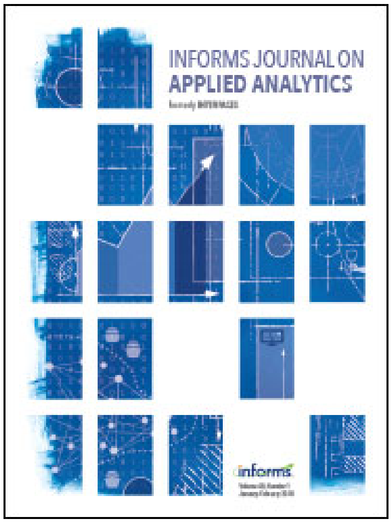

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Waste Collection in Urban Areas: A Case Study

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Abstract. The Optimization for Networked Data in Environmental Urban Waste Collection (ONDE-UWC) project is, to the best of our knowledge, the first attempt to apply the Internet of Things (IoT) paradigm to the field of waste collection. Sensors installed in dumpsters and garbage trucks share data, such as weight measurements and the number of user accesses. In this study, we schedule the weekly waste-collection activities for multiple types of waste without imposing periodic routes. An important characteristic of this project is that we consider heterogeneous stakeholders with different backgrounds and knowledge. In this context, we apply the GUEST OR methodology, highlighting how it can support the decision-making process to reduce the effects of these differences. As a result, we reduced the time required to implement the solution, increased operational efficiency, and achieved cost savings.

History: This paper was refereed.

Keywords: smart cities • vehicle routing and scheduling waste collection • manpower planning • Internet of Things

Introduction

Waste collection in urban areas can be a significant problem. Factors such as population growth and urbanization have resulted in increased consumption, thus also increasing the generation of waste. Citizens of the European Union generate more than 2.3 billion tons of refuse each year. Although municipal waste represents only about 10 percent of total waste (European Environment Agency 2015), several factors affect it. According to Blumenthal (2011), municipal waste is politically important because of its composition, distribution among the many generators of waste, and link to consumption patterns. Furthermore, waste management influences various aspects of urban management: (1) economic (e.g., the cost efficiency of collection services and processing); (2) political-local administrative (e.g., imposition of taxes and determination of disposal frequency); and (3) social and environmental (e.g., emissions, which compromise the health of citizens, and visual pollution, which affects the urban landscape). Optimizing waste management can result in substantial advantages for the community. This paper addresses the issue by proposing the solution developed under the Optimization for Networked Data in Environmental Urban Waste Collection (ONDE-UWC) (http://onde.city), a project funded by the Regional Council of Piedmont and applied to waste-collection management in an urban area near Turin, Italy. To the best of our knowledge, the contribution our paper makes to the literature is innovative in three ways. First, it shows how the solution implemented under the ONDE-UWC project allows greater flexibility in service design by considering all types of waste and by removing the typical constraint of emptying each dumpster at a fixed frequency (Mansini and Speranza 1998, Sahoo et al. 2005). Instead, we dynamically adapt the collection schedules by combining data from historical data sources, on-vehicle weight systems, and a sensor network built according to the Internet of Things (IoT) paradigm. The data gathered are used by a mathematical heuristic optimization algorithm to provide efficient solutions and by the municipalities to improve the awareness of citizens about waste production and management. Second, the adoption of GUEST OR, a lean business methodology, is used for project management and for accelerating project development. GUEST OR (Perboli 2016) is a customized operational research version of the more extensive GUEST methodology (http://www.theguestmethod.com) proposed by a set of researchers at the Politecnico di Torino in Italy

(Perboli 2017). A waste-collection scenario is defined as a multiple-actor complex system (MACS) because of the heterogeneous stakeholders involved and the issues affecting them. Third, from our waste-management literature review, we see a disjunction between the business and technical solutions proposed to handle the operational activities. This creates difficulties in communicating results to stakeholders with different backgrounds, and particularly to nontechnical stakeholders. Therefore, for the case study we present in this paper, we decided to develop a comprehensive framework using the GUEST methodology. Using this framework allowed us to create a knowledge base of the needs and wants perceived by the various stakeholders involved in the MACS. We provide details in the *Waste Management in Urban Areas: A Multiple-Actor Complex System* section. According to these requirements, the GUEST methodology provides stakeholders with standard tools to support their decision-making processes, and solution convergence (see the *Solution Analysis* section) and its representation.

In the *Computational Tests* section, we present a subset of the tests we conducted as part of our case study to validate the model's behavior in the real world. Our system is currently being integrated into the general information system at Cidiu Servizi S.p.A. (Cidiu S.p.A.), an Italian company that provides waste-management services. According to company forecasts, the system will be fully operational by the end of 2018.

Problem Statement and State of the Art

As discussed, waste-collection and treatment activities in urban areas are a challenging problem for municipalities because of the decisions that must be made and the resources required. The literature includes numerous papers related to the waste-collection problem. According to the classification proposed by Ghiani et al. (2014), waste-collection problems are addressed using different frameworks, which are based on the time horizon of the decision-making process. Waste management involves a number of strategic, tactical, and operational decisions; these include the selection of treatment technologies, location of treatment sites and landfills, collection-day selection for each district and waste type, determination of fleet composition, and routing and scheduling of collection vehicles. The first framework, which generally focuses on strategic and tactical problems, relates to the optimization of dumpster locations, decisions about the construction of new facilities, and vehicle capacity choices. The tactical level also includes optimizing day-to-day activities and executing strategic decisions. Several papers, such as Sahoo et al. (2005) and Das and Bhattacharyya (2015), address the computation of optimal routes for vehicles; others, such as Hemmelmayr et al. (2014) and Mansini and Speranza (1998), focus on defining the optimal emptying frequency for each dumpster and using it to solve the periodic capacitated arc routing problem, as Chu et al. (2006) discuss. In this paper, we consider the less explored tactical problem of scheduling and routing waste collection, without imposing a fixed voiding frequency, and allow our solver to define the time of a suitable next visit to empty each dumpster. To the best of our knowledge, this approach is less studied because the periodic hypothesis simplifies the model. Moreover, an aperiodic model works only if the sensors used are capable of providing data and waste-production estimates, and methods are available that consider the uncertainties related to seasonality, waste volumes, and traffic. We studied the aperiodic approach in the ONDE-UWC project; our primary goal was to create a data set of information, which the various stakeholders could share, by the innovative use of big data generated by waste-collection activities. The Department of Control and Computer Engineering of the Politecnico di Torino was involved in the project. Its objective was to develop and implement an algorithm for optimization at the tactical level. The goals of our innovative solution are to improve awareness of municipal-waste issues, increase the efficiency of the entire process, and reduce the total operating and environmental costs. Moreover, in developing this project, we sought to do the following:

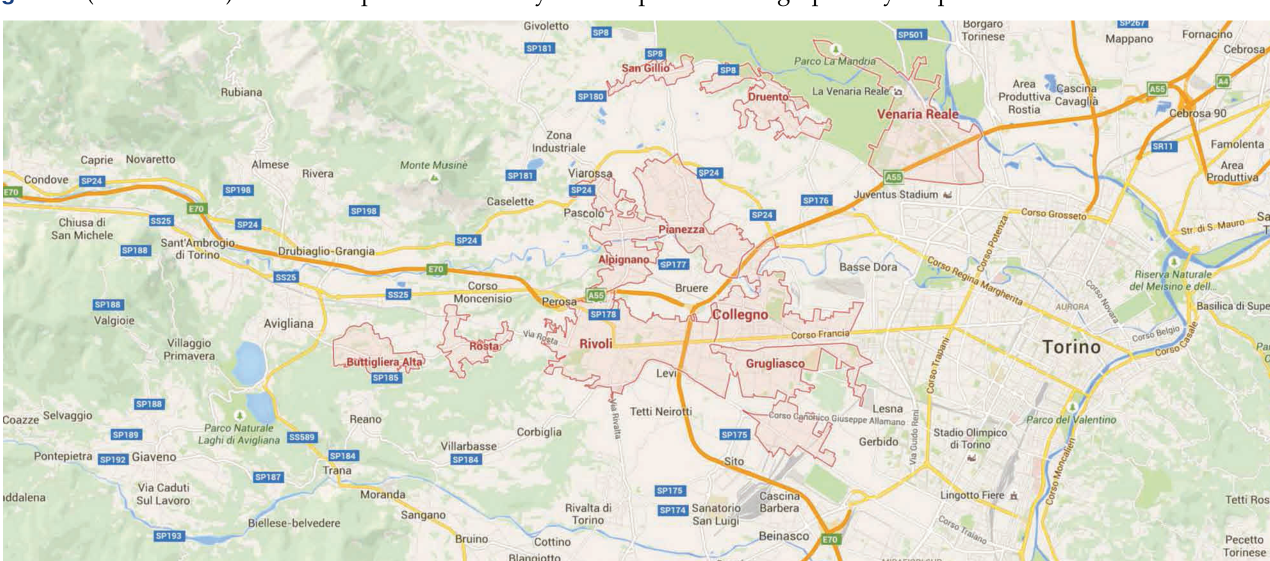
- Minimize the time required to implement the project, thereby achieving its goals in less time;
- Enhance the synergy between the company's workforce and management, thus ensuring the fulfillment of the requirements of the various stakeholders, such as public administrators who are interested in obtaining data that will help them improve how they communicate with citizens;
- Increase the awareness of citizens about the waste-management problem by integrating a mobile application into the solution. Various people could use this

application to interact more efficiently with the Cidiu S.p.A. managers who are involved in system and local administration; for example, citizens might communicate information about problems with dumpsters.

