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The Optimization for Networked Data in Environmental Urban Waste Collection (ONDE-UWC) project is, to our knowledge, the first attempt to apply the Internet of Things (IoT) paradigm to the waste collection field. Sensors installed on dumpsters and garbage trucks share data, such as the number of user accesses and weight measures. In this study, we schedule the weekly waste collection activities of all the types of waste without imposing periodic routes. An important characteristic of this project considers the network presence of heterogeneous stakeholders with different background knowledge. In this context, we apply the GUEST OR methodology, highlighting how it can support the decision-making process in order to reduce this gap. This will bring positive consequences in terms of reduced time for solution implementation, followed by operational efficiency and economical savings.

Key words: Vehicle routing and scheduling, Services, Waste collection, Manpower planning, Heuristics.

Introduction

The waste collection problem in urban areas currently has significant relevance. Social phenomena, such as population growth and urbanization, have combined into a consumption growth, causing an increase in waste generation. In the European Union, more than 2.3 billion tons per year of refuse are produced by the citizens. Although municipal waste only represents approximately 10% of total waste (European Environment Agency 2015), it is affected by several critical factors. According to Blumenthal (2011), municipal waste has a political importance because of its composition, distribution among many waste generators, and link to consumption patterns. Furthermore, waste management influences different aspects of urban management; such as, economic, for the efficiency of collection services and processing in terms of costs; political, involving local administration; and finally, social and environmental, owing to emissions, which compromise the health of citizens, and visual pollution, which affects the urban decorum. Because of its importance and frequency of service, the optimization of this activity produces a big gain for the whole community. This paper faces this issue by proposing the solution developed under the Optimization for Networked Data in Environmental Urban Waste Collection (ONDE-UWC) (ONDE - UWC Web Site 2017); a project funded by the Regional Council of Piedmont and applied to waste collection management in an urban area near the city of Turin (Italy). To our knowledge, the contribution of our paper in the literature is innovative in two directions. First, it shows how the solution implemented under the ONDE-UWC project allows greater flexibility on service design by considering all type of waste and by removing the typical constraint of emptying each dumpster with a fixed frequency (Mansini and Speranza 1998, Sahoo et al. 2005). Instead, we dynamically adapt the schedules, combining different historical data sources, on-vehicle weight systems and a sensor network built according to the IoT paradigm. The data gathered are used by a math-heuristic optimization algorithm to provide efficient solutions and by the municipalities in order to improve the awareness of the citizens, about the waste production and management. The second innovative element concerns the adoption of a lean business methodology named “GUEST OR” useful for the project management and for accelerating its development. GUEST OR (Perboli 2016) is a customized operational research problem version of the more extensive GUEST methodology proposed by a pool of researchers of the Politecnico di Torino (Italy) (The GUEST Initiative 2017, Perboli 2017). A waste collection scenario is defined as a multi-actor complex system (MACS) owing to the heterogeneous stakeholders involved and issues affecting it. Moreover, from the literature review concerning the waste management, it reveals a disjunction between the business perspective and technical solutions proposed to handle the operational activities. This creates a difficulty in the communication of results to actors involved in a non-technical team, and generally, between stakeholders with different backgrounds. For these reasons, in the case study presented in this paper, we decided to develop a comprehensive framework using the GUEST methodology. This framework is capable of creating a knowledge base of the needs and wants perceived by the different stakeholders involved in the MACS (see Section "Waste management in urban areas as a MACS"). Thus, according to these requirements, the GUEST methodology provides at the stakeholders standard tools for the decision and solution convergence (see Section "Solution Analysis"), as well as its representation, supporting them in the control of the decision-making process. Finally, the last phase of the methodology entails the testing of the implemented solution and the evaluation of its outcomes. In this direction, Section "Computational Test" presents a part of the tests conducted in our case study, useful to validate the behavior of the model in the real world. Our procedure is under integration into the general Information System of the company. According to some forecasts, the system will be fully operational at the end of 2017.

Problem Statement and State-of-the-Art

As previously discussed, waste collection in urban areas represents a challenging problem for municipalities in regards to both the collection and treatment activities, owing to the different decisions and resources involved. Several papers concerning the waste collection problem are present in the literature. According to the classification proposed by Ghiani et al. (2014), the waste collection problems are addressed in different frameworks based on the time horizon of the decision making process. In fact, waste management involves a number of strategic, tactical, and operational decisions: such as, the selection of the treatment technologies, location of the treatment sites and landfills, collection day selection for each district and waste type, fleet composition determination, and routing and scheduling of collection vehicles. The first framework, generally focused on strategic and tactical problems, was related to the optimization of dumpster locations, decisions related to new facility construction, and vehicle capacity choices. In contrast, the tactical level included optimizing day to day activities and executing the strategic decisions. In particular, several papers, such as Sahoo et al. (2005), Das and Bhattacharyya (2015), are devoted to the computation of the optimal routing of vehicles; while others, such as Hemmelmayr et al. (2013), Mansini and Speranza (1998), are focused on the definition of the optimal emptying frequency for each dumpster, and addressing it to solve the periodic capacitated arc routing problem Chu et al. (2006). In this paper, we consider the less explored tactical problem of scheduling and routing waste collection, without imposing a fixed voiding frequency, and allowing our solver to define a suitable next visit to empty each dumpster. To our knowledge, this approach is less studied because the periodic hypothesis simplifies the model. Moreover, an aperiodic model works only if sensors are capable of providing data and waste production estimates, and methods are available that take into account the uncertainties related to seasonality, waste volumes, and traffic. We have studied the aperiodic approach in the ONDE-UWC project, where the primary goal is the innovative use of big data generated by waste collection activities, in order to create a dataset of information shared by the different stakeholders. Moreover, the Department of Control and Computer Engineering of the Politecnico di Torino was involved in the project in order to develop and implement an algorithm for the optimization of the tactical level. This innovative solution has a goal to improve awareness of municipal waste issues and increase the efficiency of the whole process with the consequential reduction of the total operating and environmental costs. Moreover, the development of this project has a threefold aim:

- reduce the total time required to implement the overall project, thereby reaching goals in less time;
- enhance the synergy with operational actors. This is to ensure the fulfillment of requirements of the different stakeholders, such as public administrations, interested in obtaining statistics to improve the communication flow with citizens. The consequential benefit is the increased value of these data;
- improve the awareness of citizens regarding the waste management problem through the integration of a mobile application solution. This can be utilized by different people to interact in a more efficient way with firm management involved in system and local administration, such as communicating information or issues (e.g., problems with dumpsters).

