Waste Management 32 (2012) 1291–1296

Contents lists available at SciVerse ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Capacitated location of collection sites in an urban waste management system

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ARTICLE INFO

Article history:
Received 24 August 2011
Accepted 20 February 2012
Available online 17 March 2012

Keywords:
Urban waste management
Location
Heuristics

ABSTRACT

Urban waste management is becoming an increasingly complex task, absorbing a huge amount of resources, and having a major environmental impact. The design of a waste management system consists in various activities, and one of these is related to the location of waste collection sites. In this paper, we propose an integer programming model that helps decision makers in choosing the sites where to locate the unsorted waste collection bins in a residential town, as well as the capacities of the bins to be located at each collection site. This model helps in assessing tactical decisions through constraints that force each collection area to be capacitated enough to fit the expected waste to be directed to that area, while taking into account Quality of Service constraints from the citizens' point of view. Moreover, we propose an effective constructive heuristic approach whose aim is to provide a good solution quality in an extremely reduced computational time. Computational results on data related to the city of Nardò, in the south of Italy, show that both exact and heuristic approaches provide consistently better solutions than that currently implemented, resulting in a lower number of activated collection sites, and a lower number of bins to be used.

1. Introduction

Urban Waste Management (UWM) is becoming one of the most relevant issues for modern society municipalities because of its social, political, and economical impact. Its social relevance is mainly due to the growing public concern for environmental preservation and pollution aversion. The political importance of this problem is evident not only from citizens' point of view, who give a lot of awareness to UWM when choosing their representatives, but also from institutions' point of view. The economical importance of this problem is shown from the huge resources put in play behind UWM, and from the number of actors involved in this process. From one side, municipalities that allocate an important portion of their own budgets to deal with this task, as well as citizens who support this service by paying taxes. From the other side, private companies that are interested either in performing direct UWM activities or taking advantage from many spin-off businesses, such as material recycling and waste-to-energy production.

Nowadays, municipalities generate huge quantities of wastes, both in industrialized and developing countries. For instance, the average per-capita residential waste generation (in kg/day) is about 0.51 in India (Esakku et al., 2007) and 1.03 in Canada (Statistics Canada, 2010). Moreover, the per-capita waste production is rapidly increasing, with values ranging from 8% in North America to 14% in the EU during a period of 11 years, from 1995 to 2006. Table 1 reports the total and per-capita waste generation increase between the years 1995 and 2006 in North America, the EU, and Italy (OECD, 2008).

UWM consists in various activities that can be clustered into four stages of the waste life-cycle: generation, collection, transformation, and disposal. The efficient execution of each of these stages requires taking many decisions at the strategic, tactical, and operational levels. Examples of decisions involved in these processes are: the selection of wastes treatment technologies, the location of wastes treatment sites and landfills, the future capacity expansion strategies of the sites, waste flow allocation for transformation facilities and landfills, service territory zoning into districts, collection days selection for each zone and for each waste type, fleet composition determination, and collection vehicles' routing and scheduling. A detailed description of these problems is beyond the scope of this paper. Interested readers may refer, for instance, to Pichtel (2005) who describes the main issues related to UWM.

This study focuses on the second stage of the waste life-cycle: the collection stage. Specifically, we face the problem of locating unsorted waste collection sites in a residential town. This problem

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doi:10.1016/j.wasman.2012.02.009

Table 1
Waste production in North America, the EU, and Italy.

	Total production (tons/year)			Per-capita production (kg/day)		
	1995	2006	Increase (%)	1995	2006	Increase (%)
North America	242,000,000	291,000,000	20.2	1.70	1.84	8.2
EU	182,000,000	219,000,000	20.3	1.34	1.53	14.2
Italy	25,780,000	32,523,000	26.2	1.23	1.51	22.8

concerns countries like Italy, where the households bring their waste to collection points, contrary to several European countries with a door-to-door collection. We propose an integer programming model, whose aim is to help decision makers in choosing where to locate the garbage collection bins, as well as defining the capacities of the bins to be allocated to each collection site. Our approach is tested on real data related to the city of Nardò, in the south of Italy, which represents a good sample of medium-sized urban area, with its 30,000 inhabitants.

