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ORIGINAL PAPER

Exact and heuristic approaches for the locational planning of an integrated solid waste management system

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Abstract The management of solid waste has received increased public attention over the last few years as a result of industrialization and its effect on the natural and social environment. The location of proper facilities for treating waste is a sensitive issue that has often caused political and social tension. We study the problem of simultaneous design of a distribution network with central treatment facilities, transfer stations and sanitary landfills, and the coordination of waste flows within this network. In order to determine the number, sizes and locations of the solid waste management (SWM) facilities we propose a MIP formulation of the problem. We present a series of valid inequalities for improving the formulation and discuss their effectiveness. We also present an interchange heuristic that enables us to solve large problems efficiently. Finally, we apply these concepts in an action research project for the development of a SWM system for a specific region in Greece.

Keywords Facility location · Strategic planning ·
Municipal solid waste management

1 Introduction

In recent years many European countries have increasingly focused their attention on developing policies at national level for waste reduction and for finding alternatives to landfilling which was the traditional means of waste disposal. European legislation recommends the development of local integrated management plans, which give

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priority to prevention, waste reduction and recovery, and allow using landfilling only for the disposal of refuse that cannot be recovered. The responsibility is currently on local authorities to implement strategies to effectively deal with their waste in a sustainable, cost-effective, self-sufficient and environmentally acceptable manner. However, there are several technical and economic aspects concerning the management of municipal solid wastes. In order to take decisions that consider all such issues, it is necessary to accurately model the system, analyzing material recovery versus disposal, and representing the solid waste flows, as well as their cost and environmental impact. Furthermore, the development of a complete model of municipal solid waste management (SWM) requires a wide knowledge and a deep analysis of the possible treatment processes of the materials composing the refuse. Additionally, the various possible kinds of plants and processes for treatment of solid waste have also to be considered. In this framework, the use of analytical models can provide the managerial tools that will assist decision makers and other stakeholders involved in the planning process in order to gain the necessary understanding and to identify the consequences of their decisions.

The objective of this paper is to introduce an integrated solution process that will assist planners by assessing the performance of the SWM system under alternative scenarios and will, thus, enable them to reach better decisions.

The rest of the paper is organized as follows. In Sect. 2, we present the statement of the problem and provide a brief review of the relevant literature. In Sect. 3 we introduce a mixed integer programming (MIP) formulation of the problem. In Sect. 4 this formulation is strengthened with a series of valid inequalities. In the same section, we also provide a heuristic algorithm and then demonstrate its effectiveness through computational results on a large scale application as well as a series of randomly generated test problems. In Sect. 5 we illustrate this modeling approach with a realistic application concerning the Prefecture of Achaia in Greece and in Sect. 6 we specify and analyze the results. Finally, we draw some conclusions and identify possible future research directions.

2 Problem statement

Most European countries, including Greece, have explicit waste minimization policies or strategies. European legislation is one of the key drivers behind the National Waste Strategy. The European Union directive establishes national targets for quantifying waste flows, stabilizing waste production and implementing integrated waste policies.

In this context it is necessary to examine how these policies can be practically applied in the development of local integrated management plans. It is also necessary to evaluate ways of achieving an environmentally sustainable, economically viable and socially acceptable waste management. The concept of the waste hierarchy has been developed over the last two decades (DoE 1995). The waste hierarchy provides a framework within which waste-management options are prioritised. This approach is intended to encourage waste management to move through the hierarchy of options on the basis of the best practicable environmental option and best available techniques not entailing excessive costs. The choice of waste management options within the waste hierarchy for a particular waste stream takes into account both the environmental and economic costs and benefits of different options. When properly interpreted, it provides a range of opportunities for the effective management of wastes.

The overall effort of planners and decision makers is to ensure that the waste management system developed is in accordance with the best practicable environmental option and conforms to the principles of sustainable development and integrated waste management, and makes the maximum possible contribution towards reducing society's environmental impact at an acceptable cost.