Even if the aperiodic approach is less explored in the literature, our study is not the sole that does not consider period routes. In fact, Mes et al. (2014) propose a heuristic for the inventory routing problem applied to waste collection, considering data from sensor equipped containers. Although both Mes et al. (2014)'s and our study face the same problem to optimize the waste collection operations by integrating the use of sensors, they present some major differences. First, Mes et al. (2014) propose a mathematical model involving decisions regarding the vehicle routing mainly connected to the fleet management. On the contrary, our approach, even if slightly simplified from the routing point of view, is more realistic by considering in the model and in the solution business and contractual constraints. The aim is to evaluate the costs that a waste management firm incurs, which is mainly labor-based staff costs. Moreover, Mes et al. (2014) cite the adoption of sensor equipped containers in order to forecast the percentage of fullness of a dumpster, but then in the model they compute it in a deterministic manner, using historical data. Also our work recurs at the IoT paradigm for gathering data concerning the fullness of dumpsters, but we incorporate in our solution the forecasts coming from the sensors. Finally, to our vision, according to the contracts commonly used, which imply a profit based on the conferred amount of waste and on the costs of work shifts, approaches as those of Mes et al. (2014) could be inappropriate. In this paper, we propose a model which considers the costs structure of the leading waste management firm involved in the project, the Centro Intercomunale di Igiene Urbana S.p.A. (Cidiu S.p.A.), and real data concerning the waste volumes provided by sensors. The firm operates in the environmental services industry managing several aspects related to the waste cycle. Cidiu S.p.A provides the collection of municipal waste service in the area shown in Figure 1, composed by the towns of Alpignano, Buttigliera Alta, Collegno, Druento, Grugliasco, Pianezza, Rivoli, Rosta, San Gillio, and Venaria Reale. It is responsible for the collection of five types of waste: paper, solid urban refuse, plastic, metallic materials, and glass.

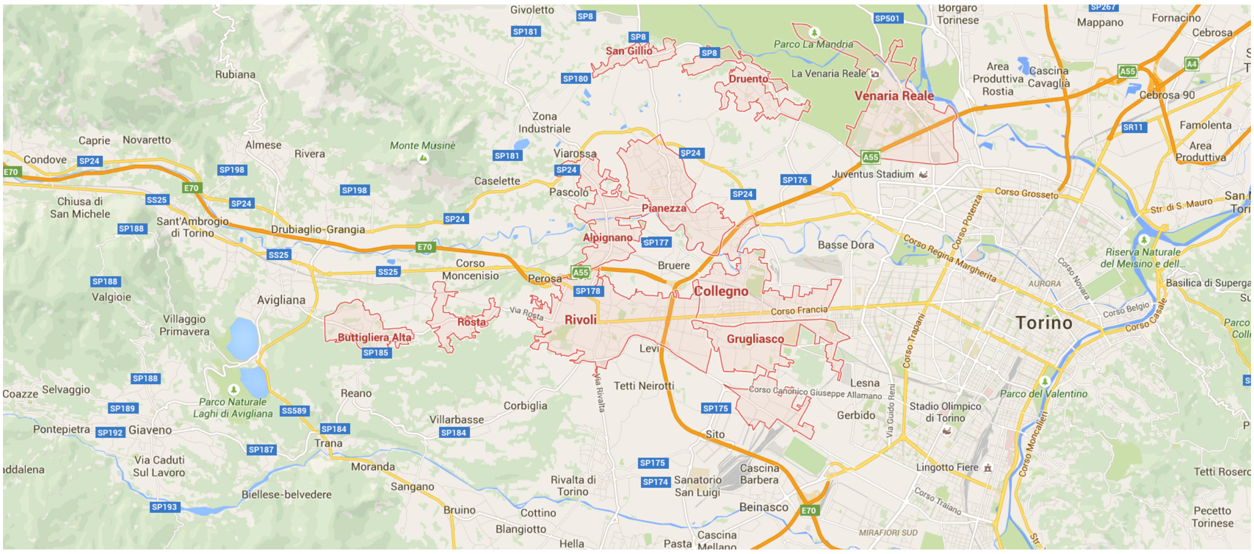

Figure 1 Municipalities served by Cidiu S.p.A.

The company is organized into two totally independent headquarters, one in Rivoli and Collegno. Each one manages the waste collection operations in its area without interacting with the other. The fleet of vehicles used to collect the waste is composed by trucks capable of giving a measurement of the refuse weight collected in each dumpster that they void. This information is useful in order to build a forecasting model for waste production. Each vehicle starts its activity from a headquarters of the company, collects waste from the dumpsters, goes to the dump, and returns to the starting headquarters. These operations are subject to several constraints imposed by contracts that Cidiu S.p.A. has with the following actors:

- Dump management that sets a certain margin on the percentage of yearly acceptable total refuse. Note that the dumps are specific and related to a certain kind of waste.
- Local administration that imposes the service level required and the emptying frequency at which dumpsters must be voided in order to guarantee the livability of cities.

Waste management in urban areas as a MACS

As above discussed, the GUEST Methodology is based on standardized tools capable to build a basic understanding of the MACS, with the aim of implementing the project in a proper way and thus developing solutions shaped on the stakeholders requirements. In this direction, we present the waste management MACS, defining 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), with the goal of supporting the definition of the value proposition fitting the needs and desiderata of each actor. Although, the value proposition design represents a first needed phase for the creation of the knowledge base valuable for the definition of the solution. We do not present in detail each canvas, because it overcomes the scope of this work. However, in this section we briefly discuss the MACS and the value propositions for each actor, while the canvas are in Appendix A. Figure 2 depicts the MACS and shows the actors involved, which are described in brief with their interactions as follows:

- Cidiu S.p.A. Management. As afore mentioned, it is responsible of the economic management of the waste collection service in ten municipalities. Moreover, Cidiu S.p.A. Management gathers the data useful for statistical purposes and accounting management, additionally providing this information to third parties, such as local administrations.
- Cidiu S.p.A. Technical Management. It is composed of the Chief Operating Officer (COO), team leaders, and drivers. The primary job performed by the technical staff is the

management of weekly operations involved in the service provided, such as the planning of shifts, routes, and emptying activities. The resulting plan is formulated by the team leader, supervised by the COO, and then communicated to the drivers. Another job performed by the actor is the monitoring of routes and vehicles by means of a platform that certifies the success of the emptying operations for each dumpster, and gathers the data useful to dimension the service.

- Final users. Citizens represent another actor segment of the ONDE-UWC project, as waste producers and users of collection services in urban areas, and as players involved in the city dynamics. In fact, they are interested to the livability of cities, as well as the usability of waste disposal services, particularly for dangerous refuse. On the other hand, final users incur in costs related to the taxes that local administrations impose for sustaining and providing the waste services, and costs in terms of effort and time for learning and executing waste collection.
- Stakeholders. They are mainly the local and regional administrations. They obtain value from the open data retrieved by the firms operating the waste collection industry, and are available to promote information to citizens and conduct outreach activities with a high success rate. Moreover, they design the services encouraging the re-manufacturing and recycling waste into usable products. Local administrations, in fact, manage the urban waste collection, outsource the connected operations to third-party firms, manage the tax collection responsibility, organize outreach activities as previously mentioned, and present periodic reports.