A huge amount of research has been produced about location problems and modeling approaches (see ReVelle and Eiselt (2005) for a survey on a number of important problems in facility location). However, contrarily to other location problems in the context of UWM, the problem we are studying has received little attention in the literature, despite its considerable impact on both individual citizens and the whole community. In addition, this is recognized to be a semi-obnoxious problem. In fact, typically, a citizen prefers having a waste collection site as close as possible to his/her home, but, at the same time, he/she aims at paying as less taxes as possible to have this service guaranteed. On the other hand, the community is interested not only in reducing the expenses related to the collection stage, but also in limiting the visual impact due to the presence of the collection bins close to the residential sites. Given that both these factors depend on the number of collection sites, ensuring a good service with the least number of collection sites represents a key objective.

We are aware of only a limited number of works on this topic. Bautista et al. (2006) propose two mathematical formulations for locating waste collection areas. In the first formulation, the problem is modeled as a set covering problem and solved by using a genetic algorithm. The second formulation models the problem as a Max-Sat problem for which the authors propose a GRASP approach. Both algorithms are tested on a real world instance representing a city in the metropolitan area of Barcelona. Badran and El-Haggar (2006) present a model for municipal solid waste management in Port Said (Egypt). The proposed model aims at minimizing the municipal waste management cost, determining the best location for collection sites among a given set of candidate locations. Erkut et al. (2008) present a mixed-integer multiple objective linear programming model, to solve the location–allocation problem of municipal solid waste management facilities in the Central Macedonia region in North Greece. Recently, Tralhão et al. (2010) propose a mixed-integer, multiobjective programming approach to identify the locations and capacities of multi-compartment sorted waste containers. The model aims at determining the number of facilities to be opened, as well as the respective container capacities, their locations, their respective shares of the total waste of each type to be collected, and the dwellings assigned to each facility. The approach is tested on a case study represented by Coimbra city (Portugal).

The main contribution of this paper is twofold. First, we solve a capacitated version of the location problem. Indeed, our model includes constraints that force each collection site to be capacitated enough to fit the expected waste to be directed to that site. Second, we include additional constraints that ensure the Quality of Service (QoS) from the citizens' point of view. This QoS requirement ensures that each citizen is served by the waste collection site closest to his/her home, rather than just any close site.

The remainder of the paper is organized as follows. Our optimization model is presented in Section 2. A heuristic solution approach is then described in Section 3. The computational results on a real-life application are reported in Section 4, and finally, concluding remarks follow in Section 5.

2. Problem formulation

The objective of our optimization model is to minimize the total number of collection sites to be located, chosen among a set of candidate locations. Such an objective ensures not only the reduction of the visual impact due to the presence of collection sites, but also the reduction of the overall cost related to the collection phase. We follow Labbé and Laporte (1986), that consider the minimization of the number of sites as a proxy for minimizing the collection cost. Indeed, the location of the collection bins is intertwined with the subsequent collection routes' determination, and should be cast as a location-routing problem (Nagy et al., 2007).

Moreover, our model determines the optimal allocation of citizens to collection sites, as well as the allocation of bins to collection sites such that the demand is satisfied. The bins allocated to such sites may be of different types, with differences in length and capacity. Finally, additional constraints impose that each citizen is serviced by a collection site which is within a threshold distance from his/her home.

Mathematically, the problem can be modeled on a bipartite directed graph $G(V_1 \cup V_2, A)$, where the vertices in V_1 represent the waste generation sources (i.e., the citizens), whereas V_2 includes the vertices representing the potential sites where to collect the urban waste.

While the meaning of the elements in V_2 is obvious, the elements in V_1 deserve some explanation. Indeed, each element in V_1 represents a cluster of citizens, grouped according to their position. A cluster may include all the citizens residing in a street, or in a portion of it, considering them as point sources. We note that, in zones which are not densely populated, a source may coincide even with a single home. We call each element in V_1 as a centroid. By using this assumption, the set of arcs $A = V_1 \times V_2$ represents the waste flow between the centroids and the potential sites. To each arc is associated an attribute d_{ij} representing the distance between the centroid $i \in V_1$ and the potential site $j \in V_2$. We also define the subset $U_i \subseteq V_2$ that represents the set of potential sites that are within a threshold distance D_i with respect to centroid $i \in V_1$, or, formally, $U_i = \{j \in V_2 : d_{ij} \leqslant D_i\}$. We note that D_i depends on the centroid i in order to give more flexibility to the model, allowing potentially different threshold values for the centroids. Indeed, decision makers may impose higher values of D_i for centroids representing sparsely populated zones, where typically there are not many collection sites. Before presenting the optimization model, we introduce the following further notation:

- K: set of different bin types available for allocation to collection sites;
- Q_k: capacity of a bin of type $k \in K$;
- l_k: linear length of a bin of type $k \in K$;
- b_k: total number of bins of type $k \in K$ available for allocation;

– q_i: daily generation of wastes related to centroid $i \in V_1$;
– L_j: linear length associated with potential collection site $j \in V_2$.