Regional planning deals with the efficient placement of land use activities, infrastructure and settlement growth across a significantly larger area of land than an individual city or town. In regional planning, we assume cooperation between municipalities and locate waste facilities to serve the entire region. These systems require central treatment facilities and transfer stations in which the solid wastes will be transferred by the collection vehicles to long haul tracts to reduce the increased transportation costs (US EPA 2002). An integrated regional approach to the solid waste facility location problem can produce lower system-wide transportation, investment, and operating costs than a piecemeal, to "one-project-at-a-time" solution. For the simultaneous design of a distribution network with intermediate facilities of transfer stations or treatment plants that constitute the first level process and waste disposal units as the final destination of the solid wastes, several modelling applications have been proposed by Antunes (1999), Eiselt (2007), Gottinger (1988). While the main issues of concern of these models were generally related to total cost, other approaches did take into account social equity issues and environmental aspects related to the siting of facilities by performing multi-objective analysis. However, most of these approaches also use similar cost oriented objectives (Adamides et al. 2008; Antunes et al. 2008; Erkut et al. 2008). Another important issue in SWM systems is the dynamic character of the problem. This is due to the fact that collection tonnages tend to increase over time which implies that some landfills need to be closed since their capacity has been used up. The closure of landfills may affect not only the required number of transfer stations, which may increase, but their actual locations as well (ReVelle 2000). Dynamic facility location models for developing a SWM system have been explicitly studied by Melachrinoudis et al. (1995) and more recently by Mitropoulos et al. (2008).

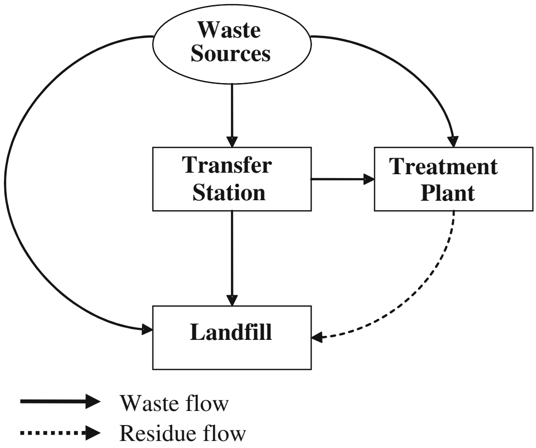
All the studies mentioned above used exact methods to solve the problem. However, the problem of developing an integrated SWM system can easily grow in terms of size and complexity in realistic instances involving many population centres, several types of treatment facilities, different types of waste, etc. Although the problem is strategic in nature, decision makers need to be able to obtain good solutions in reasonable computation time in order to assess alternative scenarios concerning the generation of waste, the configuration of the underlying transportation network or the availability of candidate sites for treatment facilities. As a result, a limited number of heuristic approaches have also been proposed. Bloemhof-Ruwaard et al. (1996) present two alternative mixed integer linear models for the waste flow transportation in a network with plants and disposal units and solve the location problem via upper and lower bounds procedures. Barros et al. (1998) provide a model for a recycling network with regional depots and treatment facilities and solve it with linear relaxation and heuristics. In addition heuristics developed for general large scale two-level or multi-level location problems can also be adopted within the SWM framework. Typical examples of such approaches, which are fairly limited in number, include the heuristics presented by Aardal (1998), Galvao et al. (2002), Narula and Ogbu (1979).

In this study we present a methodology for developing an integrated SWM system at the regional level. Our approach identifies the system units needed along with the sites where these units will be constructed in order to minimize the overall SWM cost. We determine also if a treatment facility is a feasible waste management alternative and how it will affect the coordination of waste flows within the system network. In most cases, the antagonistic targets of cost minimisation, reduction of environmental effects and high convenience for the users cannot be fulfilled by one scenario. More likely is a constellation in which high costs are linked with high environmental standards and high convenience, whereas low-cost scenarios turn out to be less environmental favourable or less convenient. In this conflict resolution the economic feasibility directly affects the project's viability. However, the social reality may significantly change the SWM plans. Therefore, even if all the treatment alternatives examined in our study are suitable under the strict regulations and environmental standards, the best practicable option may vary according to the individual waste streams and the local circumstances. Consequently the different characteristics of the facilities force us to examine not only the optimal economic configuration for the system units but also to compare several alternatives. The least cost configurations obtained from the location–allocation model are then assessed on the basis of additional criteria (social, environmental) so that planners may finally determine the choice to be implemented.

