitate this process, the proposed decision-support tool provides functionalities to help municipalities identify the system best suited to their needs. By entering municipal characteristics and requirements, the tool enables the comparison of different collection systems through filtering, sorting, and interactive map visualizations, thereby supporting informed medium- to long-term decision-making. A range of consulting services can be offered in combination with the tool, including operational improvements of the current state (e.g., by generating collection routes that reduce $\mathbf{CO}_2$ emissions) and the implementation of alternative systems. These services are provided by System Alpenluft AG (SA), a spin-off company of Schwendimann AG that provides consultancy services for municipal waste collection.

Within the scope of the project, two variants of a bring system were defined, and the associated optimization problems for collection point locations were investigated. One considers a large collection truck that transports MSW to a single disposal facility [27], while the other involves smaller, more sustainable collection vehicles (e.g., electric) that unload MSW at intermediate disposal facilities [28]. In both settings, the objective is to minimize the total cost. Users are assumed to rank candidate locations according to a given criterion (e.g., increasing walking distance, proximity to interesting points). These problems are closely related to the multi-vehicle covering tour problem (m-CTP), a variant of the LRP in which service requirements are defined in terms of coverage. In this context, a user is considered covered if their MSW can be brought to a collection point from their ranked list, and users are assigned to the highest-ranked location where a collection point is installed.

The current prototype of the tool integrates the heuristic solution approaches developed by the authors for both optimization problems, avoiding the need for commercial off-the-shelf optimization solvers. It translates optimization results into intuitive and actionable insights on both collection point locations (strategic planning) and collection routes (operational planning), allowing users with little or no background in optimization to effectively interpret and apply them. Furthermore, it is web-based (ensuring remote accessibility) and can be accessed via a standard browser (i.e., not requiring the installation of special client software), and features a comprehensive, user-oriented interface, making it suitable both for consulting purposes and for less experienced users wishing to access relevant indicators or perform small-scale system adjustments.

Several key design criteria were defined for the implemented prototype. First, it is fully parametrized, allowing users to specify the alternative collection systems to be evaluated—the same system variant with different configurations or different system variants—as well as the requirements for the compared systems (e.g., maximum walking distance, available collection vehicles, external location restrictions). Interaction with the tool is facilitated through a user-friendly interface that enables smooth modification of input data and the constraints of the underlying optimization problems via descriptive editable fields and other interactive, clickable resources. Notably, these clickable resources provide a spatial representation of collection points and routes using publicly available cartography, while additional graphical elements, such as spider diagrams, visualize the indicators associated with each evaluated system.

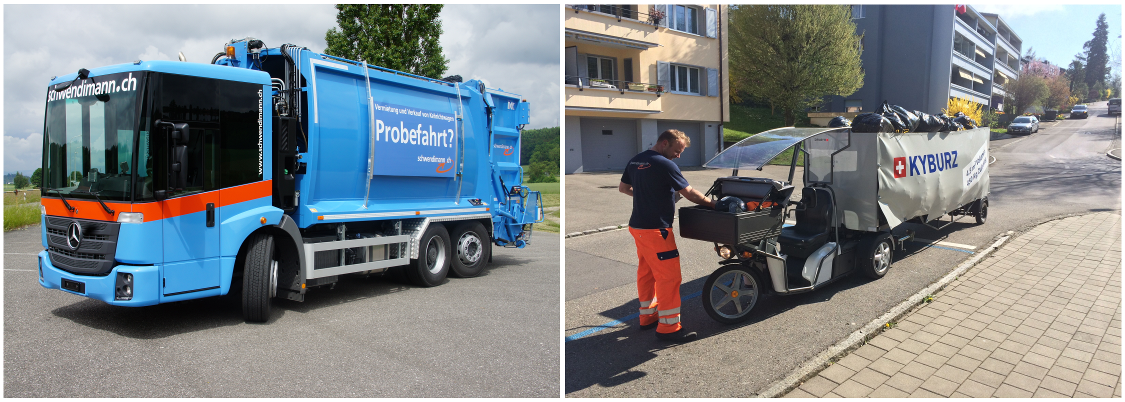
The remainder of this paper is organized as follows. Section 2 provides a brief summary of the defined bring system variants, along with the associated optimization problems and solution methods. The architecture of the decision-support tool and implementation details are included in Section 3. Section 4 reports illustrative results from a real-life case study. Finally, Section 5 presents the conclusions and discusses directions for future research. The global organization of the paper follows the research methodology proposed by [29]. The problem identification, motivation and objectives for a solution have been developed in this introduction; the design and development are described in Section 2 and 3; and, the demonstration of the utility of the application is presented in Section 4. Section 4 also presents the evaluation and communication of the application through feedback of SA that is currently using it on the ground-field.

2. Bring system variants

In Switzerland, curbside systems typically employ rear loaders (Figure 1a) to collect MSW. These vehicles are built on a conventional truck chassis and drive in a stop-and-go operation throughout the collection, picking up waste directly at users' doorsteps. The waste is loaded at the rear of the vehicle and hydraulically compacted inside the body. Rear loaders are suitable for collecting both individually provided waste bags and containerized waste. Once fully loaded, vehicles drive directly to the main disposal facility for unloading. Recently, electric chassis have become available, offering lower energy consumption and reduced noise and exhaust emissions. However, these vehicles do not fundamentally change the curbside collection process itself.

Within the project, we defined two bring system variants, motivated by the two vehicle types that could be employed by the WCC. The *classical* bring system uses rear loaders and relies on a single disposal facility, typically located outside residential areas. Waste is deposited at collection points distributed throughout the municipality, which may consist of containers or designated drop-off areas (e.g., circles painted on the ground). The *satellite* bring system, by contrast, introduces intermediate disposal facilities located closer to the collection area and combines rear loaders with satellite vehicles (Figure 1b). Satellite vehicles are lightweight, agile, and energy-efficient—potentially electric—and their compact design and low noise emissions make them particularly suitable for densely populated or constrained urban environments. They collect individual waste bags (typically by hand) and transport them to the intermediate disposal facilities for emptying. Rear loaders then handle the longer-haul transport to the main disposal facility.

Sections 2.1 and 2.2 outline the optimization problems associated with the classical and satellite bring system variants, respectively, together with the corresponding heuristic solution methods



(a) Rear loader vehicle (b) Satellite vehicle

Figure 1: Waste collection vehicles.

implemented in the backend of the prototype of the decision-support tool. For both systems, the underlying road network is modeled as a directed graph $G = (V \cup W, A)$, where V and W denote node sets and A the set of arcs. The set V includes candidate locations for collection points (V^{sto}) and road intersections, while W represents residential buildings. Each arc in A corresponds to a road segment. The graph is assumed to be strongly connected, meaning that a path exists between every pair of nodes in V.

Each residential building $i \in W$ generates a known, constant waste quantity d_i within the considered time horizon (e.g., one week). Users must bring their waste to exactly one node within their ranked list of candidate locations, $V_i^{\text{rank}} \subseteq V$, which sorts the candidate locations according to some convenience measure (e.g., walking distance, proximity to interesting points). By definition, $V^{\text{sto}} = \cup_{i \in W} V_i^{\text{rank}}$. The maximum walking distance γ, as defined by local regulations, limits the range within which users can access a collection point. Due to the lack of relevant data, V_i^{rank} is determined by sorting all candidate locations within the radius defined by γ in increasing order of walking distance. The main disposal facility is denoted by σ_w, and the vehicle depot—from which the homogeneous fleet of m vehicles departs and returns—is denoted by σ_v.

2.1. Classical bring system

Figure 2 schematically illustrates the classical bring system. The objective is to jointly select a subset of candidate locations (represented by trash cans) $V^{\text{sel}} \subseteq V^{\text{sto}}$ for placing collection points and to determine the tours that visit them, such that the total transportation and collection time is minimized. The collection points must be located so that all residential buildings are covered. A residential building $i \in W$ is considered covered if its waste is gathered at a collection point from its ranked list V_i^{rank} (illustrated as coverage radii centered on the candidate locations). Besides, the waste must be collected at the highest-ranked candidate location within V_i^{rank} that is selected for establishing a collection point (black trash cans). The waste consolidated at collection points may be split among different tours, accounting for the capacity constraints of the rear loaders.