Although the aperiodic approach is less explored in the literature, other studies that do not consider fixed routes are available. Mes et al. (2014) propose a heuristic for applying the inventory-routing problem to waste collection, considering data from sensor-equipped containers. Our study and that of Mes et al. (2014) both address the problem of optimizing waste-collection operations by integrating the sensors; however, they have some major differences. First, Mes et al. (2014) propose a mathematical model that addresses vehicle routing decisions, which mainly address fleet management. Our approach, although it is slightly simplified from a routing perspective, is more realistic because it considers business and contractual constraints in generating a solution. Our objective is to evaluate the costs, mainly labor-based staff costs, that a waste-management firm incurs. Second, Mes et al. (2014) cite the adoption of sensor-equipped containers to forecast a dumpster's level of fullness (i.e., fullness percentage); in their model, they then use historical data to compute this fullness in a deterministic manner. Our work uses the IoT paradigm to gather data about the fullness of dumpsters; however, we incorporate the forecasts from the sensors into our solution. Third, based on the contracts commonly used, which imply the costs of work shifts, approaches such as those of Mes et al. (2014) could be inaccurate. In this paper, we propose a model that considers the cost structure of the waste-management firm involved in the project, Cidiu S.p.A., and data that the sensors provide about waste volumes. Cidiu S.p.A. is a leader in the environmental-services industry and manages several services related to the waste-collection cycle. It collects municipal waste in the towns of Alpignano, Buttigliera Alta, Collegno, Druento, Grugliasco, Pianezza, Rivoli, Rosta, San Gillio, and Venaria Reale (Figure 1), and is responsible for the collection of five types of waste: paper, solid urban refuse, plastic, metallic materials, and glass.

As organized, Cidiu S.p.A. has two independent headquarters, one in Rivoli and one in Collegno. Each manages the waste-collection operations in its area without interacting with the other. The fleet of vehicles used to collect the waste consists of trucks capable of measuring the refuse weight collected in each voided dumpster. This information is useful in building a forecasting model for waste production. Each vehicle starts its activity from a headquarters location, travels to a predetermined set of dumpsters from which it collects waste, travels to one of the possible dumps, and returns to the headquarters from which it started.

Figure 1. (Color online) The Municipalities Served by Cidiu S.p.A. Are Geographically Dispersed



These operations are subject to several constraints that are imposed by contracts Cidiu S.p.A. has with the management of each dump and with local administrators, as we describe next.

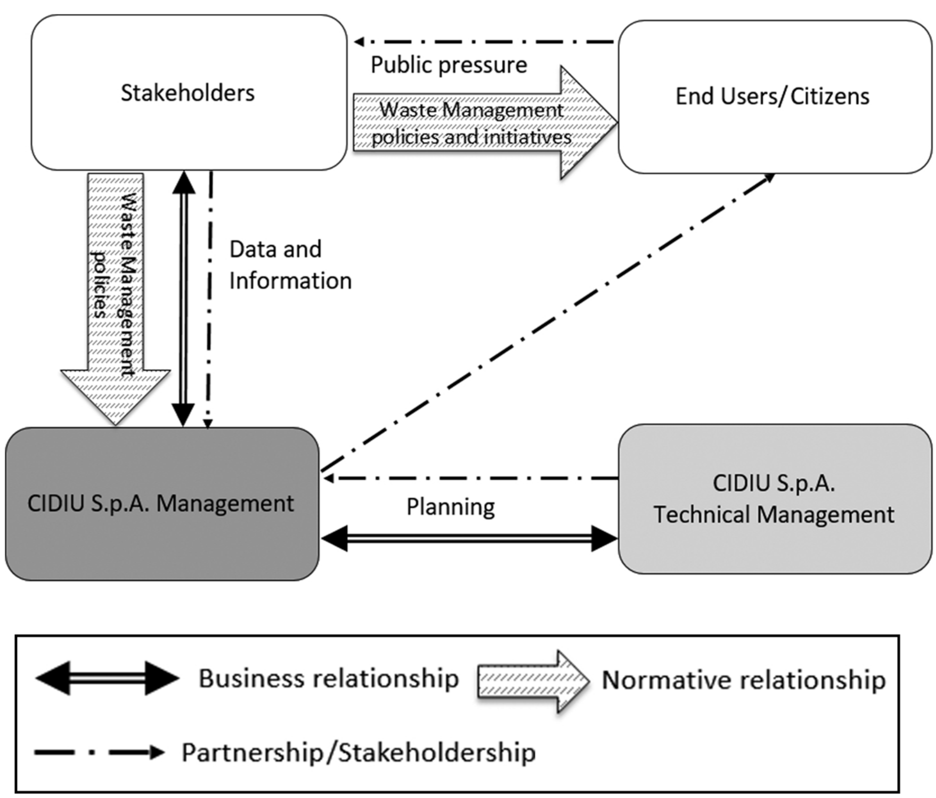
- The management of each dump interacts with Cidiu S.p.A. by specifying a limit on the percentage of yearly acceptable total refuse; management only fixes these annual limits. Note that each dump is allocated to a specific type of waste.
- Local administration imposes the service level required and the frequency with which dumpsters must be emptied to guarantee the livability of cities.

Waste Management in Urban Areas: A Multiple-Actor Complex System

As previously discussed, the GUEST methodology is based on the use of standardized tools capable of building a basic schema of the MACS. Its objective is to ensure that a project is implemented correctly, and that the solutions developed are based on stakeholder requirements. In this section, we present the waste-management MACS. We define the actors involved in the ONDE-UWC project and the value propositions that this initiative aims to offer to each of them. For this purpose, we adopted the value proposition canvas proposed by Osterwalder and Pigneur (2014). Our goal was to define the value proposition to ensure that it fits the needs and desiderata of each stakeholder. The value proposition design represents a first step in creating a knowledge base that is valuable for defining the solution. We do not present each canvas in detail, because doing so would exceed the scope of our work. In this section, we briefly discuss the MACS and the value propositions for each stakeholder; in Appendix A, we present the canvas. In Figure 2, we show the MACS components and their interactions; here, we briefly describe the actors involved.

- *Cidiu S.p.A. management*. Cidiu S.p.A. is responsible for managing the waste-collection service in 10 municipalities. The company's management gathers the data it uses for statistical purposes and for accounting management and also provides this information to third parties, such as local administrators. These managers

Figure 2. The Flowchart Shows a Representation of the Multiple-Actor Complex System



have a business relationship with Cidiu S.p.A. technical management and interact with stakeholders and end users. Through the waste-management policies, they have normative and business relationships with the stakeholders and exchange data with them.

• *Cidiu S.p.A. technical management*. Technical management is composed of the chief operating officer (COO) and the team leaders. Its primary responsibility is to manage the weekly operations of the services provided, such as planning shifts, routes, and disposal activities. The resulting plan is formulated by the team leader, supervised by the COO, and then communicated to the drivers. Responsibilities also include monitoring routes and vehicles using an information technology (IT) system that certifies the success of the emptying operations for each dumpster and gathers the data useful to dimension the service.

• *End users*. Citizens represent another actor segment within the ONDE-UWC project, because they generate waste, use collection services in urban areas, and are involved in city dynamics. They are interested in both the livability of cities and the usability of waste-disposal services, particularly for hazardous refuse. End users are also interested in costs because they pay the taxes that local administrations impose for providing waste services. By using public pressure, they influence the stakeholders, while the stakeholders influence the end users through waste-management policies and initiatives.

• *Stakeholders*. Stakeholders are principally local and regional administrators. They provide information to citizens, conduct outreach activities, and design the services that encourage the remanufacturing and recycling of waste into usable products. Local administrators manage the urban waste collection, outsource the related operations to third-party firms, manage the collection of taxes, organize outreach activities, and generate periodic reports. Thus, they benefit from the open source data that the firms operating within the waste-collection industry generate. Their most important relationships are the normative relationships they have with the end users and Cidiu S.p.A. management.