The ONDE-UWC project offers each actor a specific value proposition, which copes with the pains perceived by them, while enhancing their gains. In particular, the gain creator for the Cidiu S.p.A. Management (see Appendix A) is a tool for the optimization of the waste collection services and the automation of the operations. The automatic execution of these jobs will allow Cidiu S.p.A. to obtain several gains in terms of positioning in the waste collection market as a technological leader. On the other hand, the project offers solutions consisting in an integrated use of big data in regards to the waste collection process and final users behavior. In particular, these solutions act as pain relievers, decreasing the operating costs of the services and their environmental impact, as we will illustrate in the results section. This value proposition is strictly related to those offered to the Cidiu S.p.A. Technical Management. It consists of an optimization algorithm that solves

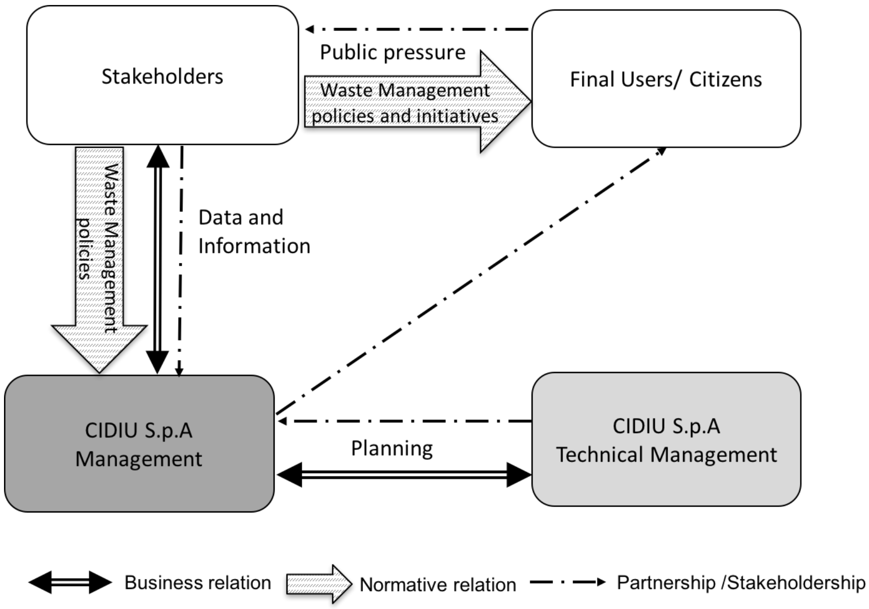

Figure 2 **Representation of the MACS**

two issues: the scheduling and vehicle routing problems (VRP). This tool automates the operation planning, reducing the inefficiencies, minimizing the total cost of dumpster emptying processes, mainly related to avoid third shifts, provide time savings, and enhance the value of the data, while releasing resources for service expansion. In fact, an efficient and optimized management of the operations allows Cidiu S.p.A. to obtain resources for extending its services to other municipalities, to gain a competitive advantage from the acquisition of new competences and innovative tools, and finally, to attain a solution, which represents the base for a future *"What if"* analysis. Moreover, an efficient use of vehicles, in terms of optimal routes and scheduling, increases the savings related to the assets, their management, and social costs connected to negative externalities. The latter represents a pillar for the value proposition that the project offers to final users. It consists of an efficient and optimized waste collection service that delivers economic and social benefits owing to less impact on the tax imposition, environment, and health, with consequent improvement of quality of life and livability of the city. Moreover, another important part of the value proposition is the mobile application that has a goal of involving citizens in the waste collection process allowing them to communicate issues with Cidiu S.p.A. The environmental protection and the involvement and empowerment of citizens on the waste collection are relevant topics for public stakeholders (Saladi and Santos-Lacueva 2016). Thus, the ONDE-UWC project provides to local administrations solutions with the aim of enhancing the information exchange that incentives a virtuous behavior from the final users and designs the waste process in an efficient way. Moreover, an important issue is related to the access to a large amount of big data, innovative services, and availability of the mobile application to local administrations, which relieves the pain related to poor value of the data as well as improves the technical and scientific know-how from being part of the “Living Labs”.

Solution Analysis

For the uniform phase, utilizing the base of knowledge created concerning 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 proposed by the GUEST OR methodology, with the goal of representing the ONDE-UWC project from a “to be” perspective. Thus, in this section, we present the whole solution implemented, in terms of a value chain, decision process, and operational model. Particularly, each component of the canvas illustrated in Figure 3 is described. First, analyzing the blocks on the right related to the decision makers, users and their relationships that must be enhanced, and objectives that must be created and clarified. Then, the attention is shifted to the left of the canvas; analyzing the constraints, decisions, information and resources to reduce, and, eventually, costs of the solution that must be avoided.

The primary decision makers (DMs), listed in their hierarchical order, are the COO or chief operating officer (COO) and foreman of each team. The first is involved in the planning process. Moreover, he ensures that the weekly plan produced by the platform is reasonable, and sends it to the foremen. The foremen will take the logistic decisions, carefully verify that the plan resulting from the planning activities is reasonable, and then extend the plan to the drivers who will operate in order to void the dumpsters according to the list received.

The users directly interested in the solution, as beneficiaries of its results and supported by the DMs to its implementation, can be split into two types: internal and external. The internal users have a full view of both the process and project, and they are:

- the Cidiu S.p.A. Management;
- the Cidiu S.p.A. technical staff composed of the foremen and drivers;
- the users of the mobile application, which permits them to exchange information and communicate problems.

The external users who have a partial view are:

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

These users establish several relationships with the DMs. In particular, the COO interacts through the platform with the foremen and drivers, in order to improve and disseminate the weekly plan produced by the algorithm. Other important interplay occurs within the decision support system, respectively the big data infrastructure, and municipalities, with the goal of providing open data with high value.

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

- Decision channels, represented by the Intranet and mobile application. The former is used to support the information flow that interconnects Cidiu S.p.A. and the workers, while the latter is used for the information flow between the involved actors and is based on the use of smart objects such as tablets, smartphones, etc.
- Implementation channels, composed by APIs and digital reports, useful to diffuse the information related to the development and improvement of the solution.

Concerning the building block of the solution canvas, which is related to the main objectives to which the solution is devoted, are those emerged by the analysis of stakeholder requirements to provide a value proposition fitting the perceived need. In particular, as previously discussed, the objectives can be classified into two main frameworks. The first regards the more operational aspects of the current activities, such as the efficient creation of weekly shifts and consequential reduction of operational costs, and minimizes the total service costs including environmental costs. The second is related to future potential, such as the attainment of freed resources to expand the service to other municipalities, and use of the solution for the *"What if"* analysis.

In order to reach these objectives, the decisions that must be considered concern the list of strategic decisions and activities to be implemented with the goal to reach the objectives defined in the solution. In this case study, the main decisions are the weekly assignment of a vehicle to a garbage type and daily definition of the vehicle route in each shift.