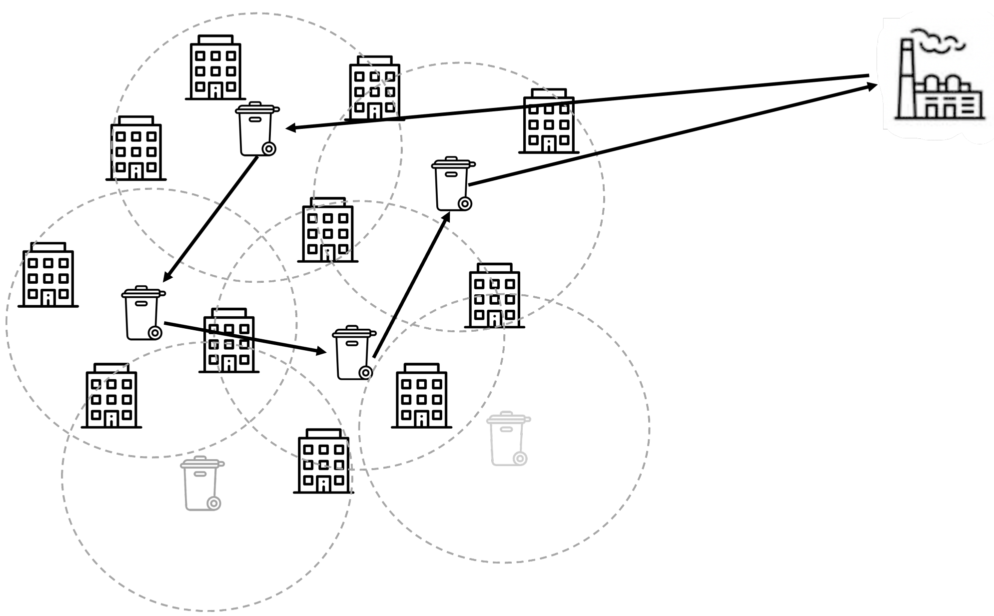


Figure 2: Classical bring system

As defined, this optimization problem can be formulated as a variant of the multi-vehicle covering tour problem (m-CTP) [30], in which the capacity constraints of the rear loaders must be respected, and each residential building must not only be covered by a collection point from its ranked list but also allocated to the highest-ranked collection point that belongs to the solution. In [27], we developed a two-phase heuristic approach that addresses the two underlying subproblems this optimization problem is built on: a set covering problem (SCP) to determine the locations of collection points (first phase) and a split-delivery vehicle routing problem (SDVRP) to determine the collection tours while accounting for the possibility that waste may be split among multiple tours (second phase).

In the first phase, we generate set covers, i.e., subsets of candidate locations that ensure coverage of all residential buildings in W. Each set cover is associated with a cost, representing an estimate of the total transportation and collection time. If a set cover has already been processed in the second phase, a penalty is applied so that this set cover is reconsidered only when no other unprocessed set covers remain. A set cover is retained if it differs from those already stored and if either (i) its cost is lower than the highest cost among the set covers currently in the list, or (ii) the number of stored set covers is below the predefined maximum number to be maintained.

The second phase aims to solve a SDVRP on the set covers generated in the first phase. In other words, this phase constructs the tours that visit the collection points—located at the candidate locations included in each set cover—while allowing for *split delivery*, i.e., waste can be collected over more than one tour. Once a set cover from the list is selected, it is marked as treated so that the feedback mechanism with the first phase can be applied. To efficiently generate a solutionn, the SDVRP is first transformed into a capacitated vehicle routing problem (CVRP), which assumes that waste cannot be split. This transformation relies on an a priori splitting strategy that creates multiple duplicates of residential buildings, such that the total waste associated with all duplicates equals the waste of the original residential building. The resulting CVRP is then solved using a state-of-the-art algorithm (HGS-CVRP). Finally, the CVRP solution is reconstructed into a feasible SDVRP solution and compared with the current best solution based on its total cost.

2.2. Satellite bring systems

Figure 3 schematically illustrates the satellite bring system, which extends the classical variant by incorporating intermediate disposal facilities (depicted as large waste containers). These facilities, located closer to the collection area (e.g., in warehouses or service yards), allow satellite vehicles to dump their load and thus fully renew their capacity. Users bring their waste to collection points—as in the classical bring system—where it is collected by satellite vehicles and transported to intermediate facilities. These facilities are subsequently visited by rear loaders, which empty the accumulated waste and transport it to the main disposal facility.

The underlying optimization problem extends the formulation introduced in Section 2.1. In addition to the candidate locations for collection points (V^{sto}) and road intersections, the node

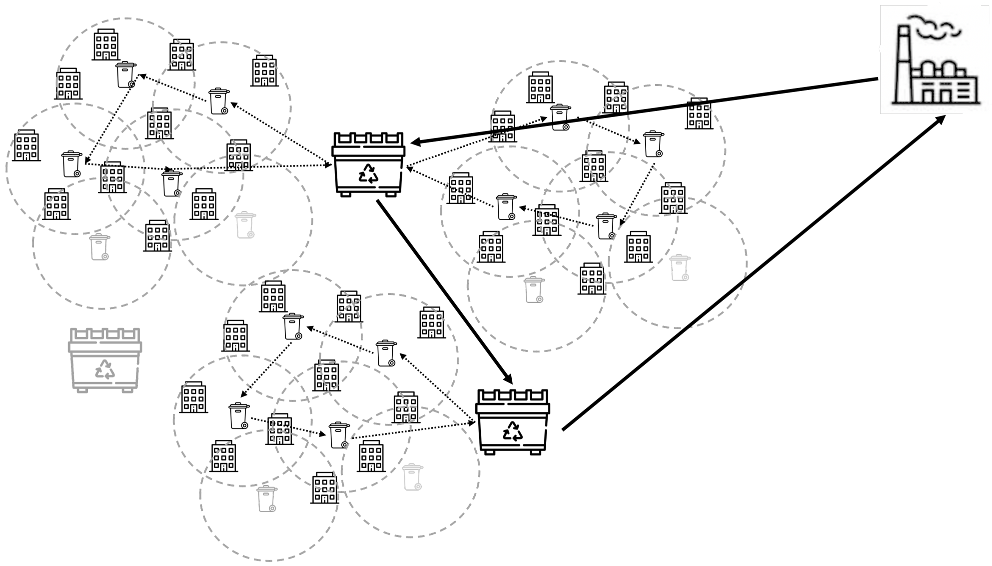


Figure 3: Satellite bring system

set V also includes the set of available intermediate facilities, denoted by V^{fac}. The optimization determines which of these facilities are used by the satellite vehicles. A single rear loader ($m = 1$) is assumed to perform exactly one rotation, in the sense of [31], i.e., a combination of single-facility routes (starting and ending at the same intermediate facility) and inter-facility routes (connecting two different facilities), with a mandatory final visit to an intermediate facility before returning to the main disposal facility σ_w. In Figure 3, the performed rotation consists of an inter-facility route connecting the two selected intermediate facilities.

The solution method proposed in [28] decomposes the problem into a SCP and a CVRP with intermediate facilities (CVRP-IF). The SCP exhibits a particular structure that is exploited to generate set covers V^{sel} in the first phase, using a novel approach based on a minimum clique cover—a partition of a reduced graph on the road intersections into the smallest possible number of cliques. The second phase then addresses the CVRP-IF, where integer routing solutions are generated by column generation for each set cover that has not yet been processed.

3. User interface

Optimization algorithms published in the scientific literature, including those outlined in Section 2, cannot be used directly by the concerned decision-makers or operational staff, as their application typically requires technical expertise in data processing, optimization modeling, and software implementation. To bridge this gap between methodological development and practical use, we developed a prototype of a web-based decision-support tool that embeds the solution methods previously described and enables stakeholders to interact with them through an intuitive and guided workflow. The prototype integrates several user-oriented components that streamline data encoding, support the visualization of optimized collection rounds, and allow users to export the routing information required for practical deployment. These functionalities were defined in close collaboration with SA, ensuring alignment with the operational needs of WCCs.