The ONDE-UWC project offers each actor a specific value proposition, which addresses the difficulties that actor perceives, while enhancing the benefits received. In particular, the tool we describe in Appendix A optimizes the waste-collection services and automates operations, thus providing benefits to Cidiu S.p.A., including helping to position it as a technological leader in the waste-collection market. The project also offers solutions that integrate the use of big data for the waste-collection process and the actions of the end users. In particular, these solutions decrease the operating costs of the services and their environmental impact, as we discuss in the *Results* section. This value proposition relates strictly to the functions of Cidiu S.p.A. technical management. It consists of an optimization algorithm that solves two problems: scheduling and vehicle routing.

This tool automates operations planning by reducing the inefficiencies and minimizing the total cost of dumpster-emptying processes (e.g., by eliminating the requirement for third shifts), provides time savings, and uses the data collected to generate the optimization model. The efficient and optimized management of operations allows Cidiu S.p.A. to release resources, which it can then use to extend its services to other municipalities, gain a competitive advantage from the acquisition of new competencies and use of innovative tools, and generate a solution, which provides the base for future what-if analyses. Moreover, an efficient use of vehicles (i.e., optimal routes and scheduling) increases the savings related to these assets, their management, and social costs associated with negative external factors, and represents a pillar for the value proposition that the project offers to end users. It consists of an efficient and optimized waste-collection service that delivers economic and social benefits, including lower taxes, less environmental impact, and improved health for citizens, thus improving their quality of life and livability in cities. The value proposition also includes the mobile applications. There are two mobile applications: one for drivers and one for end users. The goal of the end-user mobile application is to involve citizens in the waste-collection process by allowing them to communicate issues to Cidiu S.p.A. management. Environmental protection and the involvement and empowerment of citizens to address waste collection are relevant topics for public stakeholders (Saladi and Santos-Lacueva 2016). Thus, the ONDE-UWC project gives local administrators solutions that enhance information exchange, encourage good behavior by end users, and allow administrators to efficiently design the waste-removal process. Other important issues relate to accessing a large

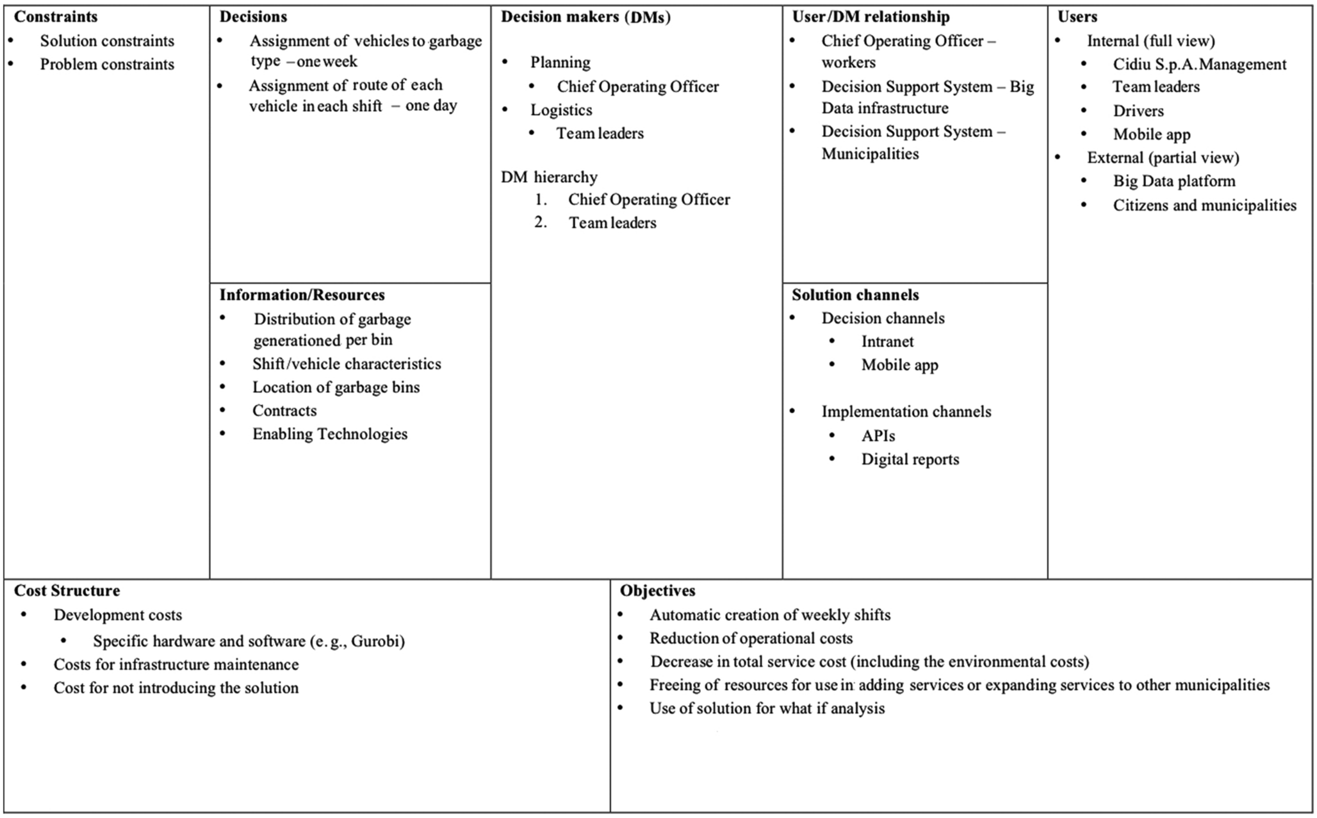


Figure 3. The Figure Depicts the Solution Canvas

amount of data, innovative services, and the availability of the end-user mobile application, thus increasing technical and scientific knowledge.

Solution Analysis

Utilizing the knowledge base created about the waste-collection problem in the urban area near the city of Turin, where Cidiu S.p.A. and the other actors operate, we adopted the solution canvas from the GUEST OR methodology. Our goal was to represent the ONDE-UWC project from an "as is" perspective (i.e., by describing the company's standard way of operating). In this section, we present the solution we implemented, including its value chain, decision process, and operational model. Each component of the canvas is described in Figure 3. First, we analyze the blocks in the middle and on the right; these blocks relate to the decision makers, users, and their relationships, which must be enhanced, and to the objectives, which must be created and clarified. On the left side of the canvas, we analyze the constraints, decisions, information and resources, and costs of implementing the solution.

The primary decision makers (DMs), listed in their hierarchical order, are the chief operating officer (COO) and the team leaders. The COO is involved in the planning process, ensures that the weekly plan, which the algorithm generates, is reasonable, and sends the plan to the team leaders. The team leaders make the logistics decisions, verify carefully that the resulting plan is reasonable, and give the plan to the drivers who will operate the equipment to void the dumpsters based on the routes and schedules they receive as part of the plan.

The users directly interested in the solution, as beneficiaries of its results and supported by the DMs, can be categorized as either internal or external. The internal users, who have a full view of both the process and project, are

- Cidiu S.p.A. management; and
- Cidiu S.p.A. technical management, which consists of the COO and the team leaders.

The external users, who have a partial view of the process and project, are

- the big data platform; and
- citizens and municipalities.

These users establish relationships with the DMs. In particular, the COO interacts through the platform with the team leaders and drivers to improve and disseminate the weekly plan that the algorithm generates. Other important interplay occurs between the decision support system, the big data infrastructure, and municipalities, with the goal of providing data with high value.

The solution developed is communicated to the end users through two main channels:

- Decision channels, represented by the Intranet and end-user mobile application. The Intranet is used to support the information flow that interconnects Cidiu S.p.A. and its employees, while the mobile application is used for the information flow between the end users (who use handheld personal devices) and Cidiu S.p.A.
- Implementation channels, composed of application program interfaces (APIs) and digital reports, which the algorithm generates and the COO receives; these reports provide information related to the development and improvement of the solution.

As we previously discuss, the objectives can be classified into two main frameworks. The first relates to the operational aspects of the current activities, such as the efficient generation of weekly shifts and the resulting reduction in operational costs, and minimizes the total service costs, including environmental costs. The second relates to future potential, such as freeing resources to allow Cidiu S.p.A. to expand its services to other municipalities and using the solution for what-if analysis. In this case study, the main decisions are the weekly assignment of a vehicle to a garbage type and the daily definition of each vehicle's route for each shift.

The primary information necessary to implement the solution relates to the garbage generation and distribution per dumpster (which is characterized by a high level of uncertainty because garbage generation by end users is uncertain), features of shifts and vehicles, and locations of dumpsters.

To implement the solution, specific resources, which we identify as enabling technologies and list next, are required.

