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A Location-Routing Approach to Optimal Sludge Management

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The general theory of location-routing optimisation, a class of locational analysis that considers vehicle routing issues, has been applied in the last decade to a large number of problems. Traditionally optimal wastewater and sludge management has been limited to the determination of the shortest path between sources and disposal facilities, which can be attained through the solution of a typical travelling salesman problem. The aim of this paper is to generalise this approach through the introduction of further issues: the convenience of a centralised treatment facility to reduce the sludge to a dry mass after preliminary onsite dewatering, the influence of different costs and/or prices on the optimisation task if the sludge is deposited in sanitary landfills (or disposed of in other ways) or is partially used as a fuel in suitable industrial processes, the modification of the shortest path approach into a full vehicle routing problem by assigning weights to the links between nodes of the network not necessarily equal to their distances.

1. Introduction

The steadily increasing volume of wastewater effluents, both from urban agglomerations and industrial sites, poses serious environmental, economic and even social problems. Indeed, growing industrialisation and urbanisation are responsible for the rapidly increasing production of wastewater sludge worldwide and this trend is expected to continue in the future (Hossain et al., 2008). In particular, the implementation of Urban Waste Water Treatment (UWWT) Directive 91/271/EC (CEC, 1991) forced European countries to improve their wastewater collecting and treatment systems so determining a significant increase of annual sewage sludge production, from 6.5 Mt dry solids (DS) in 1992 to 10 Mt DS in 2005 (Kelessidis et al., 2012). For the future, it is reasonable to predict an amount of sludge exceeding 13 Mt DS up to 2020 (Milieu Ltd., WRc and RPA, 2010).The traditional approach to wastewater management is to reclaim water (mostly for agricultural use) and to dispose of the residual sludge by sending and burying it in landfills. The exhaustion of cheap waste landfills (generally close to the sites where the sludge is generated) and the frequent opposition of local communities to the siting of nearby waste treatment facilities and to the opening of new landfills, as well as safety concerns associated with waste movement (Fabiano et al., 2010) will require a careful planning and consideration of alternative solutions. On the other hand the exhaustion of landfills despite the introduction of advanced technologies, such as bioreactor landfill or heat recovery strategies (Solisio et al., 2012) is progressing very rapidly, which makes an overall optimisation strategy for sludge disposal a matter of urgent priority for environmental engineers, city and industrial plant managers, as well as for decision-makers. One of the most promising alternative strategies for the disposal of sludge is its transformation into industrial fuel, such as fuel briquettes for boilers and kilns in large plants. In particular, incineration of sewage sludge in cement factories is becoming a more and more interesting issue worldwide. Besides contributing to the solution of problems faced by municipalities in the disposal of dewatered or dried sewage sludge, cement factories can utilise the sludge directly to an extent of about 5-6 % of the clinker production capacity of the cement plant (Käänteeet al., 2004). Recently the use of hydrocarbon-contaminated sludge from soil washing processes has also been considered (Vaccari et al., 2012). A further option is the recovery of metals from sludge and ashes, which may contribute considerably to the overall economics of the disposal process, even if it must be considered that concentrations of heavy metals in sewage sludge may vary widely, depending on the sludge origins (Fytili et al., 2008), which will require an accurate monitoring and analysis of both fluid and suspended solid

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phases (Reverberi et al., 2011). These options introduce further degrees of freedom in the optimisation task in addition to the traditional minimisation of the costs of transportation from the sources of sludge generation to the final disposal sites, which can be tackled using the Travelling Salesman Problem (TSP) approach, such as the Lin-Kernighan heuristic algorithm (Larson, 1988). A further generalisation is the introduction of weights to the links between nodes of the network not necessarily equal to their distances. Indeed, as the distances between origin and destination of sludge are bound to increase as a consequence of the use of centralised treatment plants and more distant disposal facilities, different costs (weights) are to be assigned to different routes, depending on such factors as traffic density, proximity to population centres, road conditions, altimetry and planimetry of routes, road tolls. Thus, the continuous improvement in treatment and utilisation of sludge, as well as the more and more stringent regulations in their handling, have given rise to a complex scenario, in which each stakeholder involved tries to optimise his own activity to maximise profit and/or minimise costs.