Figure 4 provides a schematic representation of the architecture of the developed prototype. The modeling components are organized into three layers: data input, collection round generation, and solution interpretation. The components in the first two layers correspond to database-backed objects—each has a persistent database entry and an associated page for encoding the data required by the solution methods. The information that can be encoded through these pages is summarized within each component block in Figure 4. In these pages, geographic data is entered through map-based interfaces (marked by (M) in Figure 4), and default values are available for many fields to ease the data-entry process. The third layer (solution interpretation) does not introduce new persistent objects. Instead, its pages rely on the data generated and stored in the previous layers, providing visualizations of the obtained collection rounds together with the performance indicators needed for analysis.

The modular design of the decision-support tool structures the data required by the optimization algorithms into thematic modules (e.g., waste information, candidate collection-point locations, bring-system variant). This facilitates the creation and reuse of project setups, as illustrated by the 1-to-n relationships between components in Figure 4. The tool also supports an iterative workflow to refine collection rounds based on operational feedback. This is represented by the dashed arrows, which allow extracting collection points from previously generated solutions or from existing routing deployments. All the components as well as their main functionalities are detailed further in this section. Figure 5 shows the tool's dashboard, from which users can navigate

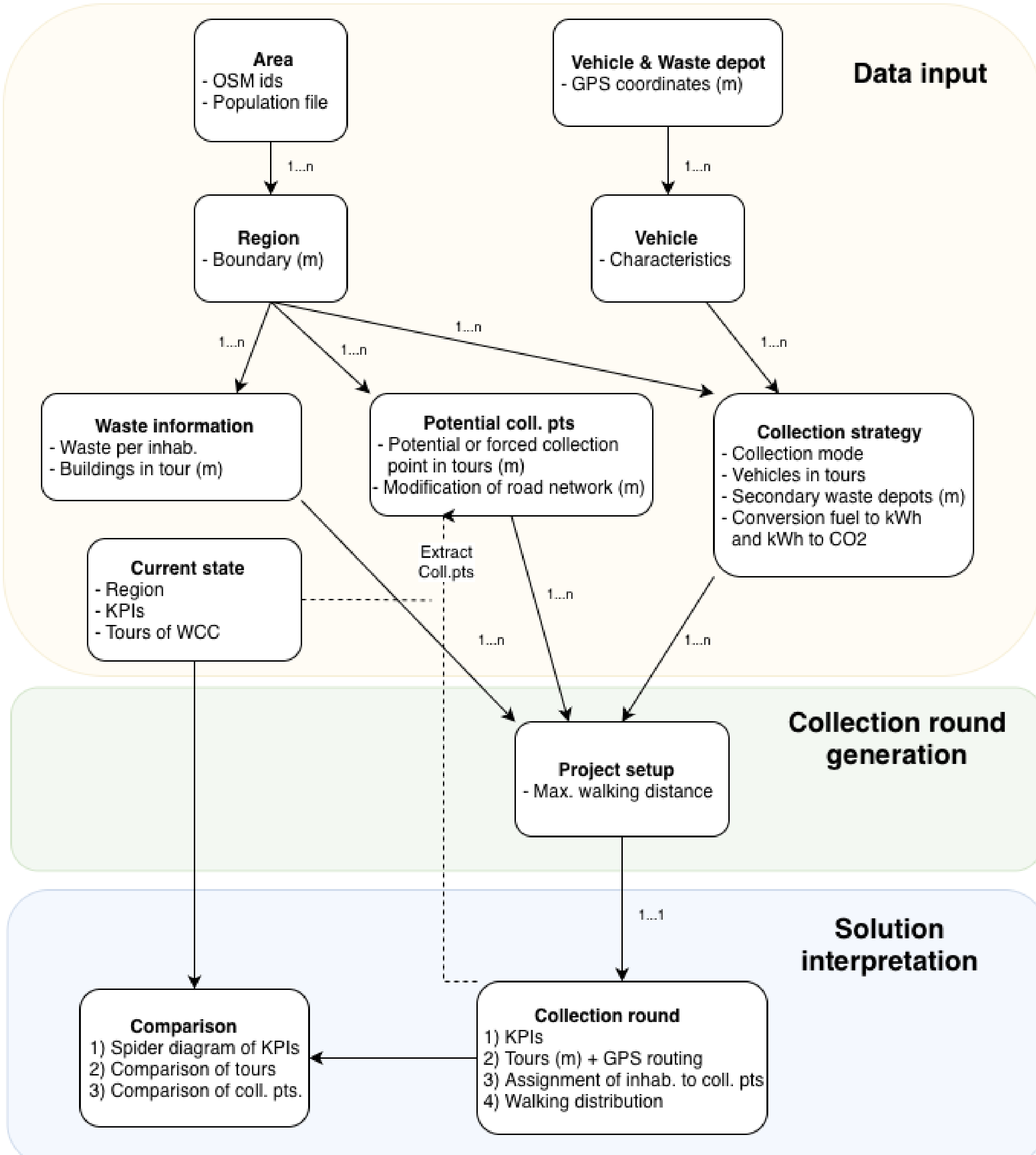


Figure 4: Simplified unified modeling language (UML) diagram of the decision-support tool architecture

across all components in an intuitive and structured manner.

The tool is implemented using the Ruby on Rails 7 framework, with PostgreSQL 15 as the database backend to ensure high performance for data-intensive requests. Tasks requiring higher computational efficiency are handled using dedicated languages, solvers, and scientific libraries. The optimization algorithms of Section 2 are implemented in Java 17 and rely on SCIP 8.0.4 as the mixed-integer optimization solver. The preprocessing of the road-network topology is performed