The primary information needed to implement the solution is related to the garbage generation and distribution per dumpster, (characterized by a high level of uncertainty), features of shifts and vehicles, and locations of dumpsters.

Moreover, to implement the solution, particular resources identified as enabling technologies are required. They are:

- Geographic Information System (GIS) containing the data regarding the locations of dumpsters;
- IoT. As above mentioned, and similarly to Mes et al. (2014), the solution developed in the ONDE-UWC project is based on the IoT principles. Although, unlike the contribution of Mes et al. (2014), which uses sensors on underground containers, we also adopted sensor equipped vehicles to guarantee the communication between dumpsters and vehicles and gather data regarding the waste quantity produced by each dumpster. This is, indeed, a breakthrough, because with these data it becomes possible to create a statistical model of the production, and build a more accurate collection schedule, giving insights concerning the fill levels of dumpsters at any time, on the contrary of Mes et al. (2014) that use historical data. Furthermore, by these sensors it is possible to know if for some reason the collection of the waste of a dumpster fails (i.e., missed collections).
- GPS system installed in mobile devices or onboard units (OBUs), capable of tracking the position of the vehicles, allowing the company to monitor the fleet in real time;
- Application Mobile to collect warnings related to bad situations from both the citizenship and vehicle drivers.

The solution is subjected to several constraints that must be addressed in order to guarantee the efficient performance envisioned in the project goals. In particular, constraints can be grouped into two types:

- Solution constraints that are related to the activities and requirements that affect the implementation of the solution. The primary constraint concerns the need to obtain a solution quickly, allowing the technical staff to define the plan in a reasonable time. This constraint and the high computational time required to solve the problem by using standard solvers have led us to implement a heuristic solution. This heuristic is composed of two steps. In the first step, the dumpsters are grouped into aggregates called clusters and, by considering each cluster as a dumpster, the problem is solved. The second step builds a solution into the network of dumpsters, given the optimal solution obtained during the first step. The heuristic, as well as the model, are described in detail in the Appendix.
- Problem constraints, concerning the technological constraints that influence the achievement of the objectives. The principal ones are:

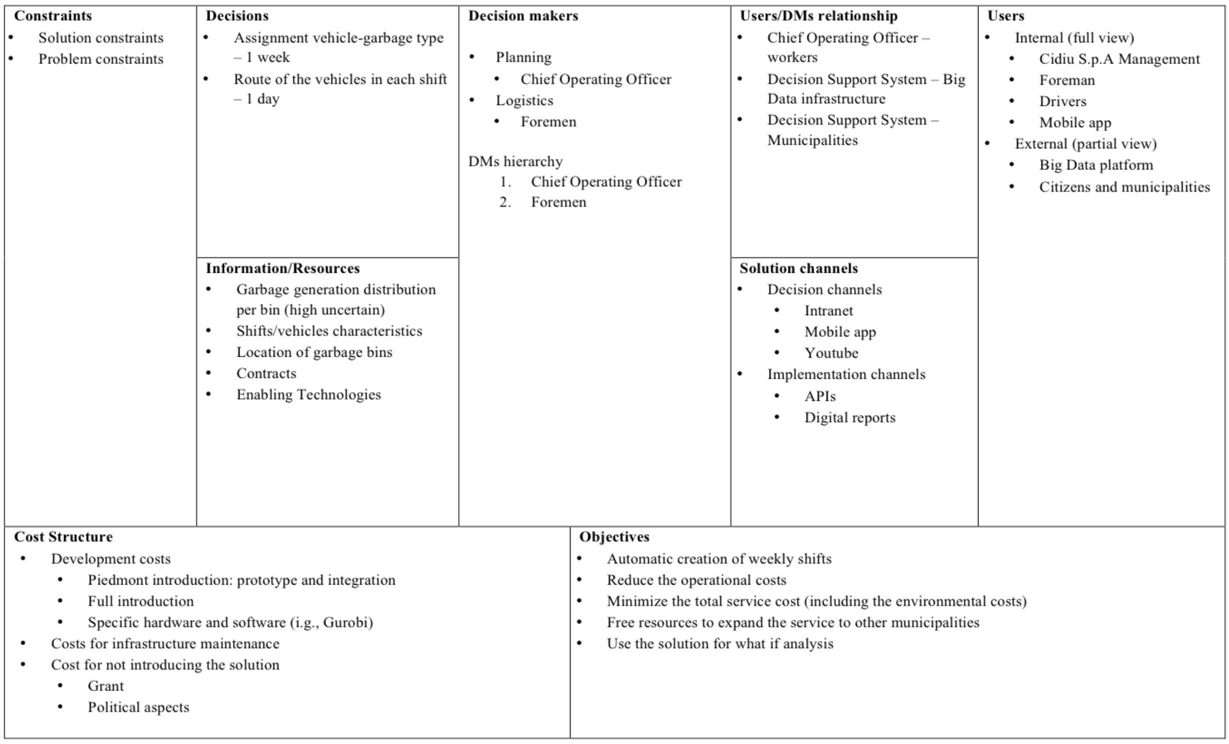

Figure 3 Solution Canvas

— the percentage of fullness of a dumpster must always be less than 80%;

— a working day is composed by 3 shifts, with each shift consisting of 6 hours;

— each vehicle can collect only a certain type of garbage; and

— each dumpster is visited from a unique vehicle for each turn.

Finally, the block of the costs structure describes the costs incurred to implement and maintain the solution presented. In particular, they are composed of prototype development and integration activity setup costs, which are inherent to the first implementation of the solution, and the subsequent full introduction. Further costs are related to the use and maintenance of hardware infrastructures and software licenses, such as the one for the optimization solver "Gurobi Optimizer". Another cost that must be considered concerns the negative impact for not introducing a solution.

Solution Implementation

The architecture of the solution shown in Figure 4 is based on a vehicle-to-infrastructure system. The building blocks are:

- Central unit. This is the core operative block of the IT architecture of the project providing two main functions, information management and optimization.

• CSI database. This contains all the data concerning the waste collection in the considered area.

• Enabling technologies. As described above in the solution canvas, they are the internal and external technologies that enhance the decision making process (e.g., providing maps, gathering data concerning the vehicles and dumpsters, etc.), and allow the exchange of information between the different components and actors. In particular, the mobile application plays an important role, allowing the drivers and customers to communicate and interact with the central unit, providing information about the waste collection system.

• Graphical user interface (GUI). It allows the users of the Cidiu S.p.A. to interact with the central unit.

Focusing on the core block, the central unit manages all the flows of data composed by the information regarding optimization from the Cidiu S.p.A. technical board and CSI database. This includes the information regarding the quantity of waste collected from the vehicles every time they come back to the depot, and information coming from customers and drivers. This information, which is regarding problems and bad conditions of the waste collection service, is communicated by means of the mobile application. Once the central unit has received this information, the optimization algorithm is executed, and the solutions are sent to the Cidiu S.p.A. technical board. The central unit also owns the task of updating the CSI database in regards to the waste collection data and sending the information regarding the activity of the company to the user of the mobile application. The timing of each of these operations is different: the update of the database takes place every time a vehicle arrives at the headquarters; the mobile application updates the information regarding the service once a week; and the optimization algorithm is run three times every day with the same frequency as the solution being sent to the technical board.