We note that, to ensure problem feasibility, the total capacity of the bins must be not smaller than the total daily waste production, i.e., $\sum_{k \in K} b_k Q_k \geqslant \sum_{i \in V_1} q_i$.

The problem's decision variables are:

– z_j: binary variable that takes value 1 if the potential collection site $j \in V_2$ is activated, 0 otherwise;
– x_{ij}: binary variable that takes value 1 if centroid $i \in V_1$ is allocated to collection site $j \in V_2$, 0 otherwise;
– y_{kj}: integer variable that represents the number of bins of type $k \in K$ to be allocated to collection site $j \in V_2$.

Thus, a mathematical formulation, that minimizes the total number of activated collection sites, is:

$$\text{Minimize} \quad w = \sum_{j \in V_2} z_j \tag{1a}$$

subject to

$$\sum_{i \in V_1} q_i x_{ij} \leqslant \sum_{k \in K} Q_k y_{kj}, \quad \forall j \in V_2 \tag{1b}$$

$$\sum_{k \in K} l_k y_{kj} \leqslant L_j z_j, \quad \forall j \in V_2 \tag{1c}$$

$$\sum_{h: d_{ij} + \delta < d_{ih}} x_{ih} \leqslant 1 - z_j, \quad \forall i \in V_1, \forall j \in V_2 \tag{1d}$$

$$\sum_{j \in U_i} x_{ij} = 1, \quad \forall i \in V_1 \tag{1e}$$

$$\sum_{j \in V_2} y_{kj} \leqslant b_k, \quad \forall k \in K \tag{1f}$$

$$z_j \in \{0, 1\}, \quad \forall j \in V_2 \tag{1g}$$

$$x_{ij} \in \{0, 1\}, \quad \forall i \in V_1, \forall j \in V_2 \tag{1h}$$

$$y_{kj} \geqslant 0, \text{ integer}. \quad \forall j \in V_2, \forall k \in K \tag{1i}$$

Inequalities (1b) and (1c) are capacity constraints and, at the same time, express obvious logical relations between the problem's variables. In particular, constraints (1b) impose that the total waste to be directed to collection site $j \in V_2$ is at most equal to the total capacity of the bins allocated to it. Constraints (1c) prevent that each potential collection site $j \in V_2$ hosts more bins than its capacity, in terms of length. Constraints (1d) avoid that a centroid $i \in V_1$ is allocated to an activated collection site which is not necessarily the closest to that centroid, even though within the threshold distance D_i. In practice, these constraints tie variables x_{ij} to variables z_j in such a way that citizens are served by the waste collection site closest to his/her house. They force the allocation of centroid $i \in V_1$ to the activated collection site $j \in V_2$ so that the inequality $d_{ij} + \delta < d_{ih}$ is satisfied for each $h \in V_2$ such that $h \neq j$, where δ is a tolerance value. To be explicit, when $z_j = 1$ all the variables x_{ih}, such that $d_{ij} + \delta < d_{ih}$, assume value 0, so centroid $i \in V_1$ is allocated to collection site j. On the other hand, when $z_j = 0$, constraint (1d) becomes redundant because of constraint (1e). The meaning of δ is the following. If a centroid i cannot be allocated to the closest activated site j because, for instance, of the total capacity of the site, it is still feasible to allocate it to any activated site j' for which $d_{ij'} \leqslant d_{ij} + \delta$. Constraints (1e) allocate each centroid $i \in V_1$ to exactly one activated collection site within the threshold distance D_i. Constraints (1f) ensure that the number of bins of each type allocated to the activated collection sites is less than or equal to the maximum available quantity. Finally, constraints (1g)–(1i) define the domain of the variables.

We remark that constraints (1d) represent a peculiar feature of our application that differentiates our location problem from those usually solved in the industrial context. However, these constraints contribute inevitably in increasing the complexity of the mathematical model. Formulation (1) results to be a Linear Programming model with integer variables. Solving it through a general purpose solver may be performed for small instances only, while solving large scale instances of such model requires specific techniques or heuristic approaches.