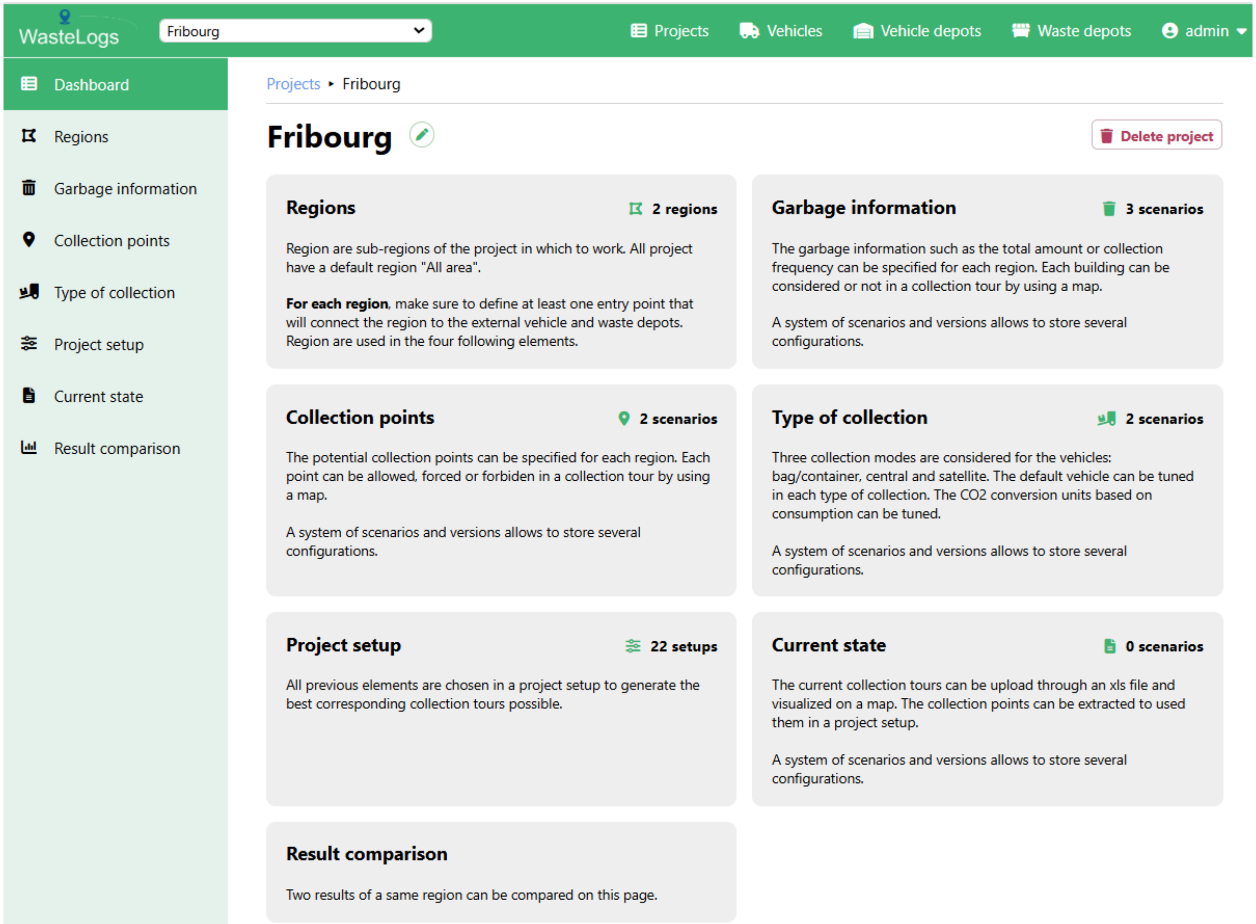


Figure 5: Dashboard of a project

in Python 3.7.1, primarily using the SciPy 1.14.1 library. The raw topological data of the underlying road network are retrieved from OpenStreetMap[2] (OSM) and visualized in the interface using the Leaflet JavaScript library[3].

3.1. Data input

Area. An `Area` is defined based on the OSM identification numbers (OSM IDs) and a population density file. Users can input the name of a municipality and the tool will automatically retrieve the corresponding OSM ID. Multiple OSM IDs can be encoded within the same `Area` to cluster various municipalities.

OSM provides detailed information on the road network, represented as a directed graph, and

[2] https://www.openstreetmap.org
[3] https://leafletjs.com

the locations of residential buildings. This topology is preprocessed to construct the graph $G = (V \cup W, A)$. Candidate locations for collection points V^{sto} are generated using a greedy heuristic that ensures that the average distance between residential buildings and their closest candidate location is 10 meters, with a maximum of 25 meters (typically in less dense areas). This choice is made to be able to simulate a door-to-door collection system. The distances between each residential building $i \in W$ and each candidate location in V^{sto} are precomputed. This allows the rapid generation of the ranked lists V_i^{rank} once the user specifies the maximum walking distance γ.

Population density data from Switzerland is sourced from the Swiss Federal Statistical Office[4]. In this population density file, the Swiss territory is partitioned into a grid of 100-meter cells, each containing the total population count. Due to the General Data Protection Regulation (GDPR) used in Switzerland (similar to the one used in the EU), the precision of this data is limited. The tool uniformly distributes the number of inhabitants within each cell to the residential buildings identified by OSM. While this provides a reasonable approximation, users can import a custom population data file with more precise data (e.g., from a municipality) under a non-disclosure agreement.

Region. Within an `Area`, users can define multiple `Regions` by drawing polygonal boundaries directly on the map. This functionality is especially useful in the final stages of strategic planning, as collection rounds need to be grouped into smaller zones to enable the creation of a collection calendar (as shown in Section 4).

Vehicle and waste depots. The locations of the vehicle depot (σ_v) and the waste depot (σ_w) can be defined based on their GPS coordinates or directly on the map. These depots are then connected to the road network given by A by calculating the shortest path from each depot to the nearest node in V, using the OSM API.

[4]https://www.bfs.admin.ch/bfs/en/home/services/geostat/swiss-federal-statistics-geodata/population-buildings-dwellings-persons/population-housholds-from-2010.html

Vehicle. To accurately represent real-world operations, each `Vehicle` is defined by a comprehensive set of parameters: hourly cost, capacity, energy consumption per 100 km, collection speed, driving speed, waste unloading time, loading time per kg, and stopping time at collection points. These values can be directly derived from observed data of existing collection rounds. By default, `Vehicles` are linked to `Vehicle depots`, but all parameters can be customized to reflect specific operational needs.

The energy source for each `Vehicle` can also be specified: fuel (classical diesel truck; rear loaders), electricity mix (electrical vehicles for which the electricity is produced by a fossil and renewable energy mix; rear loaders) and electricity clean (electrical vehicles for which the electricity is produced by renewable energies; satellite vehicles). This differentiation enables meaningful comparisons between vehicle types, making it especially relevant for evaluating future investments in electric vehicles and supporting the energy transition.

Waste information. For each `Region`, `Waste information` specifies the average waste generated per inhabitant over the selected time horizon (e.g., weekly or annually). The waste quantity d_i generated by residential building $i \in W$ is then calculated based on the number of inhabitants obtained when generating an `Area` and the disposal frequency. This approach allows for the creation of multiple waste information scenarios, which is particularly useful when different types of MSW are directed to separate collection points. Residential buildings can be visualized on a map selectively activated or deactivated—either individually or in groups—to include or exclude their waste from the scenario.

Potential collection points. Candidate locations for collection points are identified for each `Region` using a map that displays the nodes in V^{sto} (see Figure 6). This map is analogous to the one used for defining active residential buildings in `Waste information`. The user can interactively activate (green), deactivate (red), or force (blue) candidate locations, either individually or in groups. Deactivation may be necessary in zones inaccessible to collection vehicles (e.g., narrow streets), while forcing a collection point ensures that existing sites are retained. The interface also supports automatic adjustments to candidate locations based on tuning parameters, such as enforcing a min-

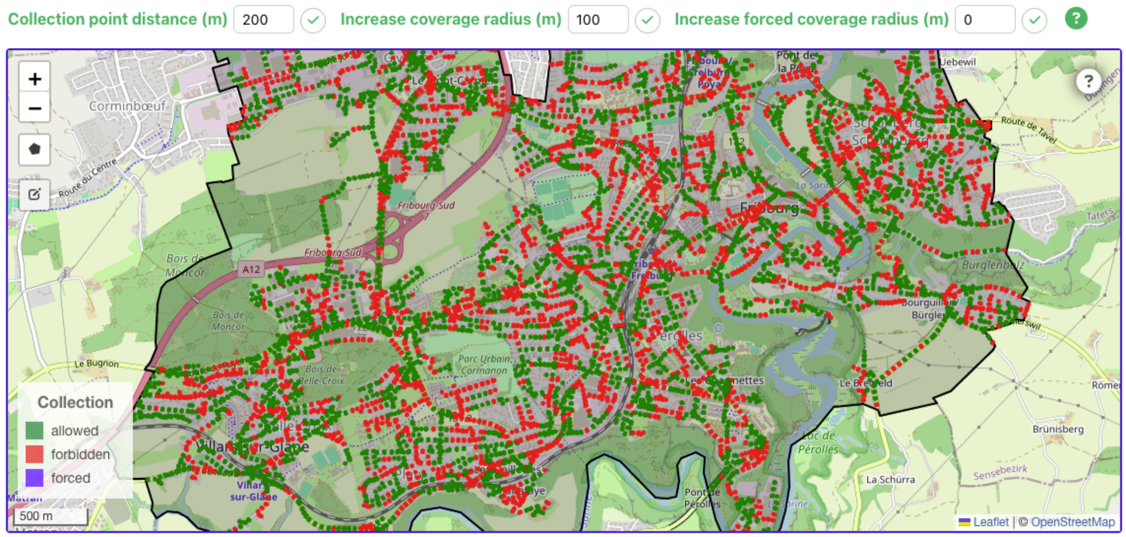


Figure 6: Definition of `Potential collection points`

imum distance between potential collection areas (e.g., radii of 200 m and 100 m, as illustrated in Figure 6). The tool further enables the design of alternative scenarios, such as reorganizing existing collection points or requiring citizens to bring their waste to more distant facilities.

