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An algorithm for the optimal collection of wet waste

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ABSTRACT

This work refers to the development of an approach for planning wet waste (food waste and other) collection at a metropolitan scale. Some specific modeling features distinguish this specific waste collection problem from the other ones. For instance, there may be significant differences as regards the values of the parameters (such as weight and volume) characterizing the various collection points. As it happens for classical waste collection planning, even in the case of wet waste, one has to deal with difficult combinatorial problems, where the determination of an optimal solution may require a very large computational effort, in the case of problem instances having a noticeable dimensionality. For this reason, in this work, a heuristic procedure for the optimal planning of wet waste is developed and applied to problem instances drawn from a real case study. The performances that can be obtained by applying such a procedure are evaluated by a comparison with those obtainable via a general-purpose mathematical programming software package, as well as those obtained by applying very simple decision rules commonly used in practice. The considered case study consists in an area corresponding to the historical center of the Municipality of Genoa.

1. Introduction

Waste management is one of the priority issues concerning protection of the environment and conservation of natural resources. Presently, there is an increasing attention by managers and planners, in order to follow a sustainable approach for waste management and to integrate strategies that can produce the best viable option. Different tools are used in the literature to assess the sustainability of the different policies and to optimize the overall operations both for planning and management purposes. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are viable tools to assess the various impacts of a solution (Schiavon et al., 2014), while optimization models define the strategies that minimize certain desired indicators (Minciardi et al., 2008). In literature, there are several works that go in this direction. For example, Rigamonti et al. (2016) define a simple but comprehensive indicator that evaluates both the environmental and economic performance for the whole Municipal Solid Waste (MSW). Other indicators can also be used taking into account the different pretreatment processes (Rada and Ragazzi, 2014). As regards waste collection, Teixeira et al. (2014) present the following three different indicators: the distance travelled by the collection vehicle per unit of waste collected, the time spent per unit of waste collected, and the amount of fuel consumed by the collection vehicle per unit of waste collected. Parkes et al. (2015), through the results of the LCA of 10 integrated waste management systems for 3 potential post-event site design scenarios of the London Olympic Park, show that advanced thermal treatment and incineration with energy recovery have the lowest Global Warming Potential (GWP) with respect to the cases where landfill is the primary waste treatment process.

Actually, solid waste management (SWM) is characterized by various kinds of objectives and constraints (environmental, technological, economic, legislative, social, etc. (Minciardi et al., 2008)) and requires to consider several problems (waste generation modelling (Fu et al., 2015), collection and transportation (Anghinolfi et al., 2013), treatment and disposal (Costi et al., 2004)) within an integrated framework, to find solutions that are economically and environmentally sustainable. In the last two decades, considerable research efforts have been directed toward developing economic-based optimization models for SWM flow allocation. Several mathematical programming models have been developed for MSW management planning (Minciardi et al., 2008). Waste collection and transportation is the interface between waste generators and waste treatment systems.

Current regulation at the European and National level is very sharp in terms of the necessity of increasing waste recycling (for

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example in Italy, at least 65% of waste should be recycled) in order to avoid incurring in fines, fees and penalties. Moreover, in the last years, the concept of "Smart City" is mentioned with an increasing emphasis. A "Smart City" is intended as an urban environment, which, supported by pervasive ICT systems, is able to offer advanced and innovative services to citizens in order to improve the overall quality of their life. Waste management, recycling, material and energy recovery are always included in these innovative services (Piro et al., 2014). Specifically, web-GIS oriented systems can be very useful for municipal solid waste selective collection (Rada et al., 2013).

However, many municipalities do not possess efficient waste management and recycling programs. This is because waste collection is a complex task, which involves many actors (citizens, political actors, technical personnel, etc.), technological expertise and investments (Brandstätter et al., 2014; Fiorucci et al., 2003; Lima et al., 2015). Many data are needed, and logistics management is required at a large scale. Moreover, recycling is costly and the major cost is due to the collection, as described in by Hazra and Goel (2009). However, it is essential to reutilize material of high quality, but, at the same time, to reduce the collection costs is a priority. Cost reduction must be achieved not through a reduction in the quality of the collected material, but by means of the application of methods and technologies that are able to improve the efficiency of the collection process. For example, El-Hamouz (2008) shows how a private company can reduce the collection cost of US $3.75/family/month through the improvement of logistics in the collection of municipal solid waste.