3. A heuristic approach

The complexity of the optimization model presented in Section 2 makes it very difficult to be solved optimally within a reasonable time by means of a straightforward use of a general purpose ILP solver. Indeed, in order to test the exact solution of our optimization model on a specific service territory, a zoning of such territory was necessary. For this reason, even though time complexity may sometimes not be a serious constraint in problems concerning long term planning, in this section we propose a two-phases heuristic approach. The first phase deals with the strategic problem of which subset of the set of collection sites is advisable to activate, as well as the allocation of centroids to such collection sites. For this purpose, a capacitated allocation problem is heuristically solved, and an improved procedure with the aim of reducing the number of the activated collection sites is performed on the heuristic solution. On the other hand, in the second phase we heuristically face the tactical problem related to which bin types to allocate to the collection sites that have been selected at the end of the first phase. We notice that the advantage of our heuristic procedures consists in their ability in tackling a big territory as a whole, while providing good feasible solutions in a very short amount of time. The procedures performed in the first phase are described in Algorithms 1 and 2, whereas the second phase is depicted in Algorithm 3.

Algorithm 1. A constructive heuristic for the location of collection sites

procedure CONSTRUCTHEURISTIC(V_1, V_2)
  $V^* \leftarrow$ ALLOCATECENTROIDS(V_1, V_2)
  if $V^* = \emptyset$ **then**
    return null
  else
    for all $j \in V^*$ **do**
      $V' \leftarrow$ ALLOCATECENTROIDS ($V^* \setminus \{j\}, V_1$)
      if $V' \neq \emptyset$ **then**
        $V^* \leftarrow V'$
      end if
    end for
  end if
  return V^*
end procedure

Algorithm 2. The procedure for allocating centroids to collection sites

procedure ALLOCATECENTROIDS(V_1, V_2)
  $V^* \leftarrow \emptyset$
  for all $i \in V_1$ **do**
    $V' \leftarrow V_2$
    check $\leftarrow$ **false**
    while check = **false do**
      $j \leftarrow$ CLOSESTSITE(i, V', δ)
      if $j \neq$ **null then**
        if $<j$ has enough capacity $>$ **then**
          $<$ allocate i to $j >$
          $V^* \leftarrow V^* \cup \{j\}$
          check $\leftarrow$ **true**

```
13:         else
14:             V' ← V' \ {j}
15:         end if
16:       else
17:         return null
18:       end if
19:     end while
20:   end for
21:   return V*
22: end procedure
```

More specifically, in the first phase we implement a constructive heuristic inspired from the drop heuristic for facility location (Feldman et al., 1966). The basic idea is to start with a large number of activated sites, and then try to remove one site at a time. This removal is confirmed only if it is associated with a cost reduction. In particular, we first assign each centroid to the potential collection site which is the closest, with a tolerance of δ, having a residual capacity greater than the daily generation of wastes of the centroid, without taking care of minimizing the number of activated collection sites (Algorithm 1, line 2). If such conditions are not satisfied for a particular centroid, then it cannot be assigned to any site. After this preliminary step, we temporarily drop, in turn, each activated collection site, allocating its centroids to the remaining activated sites. If this operation succeeds, then the collection site is permanently dropped, and another iteration is performed (Algorithm 1, lines 6–11). At the end of this phase, the procedure returns the subset of collection sites to be activated.

In the second phase of our approach (Algorithm 3), the decisions involve which bins of which type to allocate to the collection sites that have been selected at the end of the first phase. In particular, for each collection site j, we first check whether the sum of the waste generation of the centroids allocated to it can be satisfied by a single bin of type k, such that $l_k \leqslant L_j$, and its capacity Q_k is greater than the total waste to be directed to j (Algorithm 3, line 6, MINIMUMCAPACITYBIN() method). If this control does not succeed, we choose a bin type k having the maximum capacity among those available (Algorithm 3, line 8, MAXIMUMCAPACITYBIN() method), and we iterate until the sum of the capacities of the bins allocated to j is greater than the total waste to be directed to it.

