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Modeling energy consumption in automated vacuum waste collection systems☆

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A B S T R A C T

In a world where resources are scarce and urban areas consume the vast majority of these resources, it is vital to make cities greener and more sustainable. A smart city is a city in which information and communications technology are merged with traditional infrastructures, coordinated and integrated using new digital technologies. The increasing amount of waste generated, and the collection and treatment of waste poses a major challenge to modern urban planning in general, and to smart cities in particular. To cope with this problem, automated vacuum waste collection (AVWC) uses air suction on a closed network of underground pipes to transport waste from the drop off points scattered throughout the city to a central collection point, reducing greenhouse gas emissions and the inconveniences of conventional methods (odours, noise, etc.). Since a significant part of the cost of operating AVWC systems is energy consumption, we have developed a model with the aim of applying constraint programming technology to schedule the daily emptying sequences of the drop off points in such a way that energy consumption is minimized. In this paper we describe how the problem of deciding the drop off points that should be emptied at a given time can be modeled as a constraint integer programming (CIP) problem. Moreover, we report on experiments using real data from AVWC systems installed in different cities that provide empirical evidence that CIP offers a suitable technology for reducing energy consumption in AVWC.

1. Introduction

Awareness has arisen that cities have to develop in a greener and more sustainable way, since they consume the majority of the world resources. Urban areas face both a changing urban population size and increasing sustainability issues in terms of providing good socioeconomic and environmental living conditions. Urban planning has to deal with both challenges (Gaube and Remesch, 2013).

A new city model has been proposed in the last years (Batty et al., 2012; Lazaroiu and Roscia, 2012; Hancke et al., 2012; O'Grady and O'Hare, 2012; Xiong et al., 2012), called smart city, which represents a community of average technology size, interconnected and sustainable, comfortable, attractive and secure. A smart city is a city in which information and communication technologies are merged with traditional infrastructures, coordinated and integrated using new digital technologies. Advanced systems to improve and automate processes within a city will play a leading role in smart cities. From smart design of buildings to intelligent control systems the possible improvements enabled by sensing technologies are immense. Two of the critical problems related to cities are transport and energy (Nijkamp and Kourtit, 2013). The cities consume 75% of worldwide energy production and generate 80% of CO_2 emissions.

Considering the growth of urban population, along with the increasing amount of waste generated on wealth areas, the collection and treatment of waste poses a major challenge on modern urban planning (Eurostat and European Commission, 2012). Waste generation per inhabitant has been increased for years and, according to last projections, this will continue till 2020. The environmental issues related to waste collection are believed to be related primarily to the use and combustion of diesel in vehicles, because the emission of exhaust gases from the combustion process. In a broader context environmental issues are also related to noise and odor (Larsen et al., 2009).

☆ Thematic issue on Modelling and evaluating the sustainability of smart solutions.

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Automated vacuum waste collection (AVWC) uses air suction on a closed network of underground pipes, covering an area of a few square kilometers, to transport waste from the drop off points scattered throughout the city to a central collection point, reducing greenhouse gas emissions and the inconveniences of the conventional method of waste collection (odors, noise, combustion gas emissions, etc.), as well as allowing better waste reuse and recycling. An AVWC system has a control software that includes the implementation of a method for deciding when and which inlets, corresponding to the same fraction, should be emptied during a time interval taking into account a number of constraints (e.g., full inlets should always be emptied, inlets should be emptied at least once a day, air speed, …). The use of artificial intelligence and other IT techniques can lead to more efficient energy consumption by defining smarter daily operation plans, and increasing the environmental sustainability (Hilty et al., 2006).

Optimization of conventional methods for waste collection, using trucks to pick up waste from collecting points scattered throughout the city has received considerable attention (Guariso et al., 2009). Solomon (1987) proposed a benchmark problem set with time windows for the vehicle routing problem, building a route one at a time in a serial manner. A computational study of several heuristic algorithms was conducted, and an insertion heuristic, which is known as Solomon's insertion heuristic, generates the best routing schedules in many cases. Potvin and Rousseau (1993) built routes in parallel using Solomon's heuristic to find the initial seed customers and number of vehicles. Rochat and Taillard (1995) generated multiple initial solution by a local search heuristic. Taillard et al. (1997) used a new edge exchange heuristic and tabu search to improve vehicle routing solutions. Multiple use of vehicles in which multiple routes can be served by the same vehicle were considered. Eisenstein and Iyer (1997) used a Markov decision process to model the residential waste collection problem in the city of Chicago. Tung and Pinnoi (2000) modified Solomon's insertion algorithm and applied it to a waste collection problem in Hanoi, Vietnam. Poot et al. (2002) used several non-traditional constraints of real-life vehicle routing problems, such as multiple capacity, vehicle type, region served first or last constraints. A savings-based method is proposed for the problems that have those constraints. Angelelli et al. (2002a,b) addressed the periodic vehicle routing problem with intermediate facilities, using a tabu search algorithm. Teixeira et al. (2004) also used an heuristic approach for the separate collection of three types of waste. Bautista (2008) applied ant colony optimization to solve the urban waste collection problem in a city of the metropolitan area of Barcelona; Benjamin and Beasley (2010) solved the waste collection vehicle routing problem with time windows, driver rest period and multiple disposal facilities using tabu search and variable neighborhood search; Kim et al. (2006) addressed the same problem as Benjamin and Beasley (2010) but their solution relies on extending Solomon's insertion algorithm to this new context; and Ak and Khan (2009) defined a network model for waste collection in Northern Cyprus which produced considerable cost savings.