Another important factor that affects the planning of a SWM system is the interdependence of the waste processing plants with the corresponding landfills. The treatment of municipal wastes reduces the waste streams for final disposal thus extending the life cycle of the existing landfills and reducing the need to create new landfills that will replace the depleted ones. Hence in our study we consider the landfilling cost to be directly proportional to each site's capacity. More specifically, we determine the disposal cost per ton of waste at a particular sanitary landfill by taking into account all types of relevant costs at that landfill (standard operation and maintenance cost, post closure restoration and control cost, new sanitary landfill development cost, etc).

The proposed system that considers all the above factors, can be represented by a network (Fig. 1) were the waste generated at the sources can proceed either directly to treatment plants or through transfer stations. Similarly, sanitary landfills collect uncompacted waste directly arriving from sources, processed waste arriving from treatment plants or compacted waste through transfer stations. It must be emphasized at this point that such a network includes only sanitary landfills,

Fig. 1 Flow diagram of the proposed SWM system



namely landfills that satisfy all the environmental, geological, hygienic or other conditions imposed by the relevant regulations.

In order to develop the SWM system we introduce a MIP model that simultaneously locates all the system units (i.e. treatment plants, transfer stations and sanitary landfills) and selects the appropriate technology for each unit. The objective of this model is to select the best configuration from the different treatment technologies and the potential sites for the system units in order to minimize the total cost of the entire MSW management system.

3 Model formulation

Based on the requirements of the proposed framework, the MIP location allocation model that we develop is as follows.

3.1 Notation of the model

Index sets:

J set of collection centers ($j = 1,\ldots, J$);
K set of sites for the location of transfer stations ($k = 1,\ldots, K$);
L set of sites for the sanitary landfills ($l = 1,\ldots, L$);
F set of sites for the treatment plants ($f = 1,\ldots, F$);
G set of available technologies for the treatment plants ($g = 1,\ldots, G$);

Decision variables:

w_{jk} quantity (tons) of waste generated at center j and carried to a transfer station located at site k;
u_{jl} quantity (tons) of waste generated at center j and carried to a sanitary landfill located at site l;

x_{kl} quantity (tons) of waste sent from a transfer station located at site k and carried to a sanitary landfill located at site l;
v_{jf}^{g} quantity (tons) of waste generated at center j and carried to a treatment plant of type g located at site f;
n_{kf}^{g} quantity (tons) of waste sent from a transfer station located at site k and carried to a treatment plant of type g located at site f;
m_{fl}^{g} quantity (tons) of waste sent from a treatment plant of type g located at site f and carried to a sanitary landfill located at site l;
$y_k = 1$ if a transfer station is located at site k otherwise $y_k = 0$;
$z_l = 1$ if a sanitary landfill is located at site l otherwise $z_l = 0$;
$r_f^g = 1$ if a treatment plant of type g is located at site f otherwise $r_f^g = 0$;

Parameters:

a_g waste reduction factor for the treatment plant of type g;
c_u transport costs for collection vehicles;
c_c transport costs for trucks;
c_l variable cost of the sanitary landfill l represented per ton transported to l;
c_k fixed cost of transfer station;
c_f^g fixed cost of the treatment plant of type g site f;
p maximum number of sanitary landfills;
d_{jk} distance between center j and site k;
d_{jl} distance between center j and site l;
d_{kl} distance between site k and site l;
d_{jf} distance between center j and site f;
d_{kf} distance between site k and site f;
d_{fl} distance between site f and site l;
q_j quantity of waste generated at center j;
b_l quantity of waste disposed at sanitary landfill j;
$S_{k\max}$ maximum capacity of a transfer station at site k;
$S_{f\max}^{g}$ maximum capacity of a treatment plants of type g at site f;
$S_{l\min/\max}$ minimum/maximum capacity of a sanitary landfill at site l;