Users can visualize and edit the road network, deactivating streets (one-way or both directions) as needed. This function is particularly useful to specify the direction of travel on a road, to force the vehicle onto certain roads, to relieve traffic on others, to prevent large collection vehicles in urban centers, or to block a road due to roadworks. Dead-ends can also be deactivated based on a maximum distance. We emphasize that these features are critical in practice. While the road network is mathematically represented as a graph G, it does not encode the turning angles required by vehicles. Routing algorithms that ignore this information may generate tours exploiting narrow dead-ends to turn around as fast as possible to minimize travel time, resulting in infeasible routes in practice.

Collection strategy. For each `Region`, users define the bring system variant—either classical or satellite. The associated collection vehicles are based on preexisting `Vehicles`, but all parameters can be tuned to define the collection strategy. For the satellite bring system, the intermediate facilities V^{fac} can be specified directly on the map. To calculate CO_2 emissions of the `Collection strategy`, users input conversion coefficients that translate any energy source consumption into kWh and the corresponding CO_2 emissions.

Current state. Routing files (typically in `gpx` or `kml` format) generated for each collection round contain the coordinates of collection vehicles for a precise time discretization. From these files, both the collection rounds and the coordinates of existing collection points can be extracted and mapped to the nearest nodes in V^{sto}. Figure 7 shows an example of a collection round imported from such a routing file.

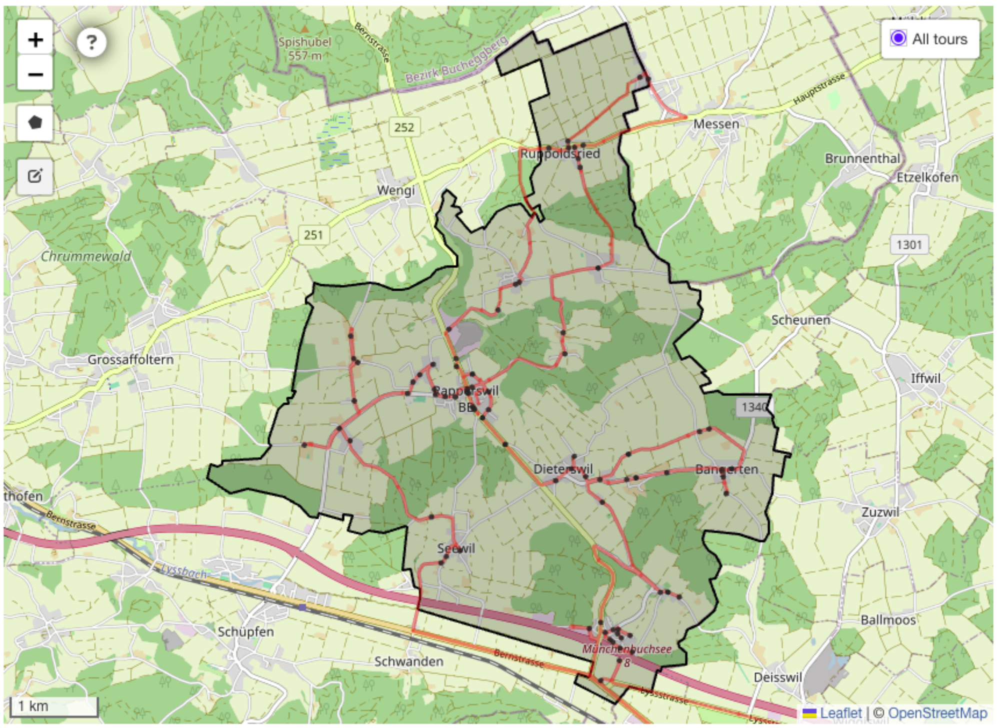


Figure 7: Current collection tour of a WCC

The `Current State` captures all existing collection points and rounds. Users can choose to activate only these points, thereby restricting optimization to routing improvements, or allow the optimization algorithms to determine only a subset of new collection points. Additionally, a `Current state` can be linked to a specific `Region`, with associated KPIs provided for comparative analysis in the solution interpretation.

3.2. *Collection round generation and solution interpretation*

Project setup. A `Project setup` integrates `Waste information`, `Potential collection points`, and `Collection strategy` within a specified `Region`, and includes a user-defined maximum walking distance γ. This modular approach allows for the evaluation of multiple configurations. As described in Section 3, setting γ to zero effectively models a door-to-door collection system.

Collection round. The `Project setup` serves as the input for the optimization algorithms (Section 2), which produce a solution formatted as a `Collection round` page. Figure 8 displays the KPIs for a `Collection round`, along with the information on the collection points to be visited. Users can examine each collection point by selecting it in the right tab of Figure 8 or directly on

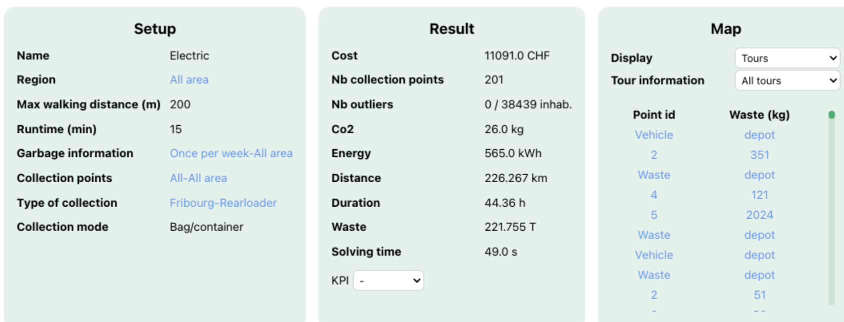


Figure 8: KPIs of a `Collection round`

the map, as shown in Figure 9.

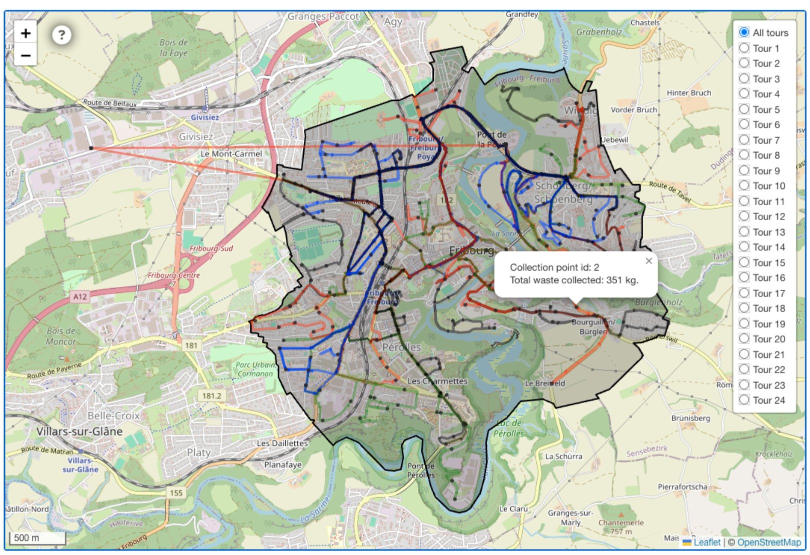


Figure 9: Routing of a `Collection round`

Collection rounds can be displayed either individually or all at once. The two straight arcs on the left of the map represent the trips between the vehicle depot and the area of collection (corresponding to the first and last tours). The tours within a `Collection round` naturally partition the considered `Region`. The visualization enables users to define smaller `Regions`, ensuring that collection tours in different neighborhoods do not overlap. This operational procedure is detailed further in Section 4. Additionally, Figure 10 provides information on residents' walking distances and their assignment to collection points.