- *Geographic information system* (*GIS*): Contains the data identifying the locations of dumpsters.
- *IoT*: Provides the principles on which the solution developed in the ONDE-UWC project is based, similar to Mes et al. (2014). However, unlike the contribution of Mes et al. (2014), which uses sensors on underground containers, we also use sensor-equipped vehicles to guarantee the communication between dumpsters and vehicles and to gather data about the waste quantity within each dumpster. This is a breakthrough, because the use of these data allows us to create a statistical model of the waste production and build a more accurate collection schedule, providing insights about the fill levels of dumpsters at any given time; in contrast, Mes et al. (2014) use historical data. These sensors also allow us to know if a dumpster's waste has not been collected.
- *Global positioning system* (*GPS*): Tracks the position of the vehicles, allowing Cidiu S.p.A. to monitor its fleet in real time; GPS devices are installed in mobile devices or onboard units in vehicles.
- *Mobile applications*: One collects data from end users, and the other collects data from the vehicle drivers about issues that require attention.

The solution is subject to several constraints that must be addressed to guarantee efficient performance, as dictated by the project's goals. Constraints can be grouped into either solution constraints or problem constraints.

- Solution constraints relate to the activities and requirements that affect the implementation of the solution. The primary constraint concerns the need to quickly obtain a solution, thus allowing the Cidiu S.p.A. technical staff to define the plan in a reasonable time. This constraint and the long computational time required to solve the problem by using standard solvers led us to implement a two-step heuristic solution. In the first step, we group the dumpsters into aggregates (i.e., clusters) and solve the problem by considering each cluster as a dumpster. In the second step, we build a solution based on the network of dumpsters, given the optimal solution obtained during the first step. We describe the heuristic and the model in detail in Appendix A.
- Problem constraints are the technological constraints that influence the achievement of the objectives. Here, we list the principal constraints.

—A dumpster must always be less than 80 percent full;

—A working day includes three shifts of six hours each;

—Each vehicle can collect only a specific type of garbage; and

—For each turn, each dumpster is visited at most by one vehicle.

The cost structure includes the costs incurred to implement and maintain our solution. These costs consist of prototype development and integration into the production system, which are inherent in a pilot that we implemented in Piedmont, and the subsequent full introduction. Other costs relate to the use and maintenance of hardware infrastructures and software licenses (e.g., for the optimization solver—the Gurobi optimizer). A cost that must also be considered is the negative impact of not introducing a solution.

Solution Implementation

The architecture of the solution (Figure 4) is based on a vehicle-to-infrastructure system. The building blocks are as follows:

• *Central unit*. This is the core operative block of the project's IT architecture and provides two primary functions—information management and optimization.

• *CSI* (*Consorzio per il Sistema Informativo*) *database*. This database contains all data related to waste collection in the area considered.

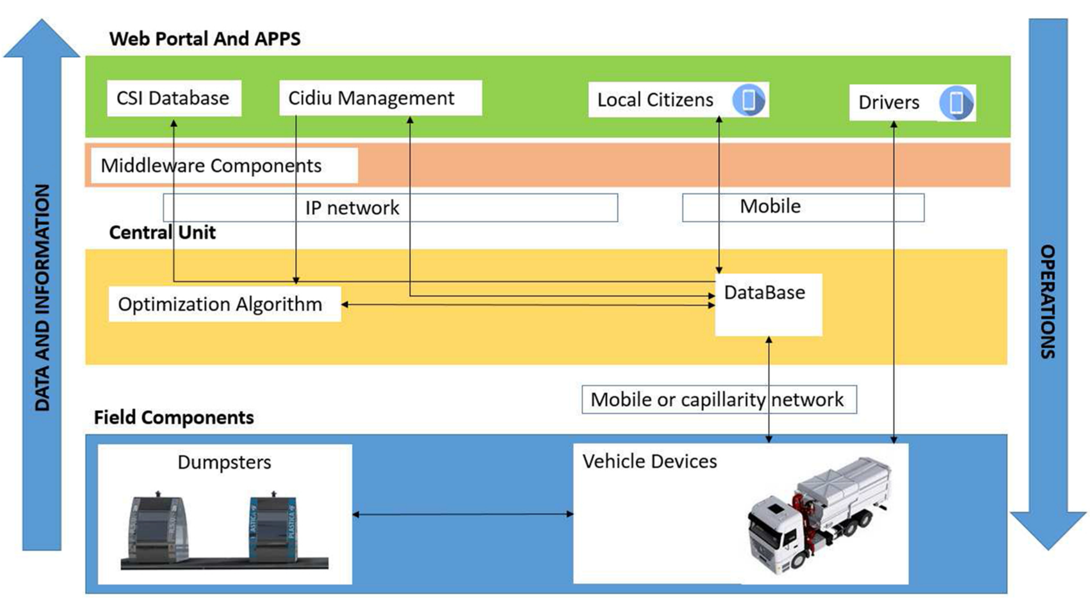
• *Enabling technologies*. As we previously describe, enabling technologies are the internal and external technologies that enhance the decision-making process and allow the exchange of information between the various components and actors. The mobile applications (one for drivers and one for citizens) play an important role, because they allow the drivers and the end users to communicate and interact with the central unit, thus providing information about the waste-collection system. The CSI database and Cidiu S.p.A. management also provide useful input pertaining to waste-collection organization.

• Middleware components allow data exchange between the enabling technologies and the communication network.

• The IP network and mobile network are channels used by the application.

The central unit manages the flow of data (i.e., the information about optimization to and from Cidiu S.p.A. technical management and the CSI database). This includes information regarding the quantity of waste collected from the vehicles each time they return to their depot (i.e., headquarters), and information from customers and drivers. This information, which relates to problems with the waste-collection service,

Figure 4. (Color online) The Architecture of the Solution



is communicated via the mobile applications. When the central unit receives this information, the optimization algorithm is executed, and the solutions generated are sent to Cidiu S.p.A. technical management. The central unit is also responsible for updating the CSI database with waste-collection data and sending the information regarding company activity (i.e., number of time shifts used, times, and routes) to mobile application (mobile in Figure 4) end users. This information is important to the end users because it familiarizes them with the levels of service that the company offers and enables them to have some control of the waste-collection activities.

The timing of each operation differs; the database update takes place each time a vehicle arrives at its headquarters location; the mobile application updates the information about the service once a week; and the optimization algorithm is run three times each day with the same frequency as the solution being sent to technical management.

Computational Tests

Results

The results obtained from the solution we propose in this paper can be classified as either methodological or computational. Methodological results relate to benefits generated by applying the GUEST OR methodology to the ONDE-UWC project. From a managerial point of view, the computational results are more oriented to evaluating the solution than from an operational perspective. Relative to the methodological results, the adoption of the GUEST OR methodology reduced the model's development time to less than one month from the beginning of the project to the definition and validation of the OR model. In comparison, the estimated time without using the GUEST OR methodology was approximately four months. As the first step in implementing this methodology, we held one kickoff meeting with Cidiu S.p.A. management and followed it with two additional meetings. Our objectives were to establish contacts within the company and build a knowledge base about the technical aspects we would need to understand to develop our final solution, as we defined it in the solution canvas. In particular, this approach allowed us to determine during the first meeting that our most important objectives in developing a solution were to reduce the number of third shifts and to determine how to efficiently use the vehicles. This enabled us to consider the needs of all stakeholders, from the initial phases driving the project to their satisfactory completion. Hence, the use of this methodology enabled us to avoid expensive modifications to the model in the final phase of the project and delays resulting from having to do multiple reviews. All these factors enabled us to rapidly achieve the project's goals with resulting savings in time and resources. Therefore, we believe that the GUEST OR methodology is an efficient project management tool for developing both OR models and the underlying IT infrastructure.

To evaluate the solution relative to the computation results, we considered six key performance indicators (KPIs):

- Average number of third shifts during a week of activity (nTS);
- Average number of vehicles used daily (nV); we calculate this value by dividing the number of vehicles used during one month of activity by the number of shifts. Note that Cidiu S.p.A. has four vehicles;
- Average percentage of waste volume at the moment of collection (WV%). When a vehicle empties a dumpster, a probe on the vehicle records the volume occupied by the waste. If we divide this value by the volume of the dumpster, we can compute the average over all the collections and all dumpsters to derive this indicator;
- Total routing time (TRT);
- Average fulfillment percentage of the vehicles (FV%) for each time shift during which a vehicle is used;
- Average number of dumpsters visited during each time shift in which when a vehicle is used (nVD).

We calculated the KPIs by considering a real month of activity for Cidiu S.p.A. and a simulated month of activity for our algorithm. We implemented the methodology in the field as a partial experiment for small periods of time with similar results. Currently, Cidiu S.p.A. is working to integrate the algorithm into its information system and to intensively test it in the field. Table 1 illustrates the values of these KPIs; the standard deviation of each value is shown within brackets. The table shows a comparison of the results obtained after the introduction of our proposed solution and those of the original condition. Column 1 lists the KPIs; column 2 shows their value registered by

Table 1. For Each KPI, We Compare the Solution Before and After Using Our Proposed Algorithm

KPIs	Cidiu S.p.A. solution	Simulated solution
nTS	1.44 (0.5)	0 (0)
nV	3 (0)	2 (0)
WV%	0.28 (0.10)	0.70 (0.05)
TRT	4.35 (0.5)	5.24 (0.3)
FV% (%)	54 (10)	87 (5)
nVD	62.3 (12)	68.5 (12)

the Cidiu S.p.A. waste-collection activities; column 3 shows the values obtained using our approach.