The mathematical model

The mathematical model that denotes Cidiu S.p.A.'s problem is described 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 easy of notation we consider that in the set $\mathcal{J}$ there are also the depot ($j=1$) and the dumps ($j=J-s,\ldots,J$). The cardinalities of these sets are I,S,J, and T, respectively. In set $\mathcal{J}=\{1,2,\ldots,J\}$ we consider that $j=1$ considers the depot, while the last indexes denotes the dumps.

For the parameters, we will use the following notation:

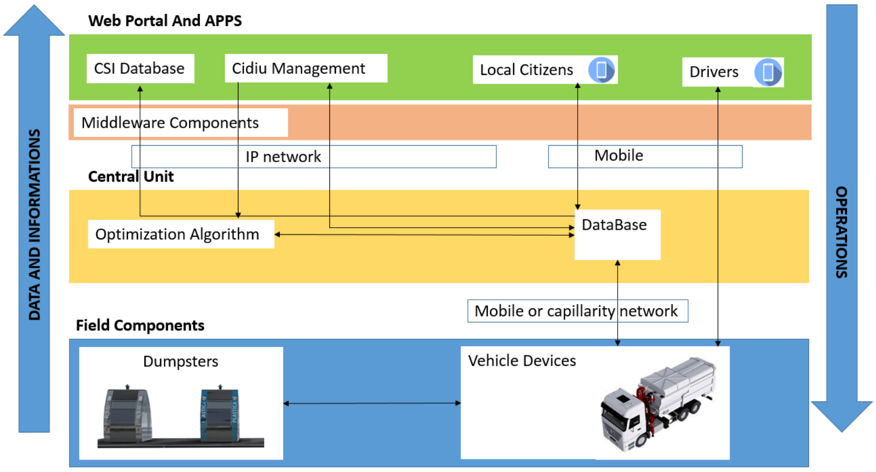

Figure 4 Architecture of the solution

- 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 last one;
- $C_{\max}$ is the maximum duration of the shift. We will consider that it lasts 6 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 is able to transport;
- l_s is the difference between a standard quantity that a vehicle can transport and real quantity if it is used to collect waste type $s \in \mathcal{S}$. This difference is due to the press action for certain types of waste;
- Θ_{jt} is the volume of waste that arrives to the 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 turn;
- a is the time that the drivers take to collect the waste from a dumpster. Notice that due to technology installed on the vehicles that Cidiu S.p.A. uses for collecting waste, the time for the collection is the same for all the dumpsters;
- α is the percentage of the dumpster capacity that we do not want to exceed.
- λ is a parameter that weights 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 the 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 the 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

$$\min. \sum_{i=1}^{I} \sum_{t=1}^{T} c_{it} w_{it} + \lambda \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{j_1=1}^{J} \sum_{j_2=1}^{J} d_{j_1 j_2} r^{it}_{j_1 j_2}, \quad (1)$$

subject to

$$w_{it} \geq y_{ijt} \quad \forall \; i,j,t \quad (2)$$

$$M y_{ijt} \geq x_{ijt} \quad \forall \; i,j,t \quad (3)$$

$$\sum_{i=1}^{I} y_{ijt} \leq 1 \quad \forall \; j,t \quad (4)$$

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

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

$$M z_{ist} \geq x_{ijt} \quad \forall \; i,s,j \in \mathcal{J}^s, t \quad (7)$$

$$\sum_{s=1}^{S} z_{ist} \leq 1 \quad \forall \; i,t \quad (8)$$

$$V_{j0} = \Theta_{j0} \quad \forall \; j \quad (9)$$

$$z_{ist} \leq y_{i(J-s)t} \quad \forall \; i,t \quad (10)$$

$$V_{jt} = V_{jt-1} + \Theta_{jt} - \sum_{i=1}^{I} x_{ijt} \quad \forall \; j, t \neq 0 \quad (11)$$

$$V_{jt} \leq \alpha V_j \quad \forall j,t \quad (12)$$

$$w_{it} \geq w_{i+1,t} \quad \forall \; t, i = 1 : I-1 \quad (13)$$

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

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

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

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

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

$$\sum_{j_1, j_2 \in S, j_1 \neq j_2} r^{it}_{j_1 j_2} \leq |S| - 1 \quad \forall S \subset \mathcal{J}, S \neq \emptyset \quad (19)$$

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

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

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

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

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

The objective function minimizes the weighted sum of two components. The first one is the sum of the fixed costs derived from the activation of a vehicle in a time shift, the second is the cost of the routing. Constraints (2) and (3) ensure that every time a vehicle is used in a time shift, that time shift is activated. Constraint (4) imposes that, in each time shift, only one vehicle can void a dumpster. Constraint (5) imposes that each vehicle must collect all the waste in the visited dumpsters. Constraint (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 (7) and (8) impose that each vehicle can collect waste from one and only one type of waste. Further, constraints (10) impose that if a vehicle is used it has to go to the corresponding dump. Constraints (9), (11), and (12) impose the dynamic of the evolution of the waste quantity of each dumpster and bounds this quantity. It is worth noting that since the constraints (9) and (11) use equalities, the value of V_{jt} can be modified only by using the variables x_{ijt}. Furthermore, if such a modification does not happen, then constraint (12) is violated. Constraint (13) imposes an order in the vehicle choice. Constraints (14), (15), (16), (17), (18), and (19) define the routing problem and set a maximum time for this activity.

The solution algorithm

A mixed integer linear model of the problem can be defined. Unfortunately, it becomes large, even for small size instances. In fact, 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 issue, and from numerous experiments, we decided to use a heuristic that is composed by the three different phases presented below. The detail description of the model is presented in the Appendix, owing to the complexity of the model and to simplify its exposition. The phases composing the heuristic are:

1. **Clusterization**. The first phase has a goal of solving the problem considering the aggregation of dumpsters in clusters, instead of a single dumpster. In particular, we emulate

the strategy of the company by aggregating dumpsters located in the same city. We have tried different policies that for the size limit of this paper we cannot present, nevertheless this choice is the best that we have found. Thus, a reasonable solution is obtained, owing to the reduction of the dimension using clusters, and to the possibility of computing the exact solution of this new problem. We then solve the mathematical model (1)-(19) by considering clusters instead of dumpsters i.e. by substituting the set of single dumpsters $\mathcal{J}$ with $\mathcal{C}$, the set of clusters (which cardinality is C). This change lead us to remove constraints (4) and (5), because more than one vehicle 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 is equal to the length of the shortest edge that connects a dumpster in c_1 and c_2, namely $d_{c_1c_2} = \min_{j_1\in c_1 j_2\in c_2} d_{j_1j_2}$. 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 (it is equal to 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 is equal to the sum of the emptying times of all the dumpsters, plus the time of a tour between all the dumpsters in the cluster.