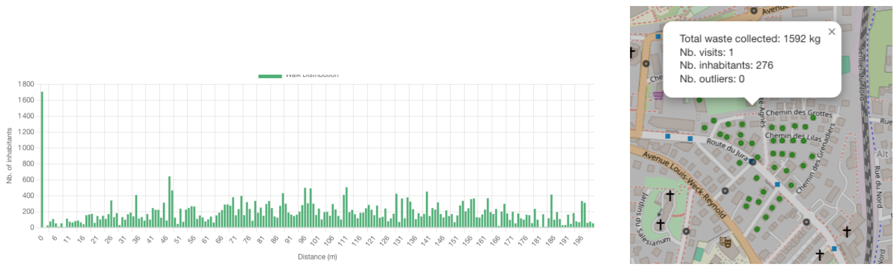


Figure 10: Walking distances of citizens and information on collection points

As for a `Current state`, the collection points from a `Collection round` can be extracted to create a `Potential collection point` scenario, activating only the points included in the tours. If certain collection points prove problematic in practice, users can easily redefine a new `Potential collection point` scenario. Convenient collection points can be automatically forced, and modifications need only to be made in problematic neighborhoods. This approach enables iterative refinement of the solution by redefining the `Project setup`. To implement the routing on the ground, users can export the locations of the collection points and the routing of each tour as an `xls` file. This file can then be converted into a `gpx` or `kml` format for visualization in GIS software or for use in routing devices installed in collection trucks.

Comparison. All `Collection rounds` within the same `Region` can be compared using the `Comparison` page as illustrated in Figure 11. Users can select multiple KPIs, which are then visualized in a spider diagram as percentages ($= \frac{\text{KPI of the collection round}}{\text{Maximum value of the KPI}}$). The interface also allows for side-by-side map comparisons of tours from two different `Collection rounds`.

The example in Figure 11 compares collection rounds using a diesel truck (Diesel) and an electric truck (Electric) in the city of Fribourg (see Section 4). While the electric truck significantly reduces energy consumption and CO_2 emissions, it incurs higher operational costs. These results are discussed in greater detail in the following section.

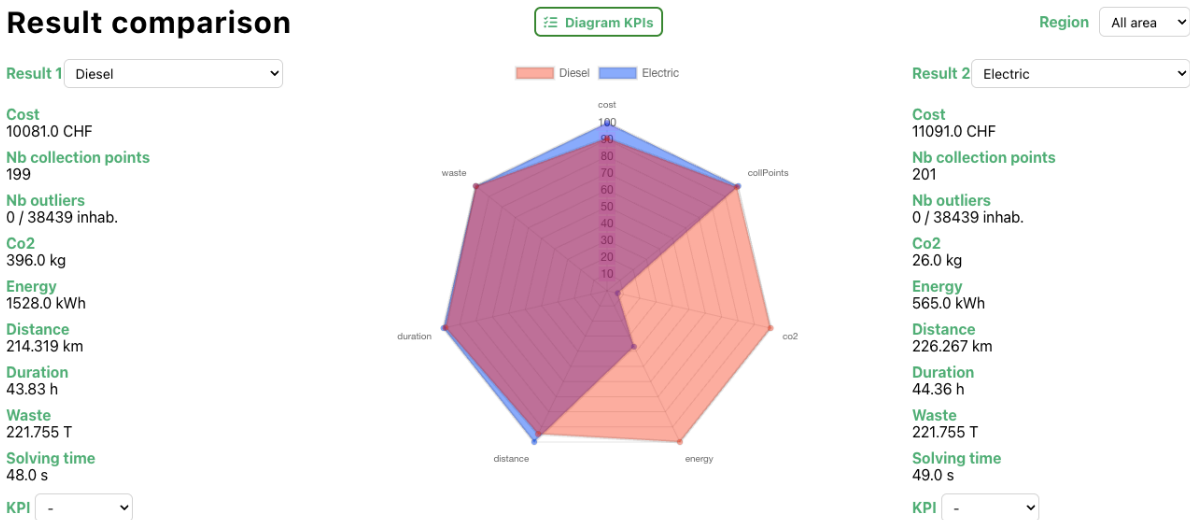


Figure 11: Spider diagram for result comparison

4. Results and discussion

System-Alpenluft AG[5] (SA) has used the application presented in Section 3 in collaboration with the municipality of Köniz, Swizerland, a municipality of approximately 43,000 inhabitants covering an area of 51 km^2. Following the identification of a saturation in the collection capabilities of the existing curbside collection system—specifically the door-to-door collection—Köniz engaged SA with the objective of reorganizing the collection tours and evaluating the potential investment in an additional waste collection vehicle.

As a result of this collaboration, SA reduced by 15% the total travel distance compared to the existing tours. The numerous tests conducted by SA, together with the municipality's ability to visualize the optimized tours and their associated key performance indicators (KPIs), were crucial in facilitating the implementation of the proposed solution. This ultimately enabled the municipality to avoid purchasing a new collection vehicle and to reduce total collection costs using the existing fleet.

In this section, we present a case study of the city of Fribourg, capital of the Fribourg canton in Switzerland, as the results of Köniz cannot be disclosed in detail for contractual reasons. We

[5]https://www.system-alpenluft.ch

present various types of scenarios that can be tested for strategic decision making and similar tests as those performed by SA in Köniz are conducted. Representative data was provided by SA based on the real-life tests performed in Köniz.

TODO

4.1. Data

Fribourg has 42412 inhabitants as of January 2025 and a surface of 9.32 km^2 [6]. The city is illustrated in Figure 12 with the location of the vehicle and waste depots, marked by a σ_v and a σ_w, respectively. The city center is indicated in gray together with nine distinct zones separated by dashed lines. These areas will be used in the case study.

Two types of waste are considered: door-to-door waste that is left in front of each household, and container waste that citizens bring at collection points. Container waste is typically sorted waste, while door-to-door waste is general waste. Note that some waste citzens placed in door-to-door waste could be brought to containers. The distribution of the type of waste in Fribourg can be found on the canton's website [7]. We consider an average yearly amount of 300 kg per inhabitant of container waste that is brought to collection points within a 200 meter walking distance. This represents a total of 221.75 T of waste to collect per week. For ease of comparison, we consider the average amount of door-to-door waste is also of 300 kg. All results reported for the door-to-door waste collection consider the rear loader system with a maximum walking distance of 25 meters. This distance is estimated based on the average distance between stops in the collection rounds observed in Köniz prior to their reorganization.

Five standard waste collection vehicles used by SA are presented in Table 1. The first vehicle, *diesel*, works on fuel and is representative of most of the trucks currently used. All others are electric vehicles as SA offers consultancy services for the transition to electric mobility. The CO_2 emissions for electric vehicles consider that electricity is produced through renewable energy sources. The last vehicle, *satellite*, is the small vehicle used in the satellite collection system and

[6] `https://www.fr.ch/deef/ssd/statistiques-par-themes/effectif-et-evolution`
[7] `https://www.fr.ch/energie-agriculture-et-environnement/dechets-et-sites-pollues/`