Model (M1)

$$\begin{aligned}\min C = {} & \sum_{j\in J}\sum_{k\in K} c_u \cdot d_{jk} \cdot w_{jk} + \sum_{j\in J}\sum_{f\in F}\sum_{g\in G} c_u \cdot d_{jf} \cdot v_{jf}^{g} + \sum_{j\in J}\sum_{l\in L} c_u \cdot d_{jl} \cdot u_{jl} \\ & + \sum_{k\in J}\sum_{f\in F}\sum_{g\in G} c_c \cdot d_{kf} \cdot n_{kf}^{g} + \sum_{f\in F}\sum_{g\in G}\sum_{l\in L} c_c \cdot d_{fl} \cdot m_{fl}^{g} + \sum_{k\in K}\sum_{l\in L} c_c \cdot d_{kl} \cdot x_{kl} \\ & + \sum_{k\in K} c_k \cdot y_k + \sum_{f\in F}\sum_{g\in G} c_f^g \cdot r_f^g + \sum_{l\in L} c_l \cdot b_l \end{aligned} \tag{1}$$

subject to

$$\sum_{l\in L} z_l \le p \tag{2}$$

$$\sum_{k\in K} w_{jk} + \sum_{f\in F}\sum_{g\in G} v_{jf}^{g} + \sum_{l\in L} u_{jl} = q_j, \ \forall j \in J \tag{3}$$

$$\sum_{j\in J} w_{jk} = \sum_{l\in L} x_{kl} + \sum_{f\in F}\sum_{g\in G} n_{kf}^{g}, \ \forall k \in K \tag{4}$$

$$\sum_{l\in L} m_{fl}^{g} = \alpha_g\left(\sum_{j\in J} v_{jf}^{g} + \sum_{k\in K} n_{kf}^{g}\right), \ \forall f \in F, \ \forall g \in G \tag{5}$$

$$\sum_{j\in J} u_{jl} + \sum_{k\in K} x_{kl} + \sum_{f\in F}\sum_{g\in G} m_{fl}^{g} = b_l, \ \forall l \in L \tag{6}$$

$$b_l \geq S_{l\,\min} \cdot z_l, \ \forall l \in L \tag{7}$$

$$b_l \leq S_{l\,\max} \cdot z_l, \ \forall l \in L \tag{8}$$

$$\sum_{j\in J} w_{jk} \leq S_{k\,\max} \cdot y_k, \ \forall k \in K \tag{9}$$

$$\sum_{j\in J} v_{jf}^{g} + \sum_{k\in K} n_{kf}^{g} \leq S_{f\,\max}^{g} \cdot r_f^{g}, \ \forall f \in F, \ \forall g \in G \tag{10}$$

$$y_k, \ z_l, \ r_f^{g} \in \{0, 1\}, \ \forall k \in K, \ l \in L, \ f \in F, \ g \in G \tag{11}$$

$$w_{jk}, \ u_{jl}, \ x_{kl}, \ v_{jl}^{g}, \ m_{fl}^{g}, \ n_{kf}^{g} \geq 0, \ \forall j \in J, \ k \in K, \ l \in L, \ f \in F, \ g \in G \tag{12}$$

The objective function expresses the minimization of the total cost (C) of the SWM system. The first six terms are the variable transportation costs of the waste flows transported to the system facilities. The next two terms concern the fixed operation and maintenance costs of the central treatment facilities and transfer stations whenever located to the system. The treatment facilities costs also include the savings from material recovery and energy production from the waste treatment process (generation of electricity, compost, etc). The last term in the objective function is the landfilling cost that is variable and directly proportional to the waste processed on site.

The first group of constraints (2) determines the maximum number of sanitary landfills allowed to be placed in the region in question. The second group of constraints specifies the balance maintenance of the waste flows. Firstly, the waste from population center at j can be shipped, either to a sanitary landfill at site l, to the transfer station at site k or to treatment plant of type g that is located at site f [constraints (3)]. Secondly, constraint set (4) ensures that the waste flow shipped into the transfer stations is equal to the waste flow transported from them. The last set of these constraints (5) implies that the process taking place at the treatment plants may cause a weight reduction that depends on the facility type. Therefore the amount of the waste flow removed from the treatment plants of type g is equal to a fraction $\alpha_g \in$ [0, 1] of the waste shipped to the treatment plant. The intermediate variable b_l appearing in (1) and (7, 8) is determined in constraints (6) as the total amount of waste disposed in sanitary landfill l. Constraints (7) impose minimum capacity limitations for a cost effective landfill operation. On the other hand, constraints (8) impose maximum capacity limitations to the sanitary landfills under the local and European Union regulations. Similarly, constraints (9, 10) ensure that the quantity of waste transported to each transfer station and treatment plant, respectively, does not exceed its capacity. Finally, constraints (11) and (12) deal with the nature of the variables.

