The Automated Vacuum Waste Collection Optimization Problem *

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Abstract

One of the most challenging problems on modern urban planning and one of the goals to be solved for smart city design is that of urban waste disposal. Given urban population growth, and that the amount of waste generated by each of us citizens is also growing, the total amount of waste to be collected and treated is growing dramatically (EPA 2011), becoming one sensitive issue for local governments. A modern technique for waste collection that is steadily being adopted is automated vacuum waste collection. This technology uses air suction on a closed network of underground pipes to move waste from the collection points to the processing station, reducing greenhouse gas emissions as well as inconveniences to citizens (odors, noise, ...) and allowing better waste reuse and recycling. This technique is open to optimize energy consumption because moving huge amounts of waste by air impulsion requires a lot of electric power. The described problem challenge here is, precisely, that of organizing and scheduling waste collection to minimize the amount of energy per ton of collected waste in such a system via the use of Artificial Intelligence techniques. This kind of problems are an inviting opportunity to showcase the possibilities that AI for Computational Sustainability offers.

Introduction

One of the challenges in modern cities is that of how to handle the amount of waste generated by inhabitants and bussinesses in our towns. All approaches to waste management, specially with regard to collection, should balance opposite goals: should be frequent enough so waste does not accumulate too much and should not happen with too much frequency to reduce cost and impact (fuel usage, traffic distortion, noises, etc.). An approach that can easily deal with some of those handicaps is the use of underground vacuum waste systems. These are a kind of automatic urban waste collection systems that, with the use of negative air pressure induced on a pipe network, transport waste from drop off points scattered throughout the city to a central collection point, where they can be dealt with.

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How it works

An underground vacuum waste collection system (Honkio 2011; Culleré 2009) consists of a network of underground pipes deployed in an area covering, usually, a few square kilometers. This network has a tree shape, i.e. it has an unique root node, located where the central collection facility is, and has no loops. This central collection point can have the means to split or differentiate the collected waste by fraction (organic fraction, paper, etc.), and is where waste is packed for disposal, usually in containers that, with trucks, will be then transported to a landfill area for recycling or mechanical/biological treatment. The pipe network can have, and usually has some, valves located on some of the branch junctions that can isolate one of the branches (to reduce the volume of air that will be subjected to suction). The drop off points are located along the branches. On each drop off point there is, if waste is separated by fractions, at least one collecting box, or inlet, for each of the fractions involved. Air valves are also located along the pipes, acting as air entry points that help produce the air flow when the central collection system starts suction. Air valves can be located next to inlets, although it is not mandatory to have an air valve for each inlet.

System description

An underground vacuum waste collection system is modeled as a set $\{\mathcal{T}, I, \mathcal{F}, \mathcal{V}^a, \mathcal{V}^s\}$. $\mathcal{T}(\mathcal{N}, \mathcal{E})$ is a rooted tree with nodes ($\mathcal{N}$) representing either waste inlets (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. 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 corresponding sector. Sectors are subtrees of $\mathcal{T}$, always containing the root node and a subset of I (I^s).

Each inlet in I is denoted by I_i^f, meanwhile v_i^a and v_i^s denote air and sector valves respectively. The status of any valve is open (o) or closed (c). Fig. 1 is a small example of

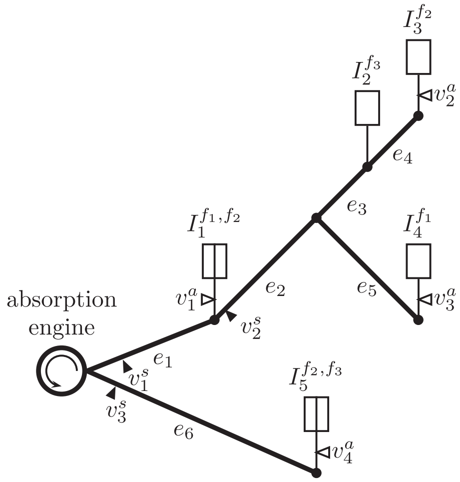

Figure 1: Schematic example of an automatic vacuum waste collection plant

the system, with 3 types of fraction, 5 inlets (two of them handling 2 types of fraction, so one can consider having 7 inlets), 4 air valves and 3 sector valves. Note that in this case, only 5 combinations of $\mathcal{V}^s$ out of the 8 possible are valid, giving 5 different sectors.[1]