2. The mathematical model

We consider three main stakeholders, who will be conventionally called sludge maker, sludge mover and sludge taker. Their interactions can be regarded as a three-party game in which each of the participants tries to optimise his own activity with the sole limitation of finding a sludge mover (or sludge taker) who accepts his conditions for volumes and prices, the rules of the game being set by provisions of law. The final equilibrium scenario is therefore the one determined by a set of conditions accepted by all stakeholders in the „sludge maker – sludge mover – sludge taker“ supply chain. This is typically a Pareto efficient situation resulting from multiobjective trade-off optimisation. To set up a mathematical model capable of realistically simulating this complex system, let us suppose we have *m* sludge makers in a pre-defined area. The definition of an area is largely arbitrary, its contour being possibly determined by geographical, administrative or general political considerations. The above mentioned European „Urban Waste Water Treatment“ Directive (91/271/EEC) requiring communities with more than 2,000 inhabitants to develop its own sludge disposal strategy implies that *m* is a comparatively large number.

Let us suppose further that each of them is located at the site with coordinates $\{x_i, y_i \mid i = 1,...,m\}$ and produces the amount of sludge $\{M_i \mid i = 1,...,m\}$.

Each sludge maker *i* has the following options:

1) Use a sewage network to convey the resulting sludge to another (likely larger) sludge maker *h* for further processing - strategy s_{ih}
2) Process the sludge to reduce the amount of water through a dewatering process and have it collected by a sludge collection service (the sludge mover) – strategy w_i
3) Reduce the amount of water and dry the final content before getting it collected– strategy d_i

No mixed strategy for each single stakeholder is considered due to uneconomic consequences.

If the network is already in place, the strategy s_{ih} is supposed to be dominant with respect to the alternatives w_i and d_i.

Conveying the sludge produced to another sludge maker is equivalent to a lower number of sources with an increased amount of sludge to dispose of for some of them. For complex networks this reduction can be carried out by considering the square matrix *Z* whose elements z_{ih} and z_{hi} are equal to 1 and –1 respectively if the sludge is moved from the source *i* to the source *h* and zero otherwise. Clearly the matrix is antisymmetric. The reduced number of sources and their increased sludge load can be evaluated iteratively as follows:

a) consider the rows that have only one non zero element equal to –1 , say z_{uv}
b) change M_v to $M^*_v = M_v + M_u$
c) cancel u-th column and u-th row
d) repeat a)-c) until the remaining rows contain only zero elements
e) the indexes of the residual rows are the sources to be considered, their loads resulting from the iteration of step b)

If the network infrastructure is to be designed and implemented, its economic convenience can be evaluated through a what-if analysis after the systems with and without the additional infrastructure have been optimised. In both cases the variables s_{ih} need not be considered in the preliminary optimisation analysis.

Let $\Psi = \{w_i, d_i \mid w_i + d_i = 1; \quad d_i \cdot w_i = 0 \mid i = 1,...,m\}$ be the decision space corresponding to the two options and $I = \{x_i^*, y_i^* \mid i = 1,...,m^*\} \otimes \{M_i^* \mid i = 1,...,m^*\}$ the reduced set of sludge makers.

Similarly, each sludge taker *k* located at $\left\{X_k, Y_k \middle| k = 1,...,t\right\}$ is supposed to use (or to dispose of) the amount T_k either as thickened sludge or as dry sludge. Let $K = \left\{X_k, Y_k \middle| k = 1,...,t\right\} \otimes \left\{T_k \middle| k = 1,...,t\right\}$ be the corresponding space and $\Phi = \left\{\omega_k, \delta_k \middle| \omega_k + \delta_k = 1;\ \omega_k \cdot \delta_k = 0 \,|\, k = 1,...,t\right\}$ its decision space. Furthermore there exists a subset $K' \subset K$ such that $K' = \left\{X_k, Y_k \middle| k = 1,...,t'\right\} \otimes \left\{T_{k'} \middle| T_{k'} \le T_{k'}^{\max}, k' = 1,...,t'\right\}$. In other words there is a limit on the capacity of a number of sludge takers.