Algorithm 3. The procedure for allocating bins to collection sites

```
1: procedure ALLOCATEBINS(V, K)
2:   for all j ∈ V do
3:     residualCapacity ← < total waste to be directed to j >
4:     residualLength ← L_j
5:     while residualCapacity > 0 and residualLength > 0 do
6:       k ← MINIMUMCAPACITYBIN(residualLength, residualCapacity, K)
7:       if k = null then
8:         k ← MAXIMUMCAPACITYBIN(residualLength, K)
9:       end if
10:      < allocate a bin of type k to j >
11:      residualCapacity ← residualCapacity − Q_k
12:      residualLength ← residualLength − l_k
13:    end while
14:  end for
15: end procedure
```

4. Computational experiments

In this section, we test the performance of both the optimization model and the constructive heuristic on a real life instance, related to the city of Nardò, in the Apulia region. Both approaches are tested on a machine equipped with an Intel processor with 2.8 GHz clock speed and 2 GB of RAM. The constructive heuristic is coded in Java, whereas ILOG CPLEX 10.0 is used for solving the linear programs. All the standard CPLEX cuts are active.

4.1. Test problem

The city of Nardò is located in the southeast of Italy, in the Apulia region. The total area of Nardò is 190.52 km^2, with a population in November 2010 of 31,762 inhabitants, and an average family size of three individuals. The area of Nardò generates 15,133 tons of waste per year, which is equivalent to 41.46 tons per day. Thus, supposing that this quantity of waste is uniformly generated by all the inhabitants, the per-capita waste production is approximately 1.3 kg/day. At present, the waste collection operations are performed using 560 collection sites, spread all over the city area, hosting bins of three different types. In Table 2 we report the total number of bins of each type located in the urban area, as well as the characteristics of the three available bin types.

4.2. Results

In order to test our approaches, we use, as a benchmark, the current situation in the city of Nardò. In particular, the set of potential collection sites coincides with the set of sites currently in use (i.e., $|V_2| = 560$). In particular, for each site $j \in V_2$, we consider a value of L_j which is equal to the length currently reserved for site j. Moreover, the population is grouped in 1163 centroids ($|V_1| = 1163$), and, for each $i \in V_1$, the parameter q_i is set equal to the number of inhabitants associated to i multiplied by the per-capita daily generation of waste. Finally, $K = 3$ and the characteristics of the bins are as reported in Table 2.

We first test the performance of the constructive heuristic, in terms of both the number of activated collection sites, and the number of bins allocated to them. Then, we compare the performance of the heuristic to the results obtained by means of the optimization model (1). However, given the complexity of the latter, this comparison can be made only by partitioning the service territory in a number of zones, whose extension is small enough to allow the solver to find optimal (or, at least, near-optimal) solutions within a reasonable computing time. In our case, we consider two zones, and we refer to them as A and B.

Table 3 reports the results obtained by the constructive heuristic on the whole territory of the city of Nardò in terms of activated collection sites, whereas Table 4 refers to the number of bins allocated to such sites. In order to perform an analysis on the performance of the heuristic under different conditions, different values for the per-capita daily generation of waste are considered. Moreover, for each centroid $i \in V_1$, we consider two values for the threshold distance from the closest activated site, i.e., $D_i = 140$ m,

Table 2
Bins available in the area of Nardò.

Type	Capacity (kg)	Length (m)	Number
1	72	0.62	197
2	154	1.37	180
3	480	1.88	405

Table 3
Results obtained by the constructive heuristic in the city of Nardò: activated collection sites.

Threshold distance (m)	Per-capita daily generation (kg)	Potential collection sites	Activated collection sites	Percentage reduction (%)
140	1.3	560	221	−60.5
	1.4	560	237	−57.7
	1.5	560	239	−57.3
150	1.3	560	212	−62.1
	1.4	560	224	−60.0
	1.5	560	228	−59.3

Table 4
Results obtained by the constructive heuristic in the city of Nardò: bins allocation.

Threshold distance (m)	Per-capita daily generation (kg)	Current allocation			Heuristic allocation			Average reduction (%)
		$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$	
140	1.3	197	180	405	58	36	142	−71.8
	1.4	197	180	405	63	37	152	−69.9
	1.5	197	180	405	64	38	152	−69.6
150	1.3	197	180	405	52	32	143	−73.5
	1.4	197	180	405	45	36	153	−73.1
	1.5	197	180	405	50	36	155	−72.1

Table 5
Results obtained by the optimization model in the city of Nardò: activated collection sites.

Zone	Potential collection sites	Activated collection sites	Time (s)	Optimality gap (%)
A	291	106	3600	6.6
B	269	92	3600	3.7

Table 6
Results obtained by the optimization model in the city of Nardò: bins allocation.