Three important subtrees that will deeply impact the system dynamics arise from the topology: emptying, air and vacuum subtrees. The emptying subtree ($\mathcal{T}_i^E$) is unique for each inlet, and is defined as the path that waste must follow from inlet i to the root node. Of course, $\mathcal{T}_i^E$ must not contain closed sector valves on it. The air subtree ($\mathcal{T}_i^A$) is the path followed by the air stream in charge of waste transport along $\mathcal{T}_i^E$. Note that $\mathcal{T}_i^E \subseteq \mathcal{T}_i^A$, being equal if inlet i has an air valve, otherwise, the airflow must come from an upstream inlet. The vacuum subtree ($\mathcal{T}_s^V$) is unique for each sector and represents the total amount of air to be moved before proceeding to waste transport. Let's denote by $d(\mathcal{T})$ the total length of a tree.

As an example, let's consider inlet number 2. In this case, $d(\mathcal{T}_2^E) = d(e_1) + d(e_2) + d(e_3)$ and $d(\mathcal{T}_2^A) = d(\mathcal{T}_2^E) + d(e_4)$. Inlet 2 can be emptied by 2 sectors; $s_{2,\bar{3}}$ and $s_{2,3}$ ($v_2^s = \mathrm{o}$, $v_3^s = \mathrm{c}$ and $v_2^s = \mathrm{o}$, $v_3^s = \mathrm{o}$ respectively). For the first case, $d(\mathcal{T}_{s_{2,\bar{3}}}^V) = d(e_1) + d(e_2) + d(e_3) + d(e_4) + d(e_5)$.

When inlets are additionally indexed by time ($I_{i,t}^f$) it indicates their waste occupancy at a given time, capturing this way the stochastic behavior of users. At any time, one can define an emptying sequence ($\mathcal{E}_t^{f,s}$) as an ordered sequence of loads to be transferred from inlets corresponding to sector s and type of fraction f, subject to a maximum transfer capacity (L_{max}^f) per sequence depending on type of fraction. That is $\mathcal{E}_t^{f,s} = \{L_{i,t}^f \,|\, L_{i,t}^f \leq I_{i,t}^f, I_i^f \in I^s, \sum_{I_i^f \in I^s} L_{i,t}^f \leq L_{max}^f\}$.

[1] Following the notation (v_1^s, v_2^s, v_3^s), $\{(\mathrm{c,c,c}), (\mathrm{c,o,c})\}$ are not valid assignments and $\{(\mathrm{c,c,o}), (\mathrm{c,o,o})\}$ give the same sector configuration.

Emptying sequences can not overlap in time and can be null (nothing to do).

Dynamics of the model

As the objective will be to define optimal emptying sequences for a time interval (i.e. a day), some dynamic elements of the model must be defined. Air speed operation (Worrell and Vesilind 2012) is an important one, being crucial to determine sequences duration and, consequently, energy consumptions. For our model, we will assume that we operate at a constant air speed during an emptying sequence (v_t). Due to structural reasons, v_t has a maximum (V_M). Furthemore, each inlet is characterized by a minimum air speed operation (V_i^f) to avoid pipe obstructs.