To each element $(w_i, d_i, \omega_k, \delta_k) \in \Psi \otimes \Phi$ there corresponds a set of (negative or positive) prices $(p_i^{(1)}, p_i^{(2)}, \pi_k^1, \pi_k^2)$.

Typically (π_k^1, π_k^2) are related to well-defined real (positive) prices for using the sludge as a fuel or as real cost (negative prices) for disposing of it, whereas $(p_i^{(1)}, p_i^{(2)})$ can be regarded as (negative) shadow prices necessary to satisfy the general financial equilibrium constraint. In other words sludge makers must comply with the necessity of having their sludges collected at whatever price results from market conditions. The prices (π_k^1, π_k^2) are strictly connected with the best technology that the sludge taker can apply and with the legislation he has to comply with. Therefore they are well determined for traditional disposal strategies, such as landfills (where the prices are obviously negative) and for well established technologies, such as the burning of sludge in cement kilns. Estimated prices are to be used for other innovative applications. Additionally we should consider the sludge mover connecting sludge production with sludge consumption/disposal. The sludge mover can satisfy the overall balance by connecting each $i \in I$ with some $k \in K$ directly or by connecting part of the nodes to intermediate storage facilities where some of the dewatered sludge can be processed to dry sludge. Furthermore the sludge can be further treated for the recovery of heavy metals, which can favour the overall economics by reducing the environmental costs and by providing valuable commodities. However, the volumes of sludge to be transported to the sites of sludge takers are not sensibly affected by these recovery processes.

For both types of sludge the existing transport network has to be used. Each facility is an element of the set $J = \left\{\xi_j, \eta_j, r_j \mid j = 1,...,g\right\}$, where $\left\{\xi_j, \eta_j\right\}$ are the coordinates of the facility *j* (which are to be determined as a result of the optimisation procedure) and r_j is the amount of dewatered sludge that is dried at the facility site. The coordinates are supposed to belong to a set of predetermined candidate sitings that satisfy all economic and environmental constraints, such as accessible location in the road network or minimum distance from population centres. The sludge mover‘s costs are:

a) Transport cost for connecting production nodes with consumption/disposal nodes and/or facilities sites. As mentioned in the introduction, costs can‘t be assumed to depend only on the distances travelled. Other factors such as traffic density, proximity to population centres, road conditions, altimetry and planimetry of routes and road tolls can have a considerable impact on overall costs. and consequently weights other than simple distances are to be assigned to the links of the network. However, once the costs have been estimated, they can be regarded as generalised distances, which makes it possible to use well established algorithms for the determination of the shortest path. For all values of the previously defined variables (production/consumption/facilities locations and volumes) there exists a set of possible routes which satisfy the balance condition: $\Gamma = \left\{\gamma_c \mid c = 1,...,n\right\}$. Using the concept of generalised distances, the minimum cost route $\bar{\gamma} \in \Gamma$ can be determined solving an equivalent routing-allocation problem for both dewatered and dried sludge $\bar{\gamma} = \left\{\bar{\gamma}_w, \bar{\gamma}_d \in \Gamma\right\}$.
b) Annualised costs of the facilities equipment P_j. In addition to drying equipment, plants for the recovery/removal of metals should be considered (Finocchio et al., 2010).
c) Amount of metals recovered. The actual value of metals recovered Q_i is likely to fluctuate considerably, due to the changing composition of sludge. However, average annual values can be reliably estimated from available time series.

Supposing a perfectly competitive market for sludge movers can be assumed (the market conditions referred to before in this section), the income of the sludge mover must be equal to his costs.

Furthermore, while in theory the variables $(p_i^{(1)}, p_i^{(2)})$ are independent variables which should be submitted to an optimisation procedure, their values are likely to be unilaterally specified by sludge movers as functions of $\left\{x_i, y_i, \xi_j, \eta_j\right\}$. In particular it will be assumed that $p_i^{(1)} = p^{(1)} f_1\left(x_i, y_i, \xi_j, \eta_j\right), p_i^{(2)} = p^{(2)} f_2\left(x_i, y_i, \xi_j, \eta_j\right)$. It will be further supposed that there exists a relation between $p^{(1)}$ and $p^{(2)}$, but the two symbols will be kept separate for clarity.