The results highlighted in Table 1 show an improvement in all the KPIs. The primary results show that (1) Cidiu S.p.A. no longer needed a third shift, and (2) the number of vehicles used decreased by 33 percent in the time window we considered. As a result, the waste-collection operational costs decreased and the company's competitiveness increased. We note that the increase in the total routing time occurs because our proposed solution uses fewer vehicles and thus requires longer routes to ensure that all dumpsters are visited. Therefore, the increment in the total routing time denotes a better usage of the vehicle resources.

This project is relevant to the company's operational strategy, because the solution generated enables it to more accurately estimate dumpster volumes. Prior to implementing our solution, Cidiu S.p.A. used periodic routes, which resulted in an overestimation of waste production. Although planning based on aperiodic time shifts is more difficult to manage than planning based on periodic time shifts, the inefficiency of its waste-production estimates caused Cidiu S.p.A. management to consider changing its operations strategy by adopting the proposed solution, which it justified based on the algorithm's good performance. It is worth noting that by changing the parameter that converts the time of the routing into cost for the company (λ in Appendix B), the solution policy changes slightly.

Nevertheless, the model seems to be sensitive to the change in the parameters that define the volume of waste that arrives at the dumpster (Θ_{jt} in Appendix B). If these coefficients increase, the total cost also increases; furthermore, the model becomes infeasible for sufficiently high values of Θ_{jt}. The duration of the time shift and the size of the dumpsters are also important parameters. Increasing both parameters results in a substantial decrease in the total cost.

The model seems to be insensitive to the increase in volume of the vehicles, because the time-shift limit is stricter than the volume constraint.

To assess the performance of the proposed heuristic, we compared its solutions to the optimal ones found using CPLEX 12.6. In particular, we considered instances with 10, 20, 30, 40, and 50 dumpsters, 6 time periods, and 2 types of waste. We could not perform tests with more than 50 dumpsters because CPLEX runs out of memory at this number of dumpsters. The dumpsters are spatially generated in scattered ellipses (as in real settings); the volume of the dumpsters, the initial condition, and the increment of waste quantity are based on historical data; the travel times and the costs of each time shift are randomly generated.

Table 2 shows the results of this comparison, where we report the differences in the costs of time shifts and of the routing, as obtained using CPLEX and our heuristic. For each setting, the table shows mean values and standard deviations (in brackets) over 20 runs.

We note that the heuristic can find the optimal time shifts for all instances, while the deviation from the optimum (3.32 percent for the largest instances) occurs only because of the routing costs. This is not a critical issue; Cidiu S.p.A. is more interested in minimizing the number of shifts than in minimizing its routing costs.

Although CPLEX cannot deal with real instances because of the long computation time and the memory required, the proposed heuristic can achieve good

Table 2. Comparing Cidiu S.p.A.'s Optimal Solutions and the Solutions Generated Using our Proposed Approach

No. of dumpsters	nTs [%]	rC [%]	Optimal time [s]	Heuristic time [s]
10	0 (0)	0 (0)	43.43 (1.64)	2.76 (0.65)
20	0 (0)	0 (0)	150.43 (10.89)	3.73 (0.56)
30	0 (0)	1.75 (1.38)	443.64 (15.92)	8.56 (0.84)
40	0 (0)	2.69 (1.43)	890.67 (30.53)	13.36 (0.74)
50	0 (0)	3.32 (2.34)	1842.86 (45.65)	26.27 (2.45)

Notes. We computed all values by using six time periods and two types of waste. Column 1 shows the number of dumpsters; column 2 shows the percentage difference in the number of time shifts (nTs); column 3 shows the percentage difference in the routing cost (rC); and columns 4 and 5 report the computational time of CPLEX and our proposed heuristic.

results in a short time for those instances; therefore, it is suitable for use in real settings.

The reduction in the computational time needed to obtain a solution is also important. As we state above, commercial solvers cannot solve our mathematical model because of memory constraints. Nevertheless, the average time that the heuristic requires to compute a solution is 4 hours and 23 minutes with a standard deviation of 20 minutes; we computed these values using 100 simulations. Management will directly use the solver in a real setting, and the use of this heuristic will provide Cidiu S.p.A. management with sufficient time to run the algorithm, find the solution, and verify it before beginning waste-collection operations.

The proposed heuristic can be run several times during each time shift, allowing management to adjust the plan and consider any missed operations (e.g., the vehicle cannot collect the waste because a parked car is blocking the dumpster). From a qualitative point of view, the project generates different results. Our proposed solution improves the work conditions of the staff, particularly the drivers. They are not required to work at night and have a more balanced workload, thus positively impacting their quality of life. Cidiu S.p.A. frees resources that it can invest in offering new services to citizens as a result of optimizing its operational activities.

Appendix A
Value Proposition Canvas

As discussed earlier, to describe the actors involved in the MACS, we adopted the Value Proposition Canvas, as proposed by Osterwalder and Pigneur (2014). It consists of two main blocks: the actor profile and the value map. The actor profile is described in a structured way by individualizing its jobs, such as the work described or life activities, pains, such as the negative outcomes, risks, and obstacles related to the jobs, and gains, such as the desired outcomes or benefits from the activities. The value map defines the value proposition that a company can offer to each actor based on its profile composition. It is articulated in products and services around which the proposition is created, and pain relievers and gain creators that describe how the bundle of products and services can reduce the pains or create advantages, respectively, for actors. The fit between the two parts occurs when the products and services offered generate pain relievers and gain creators that combine with one or more of the most important jobs, pains, and gains for the actor. For more details about the building blocks of the Value Proposition Canvas, see Osterwalder and Pigneur (2014). In Figures A.1–A.4, we represent the value propositions for the actors involved in the MACS—Cidiu S.p.A. management, Cidiu S.p.A. technical management, end users, and stakeholders, respectively.