The second element is the operation time (T_t). It is defined as the required time to operate an emptying sequence, depending on the sequence itself, the air speed of operation v_t, and the previous operation state of the system. Such a previous operation state can be: operating an emptying sequence for type of fraction f' and sector s' at speed v_{t-1} or idle ($v_{t-1} = 0$). The operation time is divided into two phases. A transitory phase (T_t^{tr}) meanwhile the previous speed (v_{t-1}) changes progressively to v_t and a stationary phase (T_t^{st}) devoted to emptying the chosen sequence. T_t^{tr} is a function of three types of parameters. First, the previous and the current operational air speed. Second, the type of fraction, because if there is a change of type of fraction among the previous and actual emptying sequences, the air speed must be dropped to a low value due to operational requirements. Otherwise, it is enough to increase or decrease the air speed from the previous value (v_{t-1}) to the actual (v_t). Third, the total amount of air to be adapted. It depends on the vacuum paths of the previous sector (s') and the current sector (s), and can be obtained as $\mathcal{T}_s^V - \mathcal{T}_s^V \cap \mathcal{T}_{s'}^V$. We can express

$$T_t^{tr} = \begin{cases} c_{1,t}^{tr} \cdot |v_t - v_{t-1}| & \\ +c_{2,t}^{tr} \cdot \left(d(\mathcal{T}_s^V) - d(\mathcal{T}_s^V \cap \mathcal{T}_{s'}^V)\right), & f = f', \\ c_{1,t}^{tr} \cdot (v_t + v_{t-1}) & \\ +c_{2,t}^{tr} \cdot \left(d(\mathcal{T}_s^V) - d(\mathcal{T}_s^V \cap \mathcal{T}_{s'}^V)\right), & f \neq f', \end{cases}$$

where $c_{1,t}^{tr}$ and $c_{2,t}^{tr}$ are constants for a given system, as detailed in the following section.

Once the transitory phase ends and the new air speed is reached, the stationary operation can be started in order to proceed with the emptying sequence. An emptying sequence consists of two operations that iterate over the ordered sequence of inlets; first, to empty a inlet over the transport pipes, and second, to proceed to waste transport. The transport of waste and the empty phase of the next inlet can overlap in time, if and only if the inlet to be emptied is upstream the estimated position of the waste being transported. Under these assumptions, we can obtain

$$T_t^{st} = \sum_{\substack{L_{i,t}^f \in \mathcal{E}_t^{f,s} \\ L_{j,t}^f = \mathrm{next}(L_{i,t}^f)}} T_t^{st}(i,j),$$

$$T_t^{st}(i,j) = c_{1,t}^{st} \cdot L_{i,t}^f + \frac{d(\mathcal{T}_i^E) - d(\mathcal{T}_i^E \cap \mathcal{T}_j^E)}{v_t},$$

where next() is the following element in the ordered sequence $\mathcal{E}_t^{f,s}$. And next() of the last element in the sequence is the root node. Note that if I_j^f is upstream I_i^f, then

$$d(\mathcal{T}_i^E) - d(\mathcal{T}_i^E \cap \mathcal{T}_j^E) = 0,$$

meaning that once emptied I_i^f, we can proceed to empty I_j^f.

The last element that defines our model dynamics is energy. Energy is closely related to the operation time, and can also be splitted into two parts; transitory and stationary. It is easy to understand that, for the transitory case, there is only energy consumption for the process of increasing air speed but not for decreasing it. That being so, we can write

$$E_t^{tr} = \begin{cases} c_{1,e}^{tr} \cdot |v_t - v_{t-1}|^+ \\ +c_{2,e}^{tr} \cdot \left(d(\mathcal{T}_s^V) - d(\mathcal{T}_s^V \cap \mathcal{T}_{s'}^V) \right), & f = f', \\ c_{1,e}^{tr} \cdot v_t \\ +c_{2,e}^{tr} \cdot \left(d(\mathcal{T}_s^V) - d(\mathcal{T}_s^V \cap \mathcal{T}_{s'}^V) \right), & f \neq f', \end{cases}$$