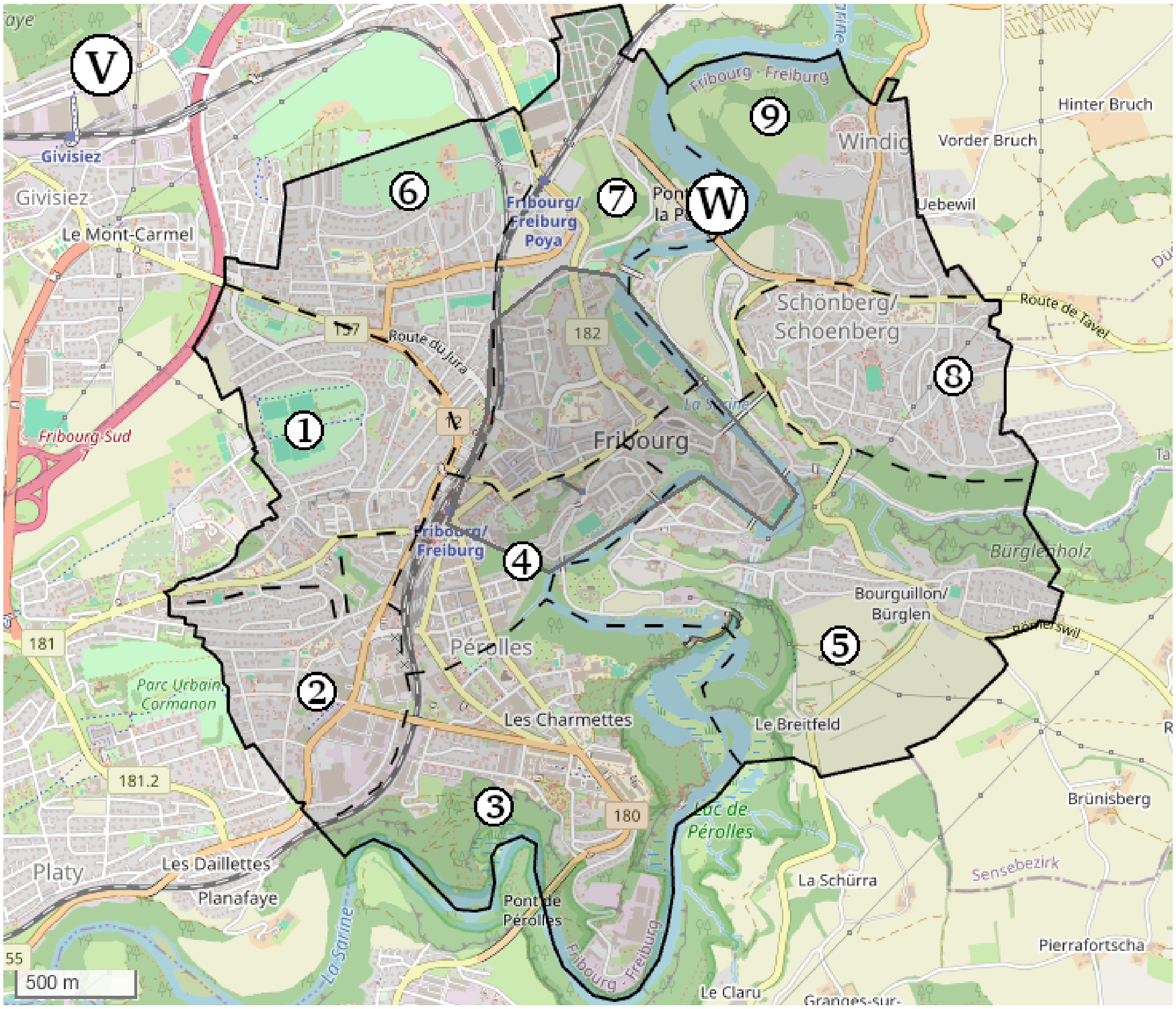


Figure 12: Fribourg city, vehicle depot (V) and waste depot (W)

Characteristics	Diesel	Rear loader	Small rear loader	Large rear loader	Satellite
Cost (CHF/h)	230	250	230	300	90
Capacity (T)	10	10	7	15	0.5
Emissions (kg CO_2/100km)	185.0	11.5	9.2	14.5	1.9
Collection speed (km/h)	5	5	5	5	8
Normal speed (km/h)	25	25	25	25	28
Drop time (min)	12	12	10	15	2
Load time (s/kg)	0.25	0.25	0.3	0.25	0.5
Stop time (s)	10	10	8	15	10

Table 1: Waste collection vehicles

is used in combination with the rear loader vehicle.

The characteristics in Table 1 are crucial to obtain representative results. The capacity of a vehicle is straightforward to obtain, and the other values can be estimated based on current collection tours. The cost per hour can easily be derived from the fuel, maintenance and operating cost observed on the ground-field. The other thinner parameters can also be computed by using the information collected by sensors during the existing collection rounds in a gpx or kml routing file that are used to extract the `Current states`.

The application can be used for purely operational purposes by optimizing the collection tours for door-to-door waste for a fixed amount of waste and predefined vehicles. Strategic decisions can also be taken by evaluating the impact of redifining collection points, or purchasing new vehicles. Table 2 reports the KPIs for the different collection vehicles for door-to-door waste by using the rear loader system. The total cost with electric vehicle is slightly higher than for the diesel ones,

Strategy	Cost (CHF)	Duration (h)	Dist. (km)	CO_2 (kg)	Nb. tours	Nb. coll. points
Diesel	14357	62.4	283	523.6	24	1225
Rear loader	15555	62.2	287	33.0	24	1226
Small rear loader	15834	68.8	353	32.5	35	1217
Large rear loader	16238	54.13	238	34.5	18	1226

Table 2: Door-to-door collection

but reduction on the CO_2 emissions is drastic. With the same collection capacity (Diesel and Rear loader), the other KPIs are similar. A capacity of 10 tons is the most interesting choice cost wise. If the workforce available is low, the large rear loader could be chosen; if the streets are narrow, the small rear loader could be the best choice. Depending on the characteristics of the collection area, the impact of using or purchasing a new vehicle can be evaluated through such simulations.

A comparison of various collection strategies are presented in Table 3. A maximum walking distance of 200m is considered for the inhabitants to the closest collection points. The first four tests considered the same vehicles than in Table 2 with a waste collection once per week. The number of collection points is significantly reduced in comparison to door-to-door collection. The

dechets/dechets-urbains/statistiques-des-dechets-urbains-collectes-par-les-communes

Strategy	Cost (CHF)	Duration (h)	Dist. (km)	CO_2 (kg)	Nb. tours	Nb. coll. points
Vehicle selection						
Diesel	10081	43.8	216	399.6	24	199
Rear loader	11091	44.1	226	26.0	24	201
Small rear loader	11254	48.9	276	25.4	34	199
Large rear loader	12496	41.6	165	23.9	15	202
Collecting twice a week						
Diesel - twice/week	7532	32.7	161	297.9	11	201
Total per week	15064	65.4	322	595.8	22	207
Rear loader - twice/week	8055	32.2	162	18.6	11	207
Total per week	16110	64.4	324	37.2	22	207
Small rear loader - twice/week	7849	34.1	177	16.3	16	200
Total per week	15698	68.2	354	32.6	32	200
Large rear loader - twice/week	9623	32.1	149	21.6	8	202
Total per week	19246	64.2	298	43.2	16	202
Walking distance impact						
Rear loader - 100 m	13014	52.0	251	28.8	25	425
Rear loader - 200 m	11091	44.4	226	26.0	24	201
Rear loader - 300 m	8173	32.7	162	23.5	23	113

Table 3: Waste collection at collection points

number of tours is similar as the same amount of waste is collected, but the total duration and distance are smaller due to the reduced number of stops. In consequence, the cost is reduced by about 30%. The following tests consider a waste collection twice per week, dividing the amount of waste by two at each collection round. For the same four vehicles, the KPIs are provided for a collection round and for a full week. The costs increase by 50% compared to collection waste once per week. This strategy could be motivated if too much waste accumulates in a week at the collection points. The last three tests consider various walking distances with the rear loader truck. Obviously, the cost is reduced as the walking distance increases. The choice could be made based on preferences of citizens, or budget constraints.

Some parts of the city might contain narrower streets that some waste collection vehicles might not be able to use. This typically occurs in city centers. We consider splitting the city of Fribourg between the historical center and the surroundings containing respectively 6091 and 31562 inhabitants as illustrated in Figure 12. The results for different collection vehicles are provided in Table 4 with a maximum walking distance of 200 meters and one collection per week. The first line is a reminder of the KPIs of the rear loader truck obtained in the previous tests on the entire city of Fribourg. The second line provides the KPIs of the rear loader truck on the surroundings of Fribourg. The other lines test different vehicles, providing the KPIs for the collection in the city center, and the total KPIs considering the center and the surroundings. Although the satellite system might seem interesting at first by introducing small electric vehicles for reduced emissions, it has the drawback of requiring a large number of tours due to its limited capacity. Consequently, the emissions are 50% higher in the center than for a truck with a capacity of 7 tons. In the ground field, the satellite system has only been used in very specific situations, typically in pedestrian areas that are growing in city centers.