Thus, the optimisation criterion can be expressed as a strategy for the selection of a set of elements of $\Psi \otimes \Phi \otimes \left\{T_k \left| k = 1,...,t\right.\right\} \otimes J$ that give rise to Pareto-optimal situations for each stakeholder $\in$ *I* and *K* with respect to their overall costs. In particular each sludge maker has the option of drying or dewatering only the sludge produced, but must accept the price charged by the sludge mover, the sludge taker can choose both amount and type of sludge at the independently set price and the sludge mover can choose the location of any treatment facility and the price charged to sludge makers, but has to deliver all the sludge produced by sludge makers to sludge takers.

Pareto optimal in this instance means that once a solution has been identified, no stakeholder $i \in I$ or $k \in K$ can be better off by changing its decisional or financial options $\left\{w_i, d_i\right\}$ *or* $\left\{\omega_k, \delta_k\right\} \otimes \left\{T_k \left| k = 1,...,t\right.\right\}$ without damaging the financial situation of at least another stakeholder. There is generally a large number of such solutions which constitute together a Pareto front. While the overall optimal solution does belong to the Pareto front, additional criteria must be introduced for the selection of the most convenient of them. This issue will be discussed in the next section, along with suitable algorithms to deal with it.

The overall model can now be cast into mathematical form as follows:

$$M_i^*(w_i p_i^{(1)} + d_i p_i^{(2)}) = \max$$

$$T_k(\omega_k \pi_k^1 + \delta_k \pi_k^2) = \min$$

(1)

subject to the constraints

$$\sum_i M_i^* = \sum_k T_k \qquad (2)$$

$$\sum_i M_i^* w_i = \sum_k T_k \omega_k - \sum_j r_j \qquad (3)$$

$$r_j \geq 0 \quad \forall j \qquad (4)$$

$$w_i \cdot d_i = 0; \quad w_i + d_i = 1 \quad \forall i \qquad (5)$$

$$\omega_k \cdot \delta_k = 0; \quad \omega_k + \delta_k = 1 \quad \forall k \qquad (6)$$

$$C(\xi_j, \eta_j, P_j, Q_j, r_j \mid \gamma = \bar{\gamma}) = \left[\sum_k T_k(\omega_k \pi_k^1 + \delta_k \pi_k^2)\right] - \left[\sum_i M_i^*(w_i p_i^{(1)} + d_i p_i^{(2)})\right] \qquad (7)$$

$$T_k \leq T_k^{\max} \quad k \in K' \qquad (8)$$

3. The optimisation algorithm

The presence of different optimisation criteria gives rise to a typical multiobjective problem, which generally provides multiple solutions. An additional strategy for the selection of the most suitable solution (sometimes referred to as superoptimal) is required to establish a tradeoff between conflicting objectives, which implies specifying a preference order. Two different approaches can be applied to establish the relative importance of each objective and obtain a unique solution: either suitable weights are introduced before the optimisation problem is solved (which actually means combining the various objective functions into a single scalar objective function) or a set of Pareto optimal solutions (constituting a suitable approximation to a Pareto front) are evaluated. In the latter case a solution is selected a posteriori based on additional criteria. In both cases an additional actor is required either for setting the weights or for selecting the final solution from the Pareto front set. This is the task of a regulatory agency, which can attain this result through taxes, subsidies and command and control regulation or a combination of them.

The goal of this paper is confined to the interactions of the three main stakeholders and consequently the analysis is limited to the evaluation of the Pareto front of the multiobjective optimisation problem (1)-(8).

The resulting optimisation task is a non linear, mixed-integer non-convex minimisation problem subject to non-linear equality and inequality constraints. It belongs to a class of problems generally referred to as location-routing problems. It can be thought of as a set of problems within location theory (Nagy and Salhi, 2007). As a consequence, algorithms are frequently trimmed to meet the special characteristics of each single problem. Since this class of problems is NP-hard, heuristic and meta-heuristic methods (ie iterative improvements of candidate solutions using derivative-free methods) are generally used. Additionally the overall optimisation is frequently cast into a hierarchical structure of suboptimisation problems in which the independent variables of the outer problem are kept unchanged (Jacobsen and Madsen, 1980).