where

$$|x|^+ = \begin{cases} 0 & x < 0, \\ x & x \geq 0. \end{cases}$$

For the stationary part of the energy, the air path plays an important role. For the same emptying path, the minimum transport energy is obtained when the shortest air path is employed, that is, opening the upstream air valve closest to the inlet being emptied. The type of fraction also affects the power requirements, needing more energy those type of fraction more dense. Under these considerations, we assume that during the stationary phase, power comsumption is a linear function of the air path, $c_{1,e}^{st}(r) + c_{2,e}^{st}(r) \cdot d(\mathcal{T}_i^A)$, with coefficients depending on the type of fraction. Stationary energy results,

$$E_t^{st} = \sum_{\substack{L_i^f \in \mathcal{E}_t^{f,s} \\ L_j^f = \text{next}(L_i^f)}} \left(c_{1,e}^{st}(f) + c_{2,e}^{st}(f) \cdot d(\mathcal{T}_i^A) \right) \cdot T_t^{st}(i,j).$$

Problem description

The objective of the problem is to find a set of emptying sequences and air speed operations, $\{\mathcal{E}_t^{f,s}\} \times \{v_t\}, 0 \leq t \leq T$, for an operative period of time T (e.g. a day), that minimizes the energy cost, $\sum_{t=0}^{T} f_c(t) \cdot (E_t^{tr} + E_t^{st})$, subject to the following constraints:

- $\underline{I_{i,0}^f}, \forall I_i^f \in I$. Constant giving the initial inlet loads.
- $I_{i,t}^f = I_{i,t-1}^f + d_{i,t-1}^f - L_{i,t-1}^f, \forall I_i^f \in I, 0 < t \leq T$. Inlets volume update. Random process $d_{i,t}^f$ denotes user waste disposal into I_i^f during slot time t.
- $I_{i,T}^f \leq \underline{\varepsilon_i^f}, \forall I_i^f \in I$. Inlets residual load.
- $I_{i,t-1}^f > \underline{\text{th}_i^f} \Rightarrow I_{i,t}^f \leq \underline{\text{th}_i^f}, \forall I_i^f \in I, 0 < t \leq T$. Inlets over load threshold must be included $\mathcal{E}_t^{f,s}$.
- $\mathcal{E}_t^{f,s} = \{L_{i,t}^f |, 0 < t \leq T \, L_{i,t}^f \leq I_{i,t}^f, I_i^f \in I^s, \sum_{I_i^f \in I^s} L_{i,t}^f \leq \underline{L_{max}^f}\}, 0 \leq t \leq T$. Emptying sequence maximum load per inlet and maximum transfer load.
- $\max_{I_i^f \in I^s}(\underline{V_i^f}) \leq v_t \leq \underline{V_M}, 0 < t \leq T$. Range of operational air speed.

The problem is described by three types of files. A first set of files `topology.xml` is used to encode the network topology of the problem (i.e. edges, valves, inlet location, etc.) as well as to provide initial inlet load and inlet specific parameters and constants.

A second set of files (`parameters.xml`) details the constants of the dynamics model ($c_{1,t}^{tr}, \cdots$), as well as the energy cost ($f_c(t)$) depending on time and according to the energy fares. The energy cost function is expressed as lookup table in terms of price per energy unit depending on date/time. This set of files also contains the constant values defined in the above constraints (constants appear underlined), such as initial inlet values, residual loads, ..., when specified as defaults for all the system or by fraction (in case of being constants specific for each inlet they are provided in the topology).

Finally, a third set of files describes the stochastic component of the system, that is, the way that the users dispose waste into the inlets, during a period of time (usually several weeks). Files `data.xml` describe the process of disposal volumes, it can give either a list of real world disposals ($d_{i,t}^f$) or a parameterized random function for arrival times and waste amount for any inlet.

Available datasets

All files are available to download on the web at http://ia.udl.cat/newmatica/ with detailed descriptions of XML file formats and contact information with authors in case more data or clarifications on data is needed. This website will be regularly updated with more files, specially real world dump data logged from existing systems, and references to implementations and uses.

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