Figure A.1. Value Proposition of Cidiu S.p.A. Management

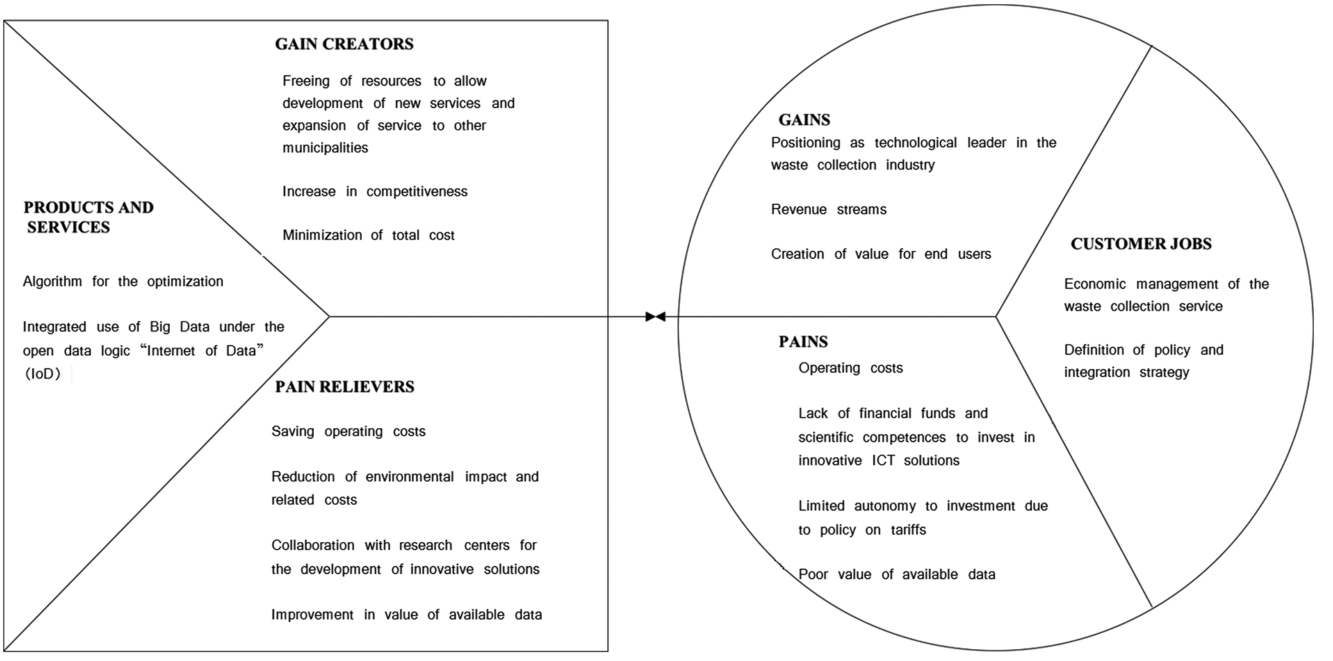


Figure A.2. Value Proposition of Cidiu S.p.A. Technical Management

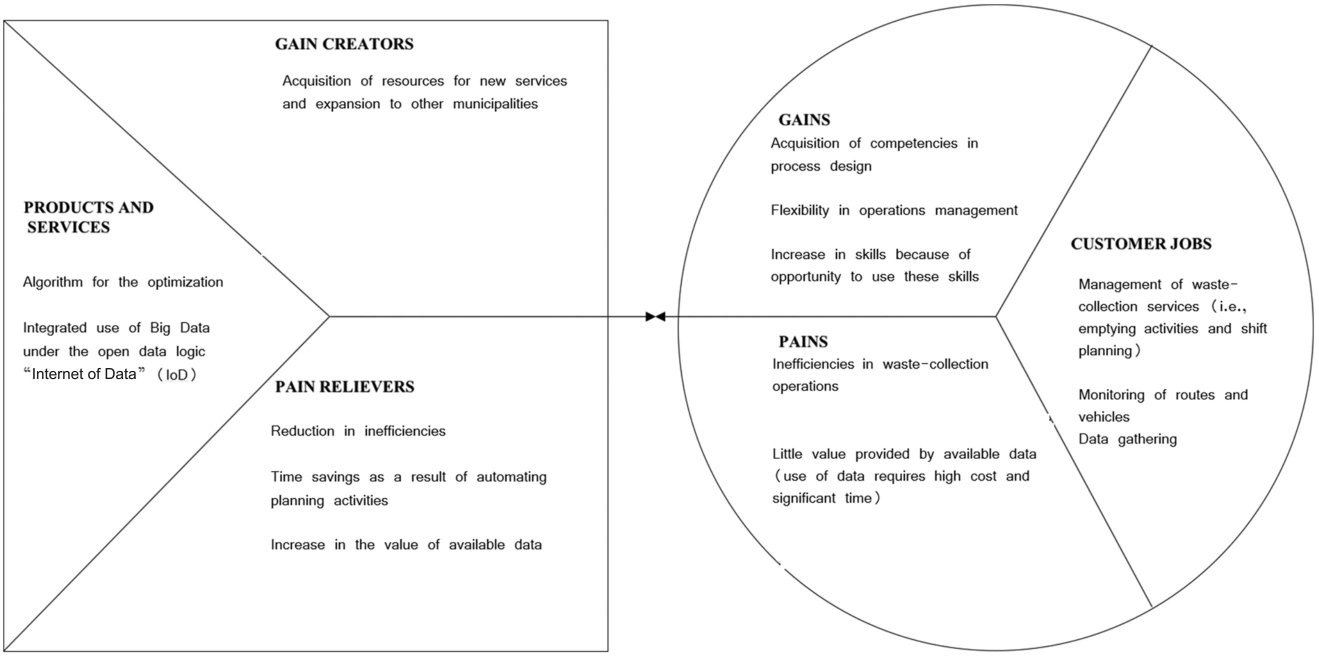


Figure A.3. Value Proposition of End Users

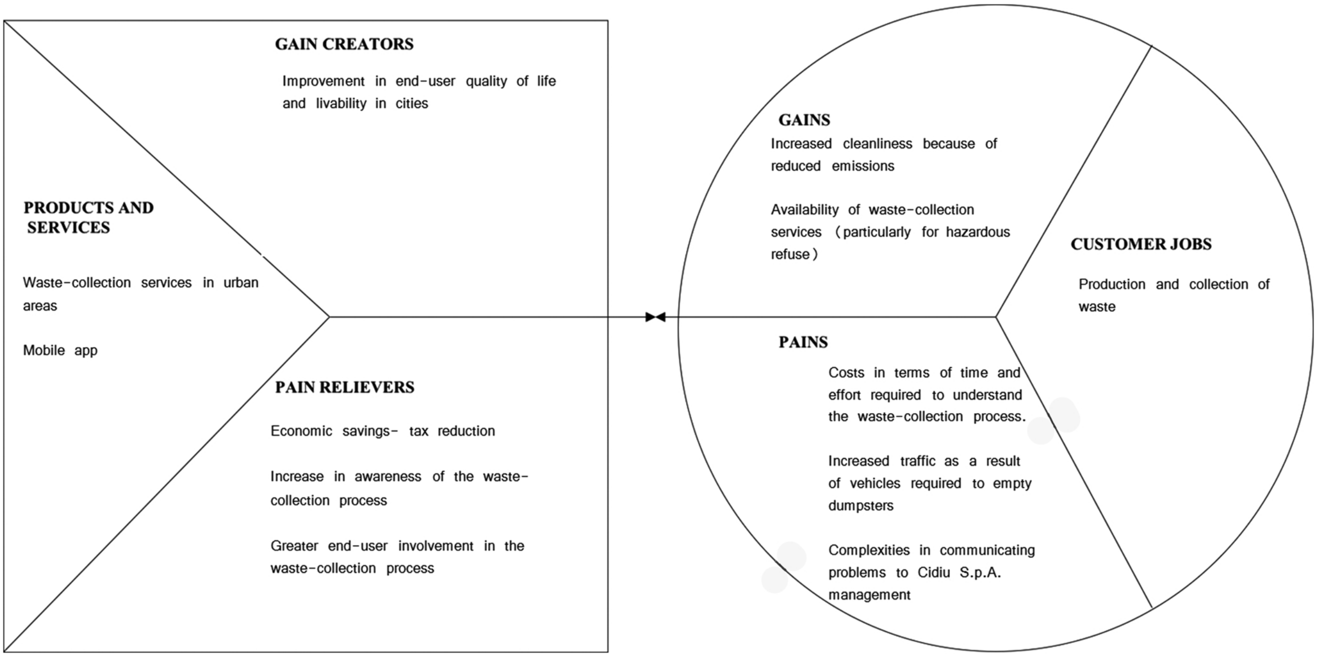
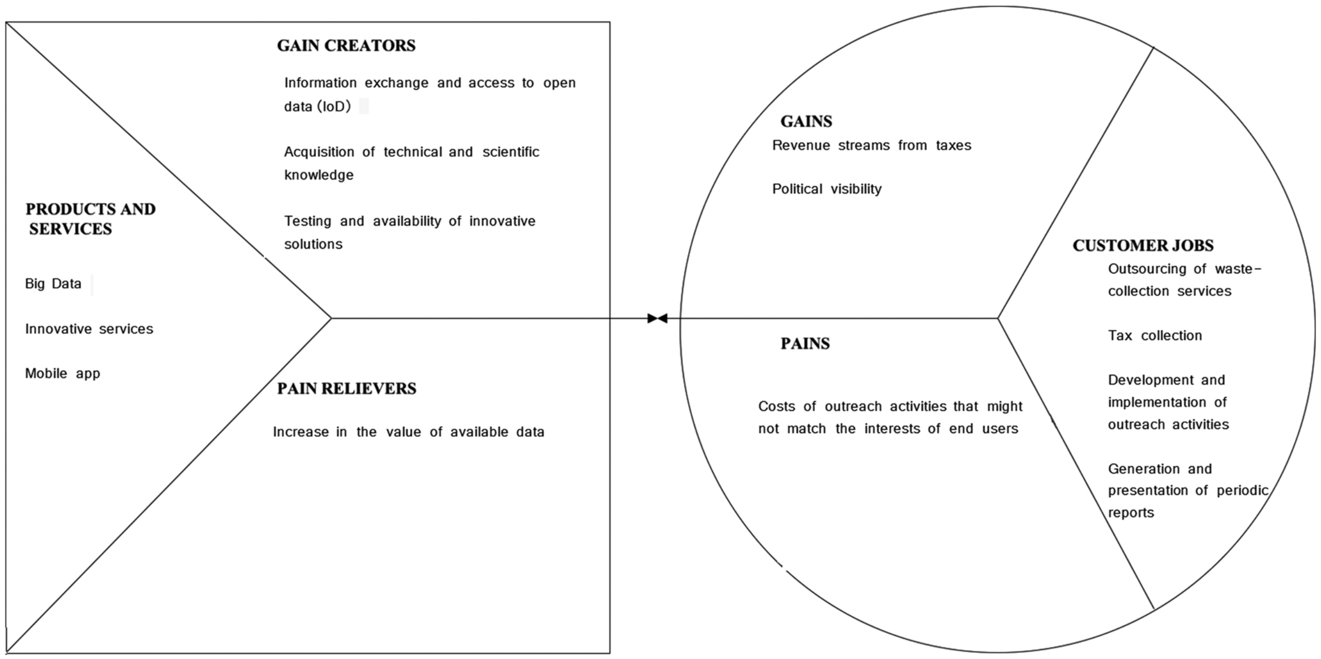


Figure A.4. Value Proposition of Stakeholders



Appendix B
Data

In running our computational tests and simulations, we considered 100 instances; each instance uses actual company data. In particular, the problems consider 525 dumpsters with 2 types of waste (i.e., paper and municipal solid waste—MSW), 8 vehicles, and a week of company activity (i.e., 15 time shifts). The data, such as the position of the dumpsters and the fulfilment rate, are actual field data for one instance; we generated the remainder using variations of this instance. We categorized the data related to the optimization problem as either geographical or technical data. Geographical data are the distances between all the dumpsters (computed using Google). By considering each dumpster as a node of a graph, we consider a complete graph (i.e., each node is connected to each other node by means of an arc). Next, we list the technical data.