Zone	Current allocation			Optimal allocation			Average reduction (%)
	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$	
A	94	99	208	24	30	62	−71.5
B	103	81	197	26	19	50	−75.3

Table 7
Comparison between the optimization model and the constructive heuristic in the city of Nardò.

Zone	Activated collection sites			Bins allocated		
	Optim. model	Constr. heuristic	Gap (%)	Optim. model	Constr. heuristic	Gap (%)
A	106	116	9.4	116	124	6.9
B	92	99	7.6	95	103	8.4

and $D_i = 150$ m, which are typical distances that can be easily covered in urban areas. In addition, the tolerance parameter δ is set equal to $0.1D_i$, for each $i \in V_1$. We do not report any detail concerning the execution times, because the constructive heuristic executes nearly instantaneously on the case study we are considering.

As can be observed from the tables, the constructive heuristic is able to provide solutions which are consistently better than that currently implemented in Nardò. In particular, in terms of number of activated collection sites, the percentage reduction ranges from 57% to 62%. On the other hand, as for the number of bins allocated to the activated collection sites, the constructive heuristic utilizes a lower number of bins than those currently in use in Nardò, with reductions varying between 69% and 73%. In both cases, the best results are obtained when the threshold distance is 150 m and the per-capita daily generation of waste is 1.3 kg/day. Indeed, this behavior is not surprising, since this situation corresponds to a lower total generation of waste, and a less constrained problem, from the citizens' QoS point of view. However, no significant variations of the performance of the heuristic are observed, as the per-capita daily generation increases, or the threshold distance decreases.

We now report a comparison between the results obtained by the constructive heuristic and the optimization model (1). As explained before, this comparison is performed by partitioning the area of Nardò in two zones, A and B. Tables 5 and 6 show the number of collection sites activated by the optimization model, and the number of bins allocated to such sites, respectively, whereas Table 7 directly compares the exact and heuristic approaches, in terms of both activated collection sites, and total number of bins allocated.

In this comparison, we focus on the case in which the per-capita daily generation of waste is 1.3 kg/day, and the threshold distance is $D_i = 150$ m ($i \in V_1$). A time limit of 3600 seconds is imposed for the execution of ILOG CPLEX.

The results show that, for both zones, the solver is not able to find the optimal solution within the imposed time limit, even though the optimality gaps are quite small. In terms of activated collection sites, the constructive heuristic provides performance which can be considered as comparable to those obtained by the optimization model within the time limit. In particular, the gap ranges between 7% and 9%. Similar results can be observed with respect to the number of bins allocated to the activated collection sites. Again, the results obtained by the heuristic approach are not far from the sub-optimal solutions.

In conclusion, the experiments show that the proposed approaches are very effective, leading to consistent reductions in the number of activated collection sites and bins allocated, with respect to the solution currently implemented in the city of Nardò. These reductions can lead to consistent monetary savings in the waste collection operations (a lower number of vehicles could be used in order to perform the collection phase), as well as to a reduced environmental impact (a lower number of bins could be installed).

5. Conclusions

In this paper we have faced the problem of locating collection sites in an urban waste management system. We have proposed an optimization model which helps in deciding the sites where to locate the garbage collection bins, as well as the number and the characteristics of the bins to be positioned at the different collection sites. This model introduces constraints that, from one side, ensure the Quality of Service from the citizens' point of view, and, from the other side, allocate bins to collection sites, so to provide the least necessary capacity to fit the expected waste to be directed to the sites. Moreover, we have devised a fast and effective two-phases heuristic procedure, which is inspired from constructive heuristics for facility location. Computational results on data related to a real-life problem have shown the effectiveness of the optimization model and the constructive heuristic, in terms of both activated collection sites (reductions of up to 62%) and bins allocated (reductions of up to 73%). These reductions can result in consistent monetary savings in the waste collection operations, as well as in a reduced environmental impact. Finally, we remark that both exact and heuristic approaches can easily address periods like the days after Christmas, which are usually characterized by larger waste production, potentially leading to a risk of overflow of the bins. Indeed, in this cases, it is enough to solve again the optimization model or re-run the heuristic, considering an increased value of waste generation for the centroids.

Acknowledgements

This research was partially supported by the Ministero dell'Istruzione, dell'Università e della Ricerca Scientifica (MIUR) of Italy, and by Regione Puglia (Progetto TI@). This support is gratefully acknowledged. The authors also thank Andrea Manni for his help with requirement analysis and with programming, and two anonymous referees for their useful comments, which helped to improve the paper.

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