Strategy	Cost (CHF)	Duration (h)	Dist. (km)	CO_2 (kg)	Nb. tours	Nb. coll. points
Rear loader - Fribourg	11091	44.4	226	26.0	24	201
Rear loader - surroundings	9931	39.7	195	22.4	20	179
Small rear loader - center	1642	7.1	43	4.0	6	28
Total	11573	46.8	238	26.4	26	207
Satellite - center	1756	15.4	166	6.2	94 + 4	109
Total	11687	55.1	361	28.6	94 + 24	288

Table 4: Separating collection strategies between the city center and the surroundings

The amount of waste citizens bring to containers depends on the walking distance to them. Table 5 provides an estimation of the partitioning of the door-to-door and container waste based on the maximum walking distance to the containers. Table 6 provides the KPIs of the door-to-door and container waste collection based on the walking distance together with the total cost. One collection per week is considered. A walking distance of 250 meters provides the smallest total cost, but the choice could again be influenced by citizen preferences.

Walking distance to container (m)	150	200	250	300
Container waste (kg)	350	300	250	200
Door-to-door waste (kg)	250	300	350	400

Table 5: Waste partitioning per year based on walking distance to collection points

All the previous results are obtained with a limited encoding of data through the features presented in Section 3. They only represent a small proportion of situations that can be studied. Real-life tours can be imported for comparison, the impact of rerouting trucks in the case roads

Strategy	Cost (CHF)	Duration (h)	Dist. (km)	CO_2 (kg)	Nb. tours	Nb. coll. points
Walking distance : 150 m						
Container, 350 kg	13012	52.0	262	30.1	27	284
Door-to-door, 250 kg	15476	61.9	291	33.5	20	1222
Total	28488	113.9	553	63.6	47	1506
Walking distance : 200 m						
Container, 300 kg	11091	44.1	226	26.0	24	201
Door-to-door, 300 kg	15555	62.2	287	33.0	24	1226
Total	26646	106.3	509	59.0	48	1427
Walking distance : 250 m						
Container, 250 kg	9112	36.4	183	21.0	20	154
Door-to-door, 350 kg	17184	68.7	308	35.4	27	1216
Total	26296	105.1	491	56.4	47	1370
Walking distance : 300 m						
Container, 200 kg	8950	35.8	178	20.5	16	136
Door-to-door, 400 kg	17879	71.5	339	39.0	32	1214
Total	26829	107.3	517	59.5	48	1350

Table 6: Total KPIs based on the maximum walking distance to a collection point

are closed can be evaluated, the benefit of clustering the waste collection between several municipalities can assessed, opening or closing a waste or vehicle depot can be tested, . . . This allows to adapt to the requirements of the municipality in which strategic decisions are to be made and test a large number of scenarios.

When collection tours are to be implemented in practice, they must be clustered by area to define a given day of collection for citizens. After a global collection strategy is defined through the previous test, the area in which the waste is collected is split into zone based on the tours observed in the entire area. The tours are naturally clustered by zone in the routings obtained as it reduced the total distance. Figure 12 illustrates the same clustering procedure of the city of Fribourg in 9 zones based on the tours obtained by the read loader truck with a 200 meters walking distance on the entire city. Tables 7 provide the KPIs for the different zones in Fribourg. The total KPIs of the collection of the entire area or divided by zone are provided on the first and last lines respectively. The clustering slightly increases the cost as less flexibility is offered to the collection tours, but the zones can now be assigned to specific truck for a full day of work. This clustering procedure was used by SA in the municipality of Köniz in Switzerland in which the tours obtained by the application are now implemented in routing devices of collection trucks. The clustering is

Strategy	Cost (CHF)	Duration (h)	Dist. (km)	CO_2 (kg)	Nb. tours	Nb. coll. points
All Fribourg	11091	44.4	226	26.0	24	201
Zone 1	1196	4.8	29	3.33	3	25
Zone 2	1322	5.3	35	4.03	3	20
Zone 3	968	3.9	30	3.45	2	21
Zone 4	972	3.9	26	2.99	3	18
Zone 5	1870	7.5	43	4.94	2	33
Zone 6	1588	6.3	33	3.79	3	25
Zone 7	1228	4.9	26	2.99	2	27
Zone 8	1438	5.7	29	3.34	4	28
Zone 9	961	3.8	22	2.53	3	18
Total by zone	11543	46.1	273	31.39	25	215

Table 7: Waste collection per zone with rear loader

illustered in Figure 13[8]. A reduction of 15% of the total travel distance was observed compared

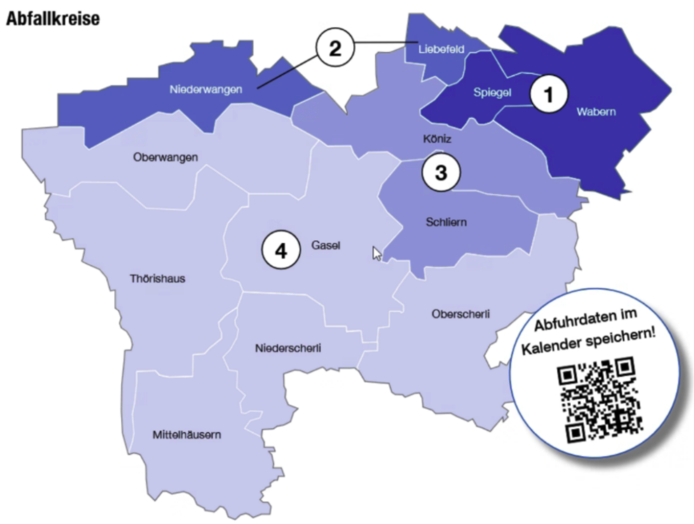


Figure 13: Clustering of Köniz

to previous tours. The total collection time predicted by the application presented an error under 5% compared to the actual collection time. The new collection strategy also canceled the project of the municipality to buy an additional waste collection truck. This is due to the collection time save that allowed to add additional shift to existing trucks.

[8]`https://www.koeniz.ch/public/upload/assets/23844/20251202abfallmerkblatt_koeniz_2026.pdf?fp=1`, last visited on October 16, 2025.

5. Conclusions

A large variety of algorithms usable for MSW management exist in the literature, but there remains a gap between these algorithms and their use on the ground-field. This paper presents a decision-support tool for MSW management integrating two state-of-the-art strategic waste collection algorithms.

The two algorithms optimize the total cost of MSW collection by defining collection points for citizens and collection tours for waste collection vehicles. The application offer a high modularity in terms of data input and result interpretation for decision making on a short-term operational level or a long-term strategic one. This data is mainly divided between the collection area, the waste information in terms of quantity and location, the potential collection points that can be used or forced to use, and the collection strategy to use for collection tours. This allows us to run numerous simulations for scenarios in which the decision goes beyond optimizing the total collection cost. Several elements such as citizens' preferences, investments in new vehicles, clustering of tours, ... can be considered as presented in the case study on the city of Fribourg in Swizerland. The application also contains a large number of parameters (operating cost of vehicles, travel speeds during collection and regular driving, ...) to calibrate the application in order to obtain KPIs as close as possible to reality. Existing collection tours can be import for comparison purposes. This is a crucial feature for decision-makers to have an accurate comparison of current KPIs and KPIs of simulations in the decision process.

The application has been used by System Alpenluft AG (SA) in the municipality of Köniz in Switzerland. Before its contact with SA, the municipality of Köniz was considering buying an additional waste collection vehicle due to an increase in their MSW. SA performed simulations, calibrating the various parameters based on the current collection tours in Köniz, and obtained a collection strategy reducing the total travel distance by 15%. The possibility of visualizing and comparing the simulation was a key factor in the discussions between SA and the municipality of Köniz to implement this new collection strategy and to avoid purchasing the additional waste collection vehicle. The error between the KPIs of the simulations and those observed in the ground-field was under 5%.

The decision-support tool presented in this paper is at a prototype level. Further useful features can be integrated, such as other optimization algorithms to generate tour, further visualization features for the results, or the automatic clustering of an area into regions. The latter is currently performed manually in the case study in Fribourg, as it was done for the municipality of Köniz. In its state, the decision-support tool proposed mainly aims at illustrating the importance of modularity of data input for ground-field strategic decision.

Acknowledgments

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