1. Fixed cost of using a vehicle during a time shift c_{it}: this cost is the same for the first two time shifts of the day, however, it is doubled for the third shift;
2. Volume of each dumpster V_j: for each type of waste, there are three types of dumpsters, with volumes of 2,400 liters, 3,500 liters, and 5,000 liters, respectively;
3. Capacity of the vehicles $\hat{C}$: 20,000 liters;
4. Extra capacity l_s: 60,000 liters for paper and 0 liters for MSW;
5. Length of a time shift $C_{\max}$: six hours;
6. Time required to void a dumpster a: five minutes;
7. Time required to reach a dump T_s: these values change based on the type of waste because each dump is associated with a specific type of waste. Because the location of each dump is distant from the dumpsters, we consider it to be a fixed constraint, equal for each dumpster from which the vehicles depart.

We extracted these technical data (shown in 1–7) from the knowledge base of the Cidiu S.p.A. management.

8. Increments Θ_{jt}: we obtained these values from Cidiu S.p.A. historical data; for each dumpster, we have a set of observations (not equally spaced) of the waste quantity observed each time a vehicle empties a dumpster. Because of the lack of information about the waste-creation probability, we assume that the quantity of waste observed in each dumpster is produced uniformly over time. If we call $\hat{\theta}_{jn}$ the observed quantity of waste collected during the collection n and we call t_n the time (expressed as time shift) of the nth collection, we use the following equation as an increment:

$$\Theta_{jt} = \frac{1}{N} \sum_{n=1}^{N} \frac{\hat{\theta}_{jn}}{t_n - t_{n-1}}, \quad \forall j, t.$$

9. Coefficient α: this value limits the quantity of waste in the dumpsters: its value is set to 0.8 based on Cidiu S.p.A. historical data.

Appendix C
The Mathematical Model

We describe the mathematical model that denotes the Cidiu S.p.A. problem by using the set $\mathcal{I}$ for the available vehicles, the set $\mathcal{S}$ for garbage types, the set $\mathcal{T}$ for the time shifts, and the set $\mathcal{J}$ for the dumpsters. For ease of notation, we consider that the set $\mathcal{J}$ also includes the depot ($j=1$) and the dumps ($j=J-s,\dots,J$). The cardinalities of these sets are I, S, J, and T, respectively. In the set $\mathcal{J}=\{1,2,\dots,J\}$, we consider that $j=1$ denotes the depot, while the last indexes denote the dumps.

We use the following notation for the parameters:

- c_{it} is the cost of using vehicle $i \in \mathcal{I}$ in shift $t \in \mathcal{T}$. This cost is the same for the first two shifts and larger for the third shift.
- $C_{\max}$ is the maximum duration of the shift. We consider that it lasts six hours.
- $d_{j_1 j_2}$ is the time that the vehicle requires to go from dumpster $j_1 \in \mathcal{J}$ to dumpster $j_2 \in \mathcal{J}$.
- $\hat{C}$ is the maximum volume that a vehicle can transport.
- l_s is the difference between a standard quantity that a vehicle can transport and the real quantity if it is used to collect waste type $s \in \mathcal{S}$. This difference results from the use of a press (i.e., an engine that can compress some types of waste).
- Θ_{jt} is the volume of waste that arrives at dumpster $j \in \mathcal{J}$ at time $t \in \mathcal{T}-0$; Θ_{jt} is the quantity of waste in dumpster $j \in \mathcal{J}$ at the beginning of the first time shift.
- a is the time that the drivers take to collect the waste from a dumpster. Because of the sensor technology installed on the vehicles that Cidiu S.p.A. uses to collect waste, the collection time is the same for all dumpsters.
- α is the percentage of the dumpster capacity that cannot be exceeded.
- λ is a parameter that weighs the importance of the routing with respect to the operational costs.
- V_j is the capacity of dumpster j.

The binary variables used in the model are w_{it}, which is one if vehicle $i \in \mathcal{I}$ is used during shift $t \in \mathcal{T}$, z_{ist}, which is positive if vehicle $i \in \mathcal{I}$ collects the garbage of type $s \in \mathcal{S}$ during shift $t \in \mathcal{T}$, y_{ijt}, which is positive if vehicle $i \in \mathcal{I}$ collects the garbage of dumpster $j \in \mathcal{J}$ during shift $t \in \mathcal{T}$, and $r^{it}_{j_1 j_2}$, which is positive if vehicle $i \in \mathcal{I}$ during time shift $t \in \mathcal{T}$ goes from dumpster $j_1 \in \mathcal{J}$ to dumpster $j_2 \in \mathcal{J}$. The continuous variables used in the model are x_{ijt}, which describe the volume of garbage collected by vehicle $i \in \mathcal{I}$ from dumpster $j \in \mathcal{J}$ during shift $t \in \mathcal{T}$, and V_{jt}, which describe the volume of waste present in dumpster $j \in \mathcal{J}$ at the end of time shift $t \in \mathcal{T}$. Our problem then is

$$\text{minimize } \sum_{i=1}^{I}\sum_{t=1}^{T} c_{it} w_{it} + \lambda \sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{j_1=1}^{J}\sum_{j_2=1}^{J} d_{j_1 j_2} r^{it}_{j_1 j_2}, \tag{C.1}$$

$$\text{subject to } w_{it} \ge y_{ijt}, \quad \forall i, j, t; \tag{C.2}$$

$$M y_{ijt} \ge x_{ijt}, \quad \forall i, j, t; \tag{C.3}$$

$$\sum_{i=1}^{I} y_{ijt} \le 1, \quad \forall j, t; \tag{C.4}$$

$$x_{ijt} \ge V_{jt} - M(1 - y_{ijt}), \quad \forall i, j, t; \tag{C.5}$$

$$\sum_{j=1}^{J} x_{ijt} \le \hat{C} + \sum_{s=1}^{S} l_s z_{ist}, \quad \forall i, t; \tag{C.6}$$

$$M z_{ist} \ge x_{ijt}, \quad \forall i, s, j \in \mathcal{J}^s, t; \tag{C.7}$$

$$\sum_{s=1}^{S} z_{ist} \le 1, \quad \forall i, t; \tag{C.8}$$

$$V_{j0} = \Theta_{j0}, \quad \forall j; \tag{C.9}$$

$$z_{ist} \le y_{i(J-s)t}, \quad \forall i, t; \tag{C.10}$$

$$V_{jt} = V_{jt-1} + \Theta_{jt} - \sum_{i=1}^{I} x_{ijt}, \quad \forall j, t \ne 0; \tag{C.11}$$

$$V_{jt} \le \alpha V_j, \quad \forall j, t; \tag{C.12}$$

$$w_{it} \ge w_{i+1,t}, \quad \forall t, i = 1{:}I-1; \tag{C.13}$$

$$\sum_{j_1=1}^{J} r^{it}_{j j_1} = y_{ijt}, \quad \forall t, i, j; \tag{C.14}$$

$$\sum_{j_1=1}^{J} r^{it}_{j j_1} = \sum_{j_1=1}^{J} r^{it}_{j_1 j}, \quad \forall t, i, j; \tag{C.15}$$

$$\sum_{j=1}^{J} r^{it}_{1j} = w_{it}, \quad \forall t, i; \tag{C.16}$$

$$\sum_{j=1}^{J} r^{it}_{j1} = w_{it}, \quad \forall t, i; \tag{C.17}$$

$$\sum_{j_1=1}^{J}\sum_{j_2=1}^{J} d_{j_1 j_2} r^{it}_{j_1 j_2} + a \sum_{j=1}^{J} y_{ijt} \le C_{\max}, \quad \forall i, t; \tag{C.18}$$

$$\sum_{j_1, j_2 \in S, j_1 \ne j_2} r^{it}_{j_1 j_2} \le |S| - 1, \quad \forall S \subset \mathcal{J}, S \ne \varnothing; \tag{C.19}$$

$$x_{ijt} \in \mathbb{R}^+, \quad \forall i, j, t;$$

$$z_{ist} \in \{0,1\}, \quad \forall i, s, t;$$

$$y_{ijt} \in \{0,1\}, \quad \forall i, p, t;$$

$$r^{it}_{j_1 j_2} \in \{0,1\}, \quad \forall i, j_1, j_2, t;$$

$$V_{jt} \in \mathbb{R}^+, \quad \forall j, t.$$

The objective function minimizes the weighted sum of two components. The first component is the sum of the fixed costs derived from activating a vehicle during a time shift; the second is the routing cost. Constraints (C.2) and (C.3) ensure that each time a vehicle is used during a time shift, that time shift is activated. Constraint (C.4) imposes that, in each time shift, only one vehicle can void a dumpster. Constraint (C.5) imposes that each vehicle must collect all the waste in the dumpsters it visits. Constraint (C.6) ensures that the capacity of the vehicles is not exceeded; it considers that, for some types of waste, the vehicle can use a press to diminish the volume, which is equivalent to gaining extra capacity. Constraints (C.7) and (C.8) impose that each vehicle can collect waste only from dumpsters assigned to the storage of the same type of waste. Constraints (C.10) impose that if a vehicle is used, it must go to the assigned dump. Constraints (C.9), (C.11), and (C.12) impose how the quantity of waste evolve in each dumpster and bounds this quantity. It is worth noting that because constraints (C.9) and (C.11) use equalities, the value of V_{jt} can be modified only by using the variables x_{ijt}.