The problem of optimizing AVWC systems to reduce energy usage has not been studied so far, despite a significant part of the cost of operating AVWC systems is energy consumption. This paper establishes a first step in this direction by formally defining AVWC systems, modeling the problem of scheduling the drop off points that should be emptied at a given time, taking into account energy consumption, as a constraint integer programming (CIP) problem (Achterberg, 2009; Achterberg et al., 2008), and solving it in real-time. Moreover, we report on experiments using real data from AVWC systems installed in different cities that provide empirical evidence that CIP offers a suitable technology for reducing energy consumption in AVWC. These results pave the way for developing an scheduler capable of producing optimal plans of the daily emptying sequences of the drop off points in such a way that energy consumption is minimized.

A Constraint programming approach has been adopted because constraint programming is a powerful technology for solving hard combinatorial problems in a diverse range of application domains, including complex real-world planning and scheduling problems; see for example (Moura et al., 2008; Lopes et al., 2010) for the application of constraint programming for solving real-world operation problems over oil pipeline networks. Its solving techniques have their roots in artificial intelligence, mathematical programming, operations research, and programming languages, and benefits from the experience of all these research communities (O'Sullivan, 2012).

The paper is structured as follows. First, AVWC systems are formally described, as well as the problem dynamics, giving expressions for the time and energy calculations that define the system operation. Then the problem is defined, scheduling the daily emptying sequences of the drop off points in such a way that energy consumption is minimized. An example of the system dynamics is provided and the CIP model is presented. Finally, an empirical investigation on real-world instances is reported, analyzing the obtained results. To conclude, we present our current ongoing work on using our CIP approach for solving the more general dynamic problem, when one has to optimize the selected operations over a full period of time. This paper is an extended version that completes the work presented in (Béjar et al., 2012a,b). In Béjar et al. (2012b), we formally define the problem of optimizing energy in AVWC systems, and in Béjar et al. (2012a), we describe the solving approach we used to solve that problem. Here, we provide a more detailed explanation of the problem and of the solving approach by clarifying the main concepts with additional examples, incorporating the topology of a real-world AVWC plant that operates in a Spanish city, showing step by step the operations performed by an AVWC plant for emptying a sequence of inlets, improving the explanation of how inlets are ordered, making publicly available a wider range of data sets, and adding a list of acronyms and symbols.

2. System description

In AVWC the pipe network has a tree shape, and the central collection point is located at the root node. This central collection point has the means to split the collected waste by fraction (organic fraction, paper, etc.), and is where waste is packed for disposal in containers that are then transported with trucks to a landfill area for recycling or Mechanical Biological Treatment. The network usually has sector valves located on some of the branch junctions that can isolate one of the branches (to reduce the volume of air that will be suctioned). The drop off points are located along the branches, and contain inlets for the different fractions. There are also air valves that act as air entry points that help produce the air flow when the suction starts. Air valves can be located next to inlets, although it is not mandatory to have an air valve in each drop off point. Fig. 1 shows a general view of an AVWC system.

An underground vacuum waste collection system is modeled as a set $\{\mathcal{T}, \mathcal{I}, \mathcal{F}, \mathcal{V}^a, \mathcal{V}^s\}$. $\mathcal{T}(\mathcal{N}, \mathcal{E})$ is a rooted binary tree with nodes ($\mathcal{N}$) representing either waste inlets ($\mathcal{I}$) or pipe junctions, and edges ($\mathcal{E}$) corresponding to union pipes between nodes. $\mathcal{F}$ represents the set of fractions waste is divided into. Typical fractions include organic refuse, paper, plastic and glass. Air valves ($\mathcal{V}^a$), located at some inlets, create air streams able to empty downstream inlets. Sector valves ($\mathcal{V}^s$) are disposed along the tree in order to segment the whole tree structure, defining isolated sectors (s), making a more efficient transport for the inlets comprised in the