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

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

(b) create the list *list0* and insert all dumpsters for each cluster such that $y_{ict} = 1$ where $i \in \mathcal{I}$, $c \in \mathcal{C}$, $t \in \mathcal{T}$;

(c) remove from *list0* all dumpsters that are void;

(d) sort *list0* in decreasing order of quantity of waste;

(e) Create *list1*;

(f) add, one by one, all the dumpsters of *list0* into *list1* until constraints (6) or (18) hold with equality;

(g) if all the dumpsters in *list0* have been added then:

i. if there is a dumpster in *list1* 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 *list1*. Then, go to step (a).

3. **Post optimization**. After the previous two phases, we obtain a feasible solution of the original problem. Thus, we refine it solving a TSP problem for each route, using the Chained-Lin-Kernighan heuristic for asymmetric networks Applegate et al. (2003).

Since the **Building of a feasible solution** and **Post optimization** run very fast, 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 have used 20 values equally spaces between 50% and 70%.

It is worth noting that the results are strongly dependent by the clusterization policy used. For the lack of space, we will consider this dependencies in future works.

Computational Tests

Data

We consider 100 instances to run the computational tests and simulations, each one of them consider the real size of the problem of the company. In particular, the problems consider 525 dumpsters with 2 types of waste, 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 the one from the real field for 1 instance, while the others are generated by variations. The data related to the optimization problem can be divided into two types: geographical and technical. The first are the parameters $d_{j_1 j_2}$ obtained from Google describing a complete graph. The technical data are:

1. the fixed cost of using a vehicle during a time shift c_{it}; which is the same for the first two time shifts of the day, however, doubles for the third shift;

2. the volume of each dumpster V_j, of which there are three types with volumes of 2400, 3500, and 5000;

3. the capacity of the vehicles $\hat{C}$, of which the value is 20000 l;

4. the extra capacity l_s, of which is 60000 l for paper and 0 l for MSW;

5. the length of a time shift C_{max}, given as 6 hours;

6. the time to void a dumpster a, given as 5 minutes;

7. the time to reach a dump T_s. These values change in function of the type of waste because the dump are type specific. Since every dump is very far away from the dumpsters,

we consider it to be a fixed constraint, equal for each dumpster from which the vehicle depart.

These technical data between the points 1 to 7 are extracted from the Cidiu S.p.A. database.

8. the increments Θ_{jt} obtained from the historical data of the company. Moreover, for each dumpster, we have a set of observations (not equally spaced) of the waste quantity observed each time a vehicle voids the dumpster. Due to the lack of information about the waste creation probability, we assume that the quantity of waste observed in each dumpster is produced uniformly in 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 in time shift) of the n-th collection. We use as an increment:

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

9. the coefficient α that limits the quantity of waste in the dumpsters has its value is set to 0.8 according to the Cidiu S.p.A. experience.

Results

The results obtained from the solution proposed in this paper can be classified into two types: methodological and computational. The first is related to the benefits generated by the application of the GUEST OR methodology to the ONDE-UWC project. From the managerial point of view, the computational results are more addressed in the evaluation of the solution than in an operative point of view. Concerning the methodological results, the adoption of the GUEST OR methodology reduced the development time of the model to less than one month from the beginning of the project to the definition and validation of the OR model. On the contrary, the estimated time without the use of the GUEST OR was approximately four months. In the first step of the methodology, one kick-off meeting followed by other two meetings with the Cidiu S.p.A. management were held in order to establish a contact with the company and build a base knowledge regarding technical aspects on which all activities relevant to the achievement of the final solution defined in the solution canvas are developed. In particular, this approach allows to already derive from the first meetings the main constraints of the problem, as those referred to the third shifts. This enabled the needs of all stakeholders to be considered, from the initial phases driving the project to their satisfactory completion. Hence, the methodology avoids the expensive modifications of the model in the last phase of the project and delays generated by different reviews. Moreover, this methodology produced an anticipation in the implementation of the solution algorithm and IT infrastructure by defining, in a more accurate way, the input and output of the model. All these aspects have led to the rapid achievement of the project's goals with consequential benefits related to the savings in terms of time and resources involved. For these reasons, we can state that the GUEST OR methodology is an efficient project management tool for the development of OR models. Additionally, it has a positive effect on the development of the whole IT infrastructure.

Regarding the computation results, to evaluate the solution we consider eight KPIs:

- the average number of third shifts during a week of activity (nTS);
- the average number of vehicles used daily (nV), calculated as the number of vehicles used during one month of activity, divided by the number of shifts. We remember that the companies have 4 vehicles;
- the average percentage of waste volume at the moment of collection (WV%). When a vehicle voids a dumpster, a probe on board the vehicle records the volume occupied by the waste. If we divide this gathered value by the volume of the dumpster, then we compute the average over all the collections and all the dumpsters, we derive this indicator;
- total routing time (TRT);
- the average fulfillment percentage of the vehicles FV% for each time shift when a vehicle is used;
- the average number of visited dumpsters for each time shift when a vehicle is used (nVD).

The calculation of the KPIs is conducted by considering a real month of activity for Cidiu S.p.A., and a simulated month of activity for our algorithm. The methodology has already been implemented in the real field as partial experiment for small periods of time leading to similar results. Nowadays, the company is working for the integration of the algorithm in the information system of the company in order to test it intensively in the real field. The values of these KPIs are illustrated in the Table 1, in brackets there is the standard deviation of each values. By comparing the results obtained after the introduction of the proposed solution, then those of the original condition. Moreover, the first column

Table 1 KPIs before and after the use of the software

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)

of the table lists the KPIs, the second shows their value registered by the Cidiu S.p.A. activity, and the third column shows the values obtained using our approach.

The results highlighted in Table 1 shows an improvement regarding all the KPIs. In particular, the primary outcomes are that the company no longer had recourse to a third shift, and the percentage of vehicles used decreased by 33% in the time window considered. The consequences are the reduction of the waste collection operational costs and increase of the competitiveness of the company.

Moreover, this project has a relevant value to the operational strategy of Cidiu S.p.A., owing to the more efficient use of the dumpster volumes. Indeed, before the implementation of the solution, the company used periodic routes, the frequency of which caused an overestimate of the waste production. Although planning based on aperiodic time shifts is more difficult to manage than that based on periodic, the inefficiency of the waste production estimates led the Cidiu S.p.A. management to consider a change of the operative strategy in order to adopt the proposed solution, justified by the good performance of the algorithm. It is worth noting that by changing parameter λ, which converts the time of the routing into cost for the company, the solution policy changes slightly.

Nevertheless, the model seems to be very sensitive in the change of the parameters Θ_{jt}. If these coefficients increase the total cost will increase too, furthermore for values of Θ_{jt} sufficiently high the model becomes infeasible. Other very important parameters are the time shift duration and the size of the dumpsters. An increase of both these parameters brings to a substantial decrease of the total cost.