Furthermore, if such a modification is not made, then constraint (C.12) is violated. Constraint (C.13) imposes an order in the vehicle choice. Constraints (C.14)–(C.19) define the routing problem and set a maximum time for this activity.

The Solution Algorithm

We can define a mixed-integer linear model of the problem. Unfortunately, it becomes large, even for small-size instances. It has a number of variables of the order of 2^{IJ^2T}, where I is the number of vehicles, J is the number of dumpsters, and T is the number of time steps. To overcome this problem, and based on numerous experiments we did, we decided to use a three-phased heuristic, which we present next. The detailed description of the model is presented in Appendix A, because of the complexity of the model and to simplify its exposition.

1. *Clusterization*. The objective of phase 1 is to solve the problem by aggregating the dumpsters in clusters, instead of considering each as a single dumpster. In particular, we aggregate dumpsters located in the same city. We tried different policies that, for brevity, we cannot present in this paper; nevertheless, the policy we discuss in this paper is the best we found. We obtained a reasonable solution, because we reduced the problem's dimension by using clusters; by doing so, we could compute the exact solution to this new problem. We then solved the mathematical model, constraints (C.1)–(C.19), by considering clusters instead of dumpsters; that is, we substituted the set of single dumpsters $\mathcal{J}$ with $\mathscr{C}$, the set of clusters (with cardinality C). This change led us to remove constraints (C.4) and (C.5), because multiple vehicles can collect waste from the same cluster. Furthermore, some parameters assume a different interpretation and value: we interpret $d_{c_1c_2}$ to be the distance between cluster c_1 and cluster c_2. Its value equals the length of the shortest edge that connects a dumpster in c_1 and c_2, that is, $d_{c_1c_2} = \min_{j_1\in c_1, j_2\in c_2} d_{j_1j_2}$. In the new interpretation of the model, Θ_{ct} is the maximum growth rate of the dumpsters in the cluster; that is, $\Theta_{ct} = \max_{j\in c}\Theta_{jt}$ and V_c is the maximum capacity of the cluster and equals the sum of the capacities of all the dumpsters $V_c = \sum_{j\in c} V_j$. We interpret $\hat{a}$ as the time spent to empty a cluster. It equals the sum of the emptying times of all the dumpsters, plus the time of a tour between all dumpsters in the cluster.

2. *Building a feasible solution*. Given the solution obtained in the phase 1, phase 2 produces a feasible solution for the original problem, returning the list of dumpsters that each vehicle must visit in each shift. We show the operation performed in the following pseudocode:

(a) for each $w_{it} = 1$, where $i \in \mathcal{I}$, $t \in \mathcal{T}$;

(b) create the list *list*0 and insert all dumpsters for each cluster, such that $y_{ict} = 1$ where $i \in \mathcal{I}$, $c \in \mathscr{C}$, $t \in \mathcal{T}$;

(c) remove from *list*0 all dumpsters that have been voided;

(d) sort *list*0 in decreasing order of quantity of waste;

(e) create *list*1;

(f) add, one by one, all the dumpsters of *list*0 into *list*1 until constraints (C.6) or (C.18) hold with equality;

(g) if all the dumpsters in *list*0 have been added, then:

i. if there is a dumpster in *list*1 that is γ full or more, go to step (h);

ii. otherwise, go to step (a);

(h) set to zero the percentage of volume occupied from the waste in each dumpster in *list*1. Then, go to step (a).

3. *Postoptimization*. In phase 3, we obtain a feasible solution for the original problem. Thus, we refine it by solving a traveling salesman problem (TSP) for each route, using the Chained-Lin-Kernighan heuristic for asymmetric networks, as Applegate et al. (2003) discuss.

Because the *building a feasible solution* and *postoptimization* phases run quickly, we run them several times with different values of γ, and we take the solution with the best objective function. In all the simulations we ran, we used 20 values equally spaced between 50 and 70 percent.

It is worth noting that the results depend strongly on the clusterization policy used. For brevity in this paper, we will consider this dependency in future work.

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Verification Letter

Giovanni Demarco, Executive Officer of Cidiu Servizi S.p.A., writes:

"In this letter, I verify the study reported in the article 'Waste Collection in Urban Areas.' This paper is given by a team of researchers (Edoardo Fadda, Luca Gobbato, Guido Perboli, Mariangela Rosano, and Roberto Tadei) of the Department of Control and Computer Engineering of the Politecnico di Torino. They were involved in the ONDE—UWC (Optimization for Networked Data in Environmental Urban Waste Collection) project in collaboration with us (Cidiu Servizi S.p.A.) and other technological partners: moltosenso S.r.l. and Nord Engineering S.r.l.

"The study was conducted in the period November 2014–June 2015, during which operations managers and planners from several Cidiu Servizi S.p.A. Business Units actively collaborated with the researchers. The collaboration under the project born from the need to guarantee the overall efficiency of urban waste collection in the urban area near the city of Turin. In particular, the needs of the Cidiu Servizi S.p.A. that I represent were to avoid the use of critical third shifts and to reduce the operational costs.

"The reaching of these goals was possible by means of the implementation of an ad-hoc algorithm by the researchers, which is capable to plan the fleet vehicles usage of Cidiu Servizi S.p.A. Moreover, the choice to collaborate with this research team was led by their know-how and experiences both in operations research and in business fields.

"The paper proposed by the authors, accurately describes the project development, the methodology GUEST adopted that was a value-added in reaching the project goals in reasonable times, and finally the results achieved, which reflected our expectations. In conclusion, I can claim that the developed operations research procedure affects our performances in a positive way."

Edoardo Fadda received the Laurea degree in mathematical engineering from the Politecnico di Torino, Torino, Italy in 2014. He is a PhD student with the Dipartimento di Automatica e Informatica, Politecnico di Torino. His main interests are optimization under uncertainty, statistics, and their applications.

Luca Gobbato received the PhD in information and system engineering in 2015 and the Laurea Specialistica (MSc) in electronic engineering in 2010 at Politecnico di Torino. During his studies, he learned specific skills in computer science and software engineering working on complex research projects in collaboration with national and international companies such as Telecom Italia Spa and CNH Industrial. He is cofounder of Move Plus srl, a spin-off of Politecnico di Torino, working on sharing mobility topics. He is exploring innovative solutions for sustainable mobility in urban areas such as taxi-sharing and carpooling services.

Mariangela Rosano is a PhD candidate in the Department of Control and Computer Engineering (DAUIN) of Politecnico di Torino, Turin (Italy). She received a BS degree in business organization engineering and an MS degree in engineering and management from the Politecnico di Torino, Turin (Italy).

Her research interests are in business models and operations management in last mile for smart cities and city logistics applications. She is also involved in the research activities of the ICT Center for City Logistics and Enterprises (ICE).

Guido Perboli is professor of strategic management and operations research in the Politecnico di Torino and is an associate member of the CIRRELT—Centre Interuniversitaire de Recherche sur les Réseaux d'Enterprise, la Logistique et les Transport—Québec, Canada.

In 2016 he founded the ICT for City Logistics and Enterprises (ICE) center of Politecnico di Torino, a research center focused on two of the main activities supporting urban growth: logistics and enterprises. He is director of the ICE Lab. He is a member of scientific boards, including the Scientific Board of SOS Log, the main Italian association of sustainable logistics. He has received the Amazon Innovation Award, the International Award of Amazon on Last Mile, Logistics and Emerging Business Models.

Roberto Tadei is full professor of operations research at the Polytechnic University of Turin, Italy, where he is responsible for curriculum in operations research and optimization. His main research areas are in combinatorial optimization, in particular transport and logistics, network design, and production scheduling. He is a member of international scientific societies and a referee of international journals. He has been president of the Italian Society of Operations Research and of the Italian Federation of Applied Mathematics. He has published widely.