Various heuristic methods are suggested for obtaining satisfactory (possibly suboptimal) solutions (Min et al.,2005). Among them evolutionary algorithms, simulated annealing, artificial neural networks.

The particular algorithm employed in this application follows this general pattern. Only one intermediate treatment facility has been considered in this work. Generalisations to additional facilities will be considered in future works. Consequently the subscript *j* has been dropped in the sequel. The overall problem of optimal sludge management defined by the multiobjective optimisation (1) subject to the conditions (2)-(8) is split into two hierarchical suboptimisations. The outer optimisation task is carried out with respect to the set of variables $\left\{w_i, d_i, \omega_k, \delta_k, \xi, \eta\right\}$ which are kept fixed in the inner optimisation, which establishes the optimal route taking into account the constraints of the problem. In other words for each amount of sludge produced and for every selected location of the treatment facility a traditional travelling salesman problem (with weighted route distances) is solved. This makes it possible to verify if the set of variables $\left\{w_i, d_i, \omega_k, \delta_k, \xi, \eta\right\}$ belongs to the Pareto front. This set of variables is then modified in the outer optimisation loop until the Pareto front is complete. A simplified flow chart of the overall optimisation can be represented as follows:

1. Assign starting values to a set of values of $\left\{w_i^{(\lambda)}, d_i^{(\lambda)}, \omega_k^{(\lambda)}, \delta_k^{(\lambda)}, \xi^{(\lambda)}, \eta^{(\lambda)}\right\}_{\lambda=1,..,\Lambda}$. They must be chosen so that constraints (4)-(5)-(6) are satisfied. The number of tentative solutions Λ is related to the algorithm used and to the update formula used at 7.
2. Evaluate $r_1, P_1, Q_1, f_1\left(x_i, y_i, \xi_j, \eta_j\right), f_2\left(x_i, y_i, \xi_j, \eta_j\right)$.
3. Find minimum cost route $\bar{\gamma} = \left\{\bar{\gamma}_w, \bar{\gamma}_d \in \Gamma\right\}$ and optimise with respect to T_k, solving a routing-allocation problem subject to constraints (2)-(3)-(8) keeping $\left\{w_i^{(\lambda)}, d_i^{(\lambda)}, \omega_k^{(\lambda)}, \delta_k^{(\lambda)}, \xi^{(\lambda)}, \eta^{(\lambda)}\right\}_{\lambda=1,..,\Lambda}$ fixed.
4. Evaluate $p^{(1)}, p^{(2)}$ and $p_i^{(1)} = p^{(1)} f_1\left(x_i, y_i, \xi_j, \eta_j\right), p_i^{(2)} = p^{(2)} f_2\left(x_i, y_i, \xi_j, \eta_j\right)$ from Equ. (7)
5. Calculate distance of solution from Pareto front.
6. If some solutions are not Pareto dominated, add them to the Pareto front. If the Pareto front is satisfactory, stop.
7. Update set of candidate solutions and return to 2.

A genetic algorithm is particularly suited for structure and objectives of the outer optimisation (Steps 1.-2.-5.-6.-7.). Indeed, the typical „chromosome“ structure required by genetic algorithms can be easily implemented using a string whose elements are either 0 or 1 for the variables $\left\{w_i, d_i, \omega_k, \delta_k\right\}$ and a sequential number for the identification of the variables $\left\{\xi, \eta\right\}$. Similarly, the updating rules (crossover, reproduction and mutation) used by genetic algorithms in routing and allocation problems are well established (Hosage and Goodchild, 1986). Furthermore, genetic algorithms are particularly well suited when it comes to the identification of a Pareto front because the population of solutions can be made to spread out along the Pareto front through suitable adjustments of the crossover rule (Horn et al., 1994).

The inner optimisation task can be solved using a branch-and-bound mixed integer algorithm, if the number of sludge takers is limited, typically less than 20 (which is often the case), or again using a metaheuristic algorithm if their number is higher (Wang, 2010).