Instead, the model seems not to be sensitive to the increase in volume of the vehicles, being the time shift limit stricter than the constraint in volume.

Table 2 Comparison between the optimal solutions and the heuristic ones. All the values are computed by using 6 time periods and 2 types of waste. The first column shows the number of dumpsters, the second shows the percentage difference in the number of time shifts (nTs), the third one shows the percentage difference in the routing cost (rC) and the last two columns report the computational time of CPLEX and the proposed heuristic.

n. dumpsters	nTs [%]	rC [%]	Time Optimal [s]	Time Heuristic [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)

In order to assess the performance of the proposed heuristic, we compare its solutions with the optimal ones found by CPLEX 12.6. In particular, we consider instances with $10, 20, 30, 40$, and 50 dumpsters, 6 time periods and 2 types of waste. We cannot perform tests with more than 50 dumpsters because CPLEX runs out of memory. The dumpsters are spatially generated in clouds of points (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 generated randomly. The results of this comparison are shown in Table 2, where we report the differences of the costs of the time shifts and of the routing, obtained by CPLEX and our heuristic. For each setting, mean values and standard deviations (in brackets) over 20 runs are shown.

It is worth noting that the heuristic is able to find the optimal time shifts for all instances, while the deviation from the optimum (3.32% for the largest instances) is only due to the routing costs. Actually, this is not a critical issue since the company is much more interested to minimize the number of shifts than to minimize the routing costs.

While CPLEX is not able to deal with real instances because of the computation time and the memory that it needs, the proposed heuristic is able to achieve good results in a small amount of time for those instances, then it is suitable to be used in real settings.

Another important result concerned the reduction of the computational time to obtain a solution. As above stated, commercial solvers are not able to solve the mathematical model due to memory constraints. Nevertheless, the average time for computing a solution by the heuristic is of 4 hours and 23 minutes with a standard deviation of 20 minutes (we computed these value by using 100 simulations). The heuristic can be used by the company because the management have enough time in to compute and verify the solution of the software before to start the activities.

The proposed heuristic can then be run several each time shifts, allowing the plan to be adjusted, and taking into account the missed operations (e.g., when the vehicle cannot collect the waste, due to the presence of a parked car that blocks the operation). From a qualitative point of view, the project produces different results. On the one hand, the proposed solution generates an improvement in the work conditions of the staff, and particularly, of the drivers. Indeed, they will not have to work during the night and will also gain a more balanced work load, with a consequential positive impact on their quality of life. On the other hand, Cidiu S.p.A. obtains freed resources to invest in the offering of new services to the citizens from the optimization of the operational activities.

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Appendix A

Value Proposition Canvas

As above discussed, in order describe the actors involved in the MACS, we adopted the Value Proposition Canvas, proposed by Osterwalder and Pigneur (2014). It is composed by two main blocks: the actor profile and value map, which are both described below, following the reading order of the canvas. The actor profile is described in a more structured way: individualizing its jobs, such as the described work or life activities; pains, such as the bad outcomes, risks, and obstacles related to the jobs; and finally, gains, such as the desired outcomes or benefits from the activities. The value map defines the value proposition that a company has to offer to each actor according to 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 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 Value Proposition Canvas, see Osterwalder and Pigneur (2014).