Decision frameworks that integrate planning, such as sizing of plants and collection sites, and fleet sizing (Fiorucci et al., 2003; Costi et al., 2004; Huang et al., 2005; Kanchanabhan et al., 2011; Minciardi et al., 2008; Abou Najm et al., 2002; Rada, 2013; Ragazzi and Rada, 2008) and operational management issues result in optimization problems that are in general too complex to solve. This is the reason why such issues are generally separately considered. As a matter of fact, even the optimization of collection operations in itself gives rise to quite complex problems (Anghinolfi et al., 2013; Faccio et al., 2011), that are generally intractable by means of commercially available general-purpose optimization tools for large scale applications.

However, the necessity of applying viable approaches to improve the efficiency of waste collection and material recovery has led to the development of several procedures, whose results are reported in the literature (Anghinolfi et al., 2013; El-Hamouz, 2008; Johansson, 2006).

Most of such approaches, because of the high number of variables and constraints, are based on heuristic arguments (Benjamin and Beasley, 2010, 2013; Baldacci et al., 2011; Ghiani et al., 2013; Kim et al., 2006) or metaheuristic arguments (Bing et al., 2014). In particular, Bing et al. (2014) take into account the waste density (in their case, referring to plastic collection) even though they do not make use of this information in building their algorithm.

Other authors (Alagöz and Kocasoy, 2008; Alumur and Kara, 2007) have developed approaches to deal with the collection of specific kinds of waste (health-care and hazard wastes), either on the basis of door-to-door (kerbside), or "mixed" collection (that is, both bin and door to door).

In this paper, an approach for the planning of collection of wet waste materials is presented. As a matter of fact, a peculiar modeling feature characterizes this specific collection problem and is explicitly taken into account by the developed algorithm: the difference in the values specifying the waste density at the various collection points. This requires the necessity of considering, as regards the constraints over the vehicle loads, not only the volume, but also the weight of the waste carried by the vehicle.

In order to focus on this peculiar modeling feature, the wet waste collection problem considered in this paper is stated by considering a single performance objective to be optimized. This objective is the time spent to fulfill the overall service demand, which is directly related with personnel costs. However, since the position of wet waste generation and vehicles velocity are fixed, minimizing the time spent implies also the minimization of costs for fuel consumption and emissions from vehicles. In addition, even the number and the capacity of vehicles, as well as the number and the location of the delivery points are considered as given and fixed.

The procedure developed and applied in the paper is based on a "greedy" heuristics, in which the vehicle routes are incrementally built by choosing the next node in the "most convenient way". This choice makes use of information related to node distance, weight and volume of the waste material.

Section 2 provides a formalization of the optimization model considered for the considered waste collection problem. In the third section, the proposed heuristics is described. Then, Sections 4 and 5 provide a performance analysis of the proposed method, also in connection with the application to the Municipality of Genoa. In Section 6, a possible different use of the proposed procedure is proposed, regarding the choice of the location of delivery points and depots. Finally, in Section 7, some possible future developments are highlighted and conclusions are drawn.

2. A formalization of the waste collection problem

To provide a formalization of the wet waste collection problem, one can strictly follow the classical three-index formalization of the vehicle routing problem provided in Toth and Vigo (2002). In fact, in the model considered in the present paper, the collection refers to a set of nodes, in which demand is supposed to be concentrated (and not to links in a network).

Then, assume that the set of demand nodes is a subset of the nodes of a directed graph. It is assumed that there is a unique depot (at a specific node), as well as a single delivery node, coinciding with the depot. Let V be the set including all significant nodes, i.e., demand nodes, and the unique delivery/depot node. Assume to have a priori computed the shortest distance for any couple origin–destination in V.

Then, it is possible to replace the original oriented graph with a new completely connected graph (in general, non-symmetric), in which each (fictitious) link corresponds to the shortest distance between its extremes.

The complete formalization of the problem considered in this paper requires a generalization with respect to the model introduced in Toth and Vigo (2002), that is, the presence of two capacity constraints (a maximum volume capacity, and a maximum weight).

In the following formalization, it is assumed that each *work shift* of a vehicle (beginning and ending at the depot) includes a single *operational cycle*, that is, a single delivery of the collected wet waste material at the depot. All symbols' nomenclature is reported in the Appendix A.

Then, the problem can be formalized as:

$$\min = \sum_{(i,j)\in A} c_{ij}\left(\sum_{k=1}^{K} x_{ijk}\right) + \sum_{\substack{(i,j)\in A \\ j\neq 0}}\sum_{k=1}^{K} x_{ijk} c_{loading,j} + \sum_{i\neq 0}^{N}\sum_{k=1}^{K} x_{i0k} c_{unloading} \quad (1)$$

$$\sum_{k=1}^{K} y_{ik} = 1 \quad \forall i \in V - \{0\} \quad (2)$$

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