4. Conclusions

We have presented a general framework for the optimisation of sludge management based on the development of a Pareto tradeoff surface, which can serve as a guidance for regulatory agencies in the adoption of measures and rules (such as taxes, subsidies or regulations) aimed at favouring a solution on the Pareto frontier that best meets social and environmental concerns. Furthermore, the model developed makes it possible to analyse the influence of several economic and operational parameters on the overall performance of the optimal sludge management. Sensitivity analysis can identify suitable modifications of the management structure corresponding to changes of exhogenous parameters (such as prices and costs of commodities) and provide a convenient tool for the revision of optimal strategies of regulatory agencies,

References

Council of the European Communities, 1991. Council Directive of 21 May 1991 concerning urban waste water treatment (91/271/EEC), Official Journal of the European Communities, L135, 40-52

Fabiano, B., Curro', F., Reverberi, A.P., Pastorino, R. , 2010. Port safety and the container revolution: A statistical study on human factor and occupational accidents, Safety Science, 48, 980-990.

Finocchio, E., Lodi, A., Solisio, C., Converti, 2010. A. Chromium removal by methylated biomass of Spirulina platensis:the effect of methylation process, Chemical Engineering Journal, 156, 264–269.

Fytili D., Zabaniotou A., 2008, Utilization of sewage sludge in EU application of old and new methods—A review, Renewable and Sustainable Energy Reviews, 12, 116–140.

Horn, J., Nafpliotis, N., Goldberg, D.E., 1994. A niched Pareto genetic algorithm for multiobjective optimization, Proceedings of the 1° IEEE Conf. Evolutionary Computation, Orlando, FL, USA, 27-29 June 1994, IEEE Press:Washington, USA, 1, 82- 87.

Hosage C.M., Goodchild M.F., 1986. Discrete space location-allocation solutions from genetic algorithms, Annals of Operations Research, 6 (1-4), 35-46.

Hossain, M.K., Vladimir, S., Nelson, P. F., 2009. Thermal characterisation of the products of wastewater sludge pyrolysis. Journal of Analytical and Applied Pyrolysis, 85, 442–446.

Jacobsen S.K., Madsen O.B.G., 1980. A comparative study of heuristics for a two-level routing-location problem, European Journal of Operational Research, 5, 378–387.

Kääntee, U., Zevenhoven, R., Backman, R., Hupa, M., 2004. Cement manufacturing using alternative fuels and the advantages of process modeling, Fuel Process Technol, 85, 293–301.

Kelessidis A., Stasinakis A.S., 2012. Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries, Waste Management, 32(6), 1186–1195.

Larson, R.C., 1988. Transporting sludge to the 106-mile site: An inventory/routing model for fleet sizing and logistics system design, Transportation Science, 22, 186-198.

Milieu Ltd., WRc and Risk & Policy Analysts Ltd (RPA), 2010. Environmental, economic and social impacts of the use of sewage sludge on land. Final Report, Part III: Project Interim Reports, DG ENV.G.4/ETU/2008/0076r, Bruxelles, Belgium.

Min H., Jayaraman V., Srivastava R., 1998. Combined location-routing: a synthesis and future research directions, European Journal of Operational Research, 108, 1–15.

Nagy G., Salhi S., 2007. Location-routing: Issues, models and methods, European Journal of Operational Research, 177(2), 649-672.

Reverberi A.P., Cerrato C., Dovì V.G, 2011.. Reconciliation of Flow Rate Measurements in the Presence of Solid Particles, Industrial & Engineering Chemistry Research, 50, 5248-5252.

Solisio C., Reverberi A.P., Del Borghi A., Dovì V.G., 2012. Inverse Estimation of Temperature Profiles in Landfills Using Heat Recovery Fluids Measurements, Journal of Applied Mathematics, doi:10.1155/2012/747410. <www.hindawi.com/journals/jam/2012/747410>, Accessed 24/05/2013.

Vaccari M., Collivignarelli M., Canato M., 2012, Reuse of Hydrocarbon-Contaminated Sludge from Soil Washing Process: Issues and Perspectives, Chemical Engineering Transactions, 28, 169-174, doi: 10.3303/CET1228029.

Wang X., 2010. An integrated multi-depot location-inventory-routing problem for logistics distribution system planning of a chain enterprise, Proceedings of Intern. Conference on Logistics Systems and Intelligent Management, Harbin, China, 9-10 January 2010, IEEE Press: Washington, USA, 3, 1427-1431.