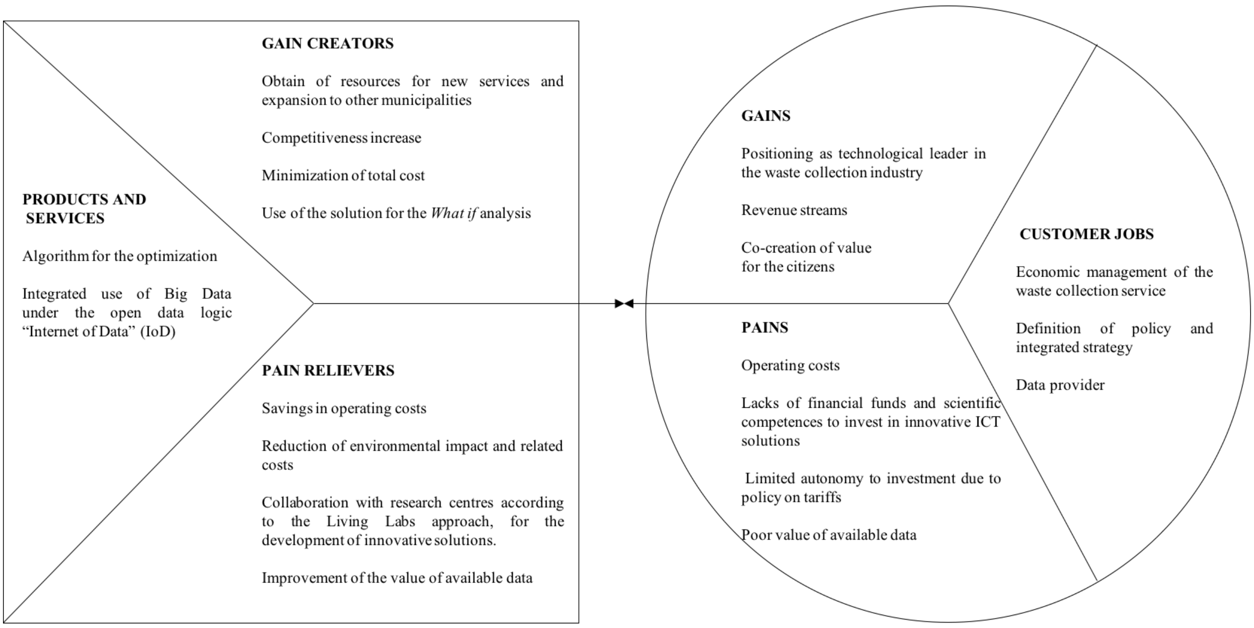

Figure 5 **Value Proposition of Cidiu S.p.A. Management**

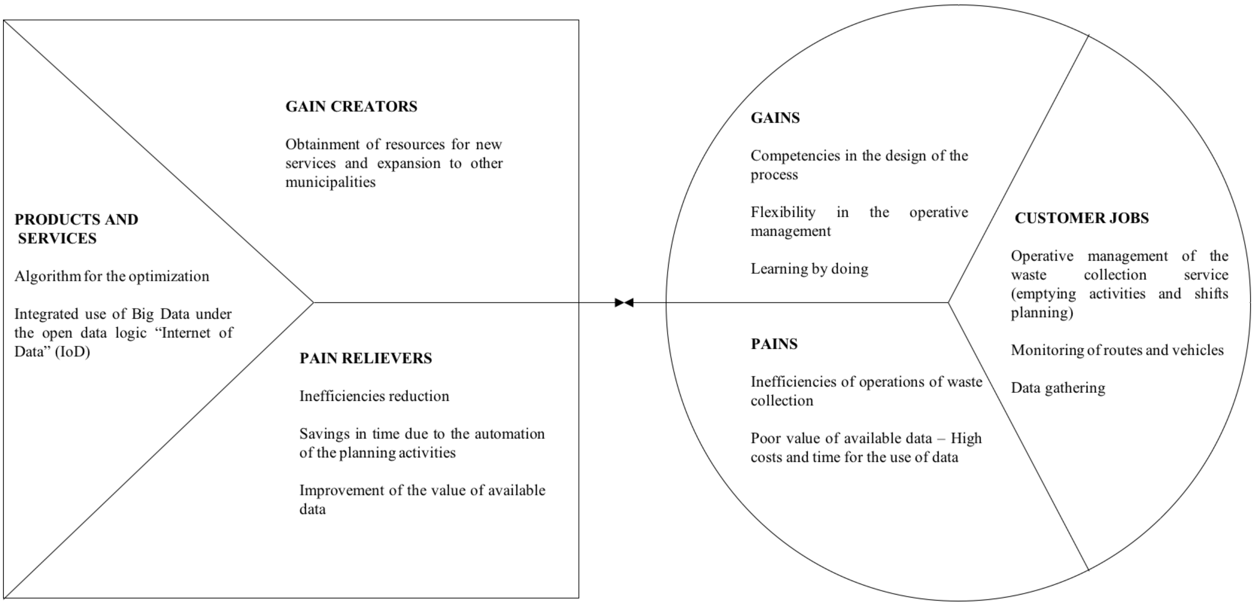

Figure 6 Value Proposition of Cidiu S.p.A. Technical Management

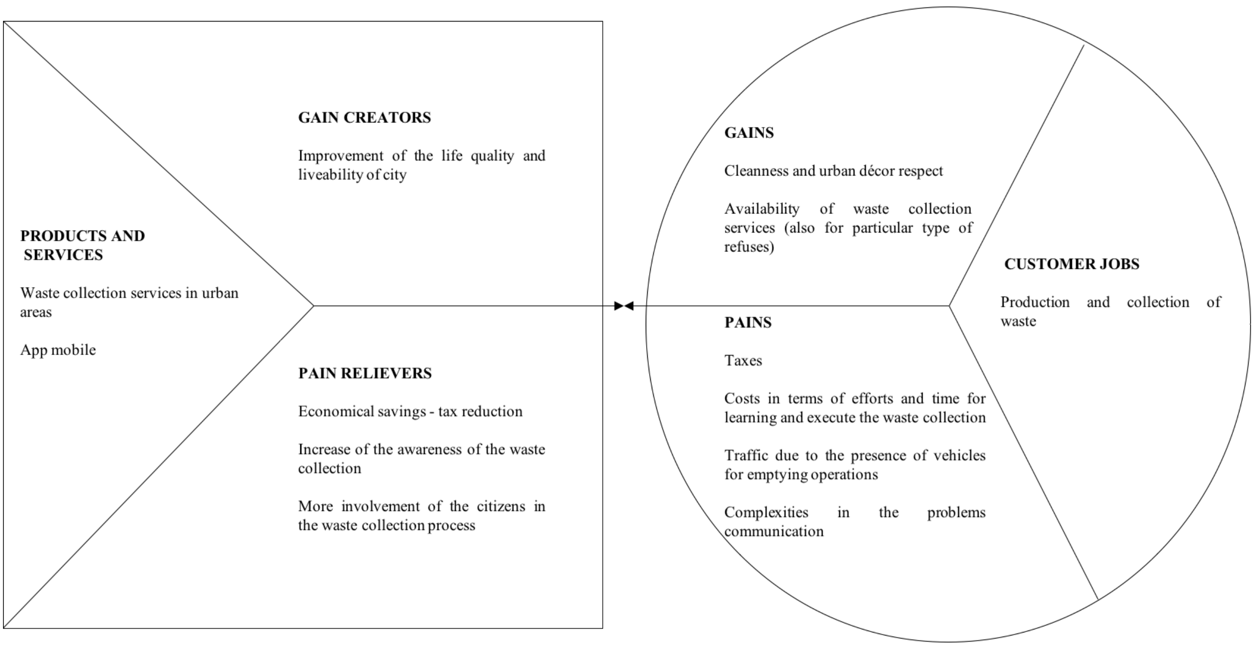

Figure 7 Value Proposition of Final Users

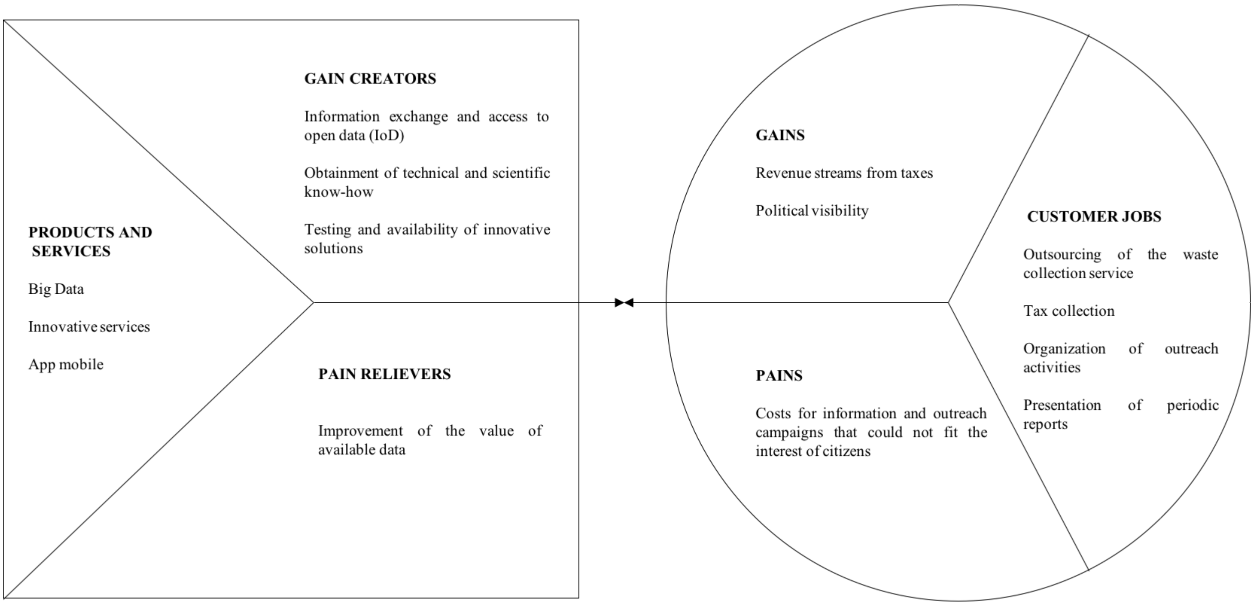

Figure 8 **Value Proposition of Stakeholders**