This mixed-integer optimization model is a straightforward formulation of a multi-level network design problem. It combines elements of a hierarchical facility location model and a capacitated facility location model with transhipments. Within hierarchical systems, one typically has to determine the locations of their interacting facilities within a multiple layer configuration (Sahin and Sural 2007). Our particular multi-level system consists of three different levels of facilities: transfer stations (level 1 facilities), treatment plants (level 2 facilities) and landfills (level 3 facilities). Moreover, according to the classification scheme proposed by Narula (1986), the facility hierarchy in the solid waste system is successfully exclusive (a level m facility offers only type m services).

Using the five position scheme of Hamacher and Nickel (1998), our model may be classified as: #,#,#/D/cap/•/Σ. The symbols in position 1 denote the number and type of facilities. In our case we have three types of facilities with no restriction on their number. The symbol in position 2 describes that the location typology is Discrete and the symbol in position 3 describes that there are capacity restrictions. Finally, the symbol in position 4 describes that there are no relations between new and existing facilities and the symbol Σ in position 5 describes the sum objective function.

4 Computational study

Even though the location of waste treatment facilities is a strategic decision making problem, its complexity is often prohibitive for solving large scale instances directly. Additionally, in order to examine alternative scenarios during the decision making process, planners need to obtain good solutions to the problem quickly. Therefore an increased effort has been made in the study of this problem in order to improve the computational performance of the MIP model. In order to solve larger instances of the problem, a set of valid inequalities are employed and a heuristic procedure is also developed.

4.1 Valid inequalities

As the above formulation concerns a capacitated facility location problem, a whole family of valid inequalities can be derived based on the capacity constraints in order to achieve a sharper formulation. In general this practice is very effective as it reduces considerably the computational effort for the problem. Valid inequalities have been mostly used to tighten the linear programming relaxation of the MIP models. However, when searching for the optimal solution, these inequalities may reduce the branches in the standard branch and bound codes providing as well a significant reduction on the CPU time. The valid inequalities considered in our study are based on the ones for the capacitated distribution and waste disposal problem by Bloemhof-Ruwaard et al. (1996) and the two level network for recycling sand by Barros et al. (1998).

A set of valid inequalities for model (M1) is given below:

$$w_{jk} \leq \min\{q_j, S_{k\max}\} \cdot y_k, \ \forall j \in J, \ k \in K \tag{13}$$

$$u_{jl} \leq \min\{q_j, S_{l\max}\} \cdot z_l, \ \forall j \in J, \ l \in L \tag{14}$$

$$x_{kl} \leq \min\{S_{k\max}, S_{l\max}\} \cdot z_l, \ \forall k \in K, \ l \in L \tag{15}$$

$$v_{jf}^g \leq \min\{q_j, S_{f\max}^g\} \cdot r_f^g, \ \forall j \in J, \ f \in F, \ g \in G \tag{16}$$

$$n_{kf}^g \leq \min\{S_{k\max}, \ S_{f\max}^g\} \cdot r_f^g, \ \forall k \in K, \ f \in F, \ g \in G \tag{17}$$

$$m_{fl}^g \leq \min\{S_{f\max}^g, S_{l\max}\} \cdot z_l, \ \forall f \in F, \ g \in G, \ l \in L \tag{18}$$

More specifically, inequalities (13), (14) and (16) ensure that total flow between population center j and a given facility (i.e. sanitary landfill, transfer station and treatment plant respectively) can never exceed the minimum of customer j's demand and the capacity of this facility. Similarly inequalities (15), (17) and (18) ensure that the flow leaving a given facility cannot exceed either the maximum capacity of this facility or the capacity of the destination.

Each of the above inequalities reduces computation time significantly. However, including them all in the formulation implies excessive memory requirements and renders the solution of realistic problems impossible. Which combination of inequalities is most effective largely depends on the nature of the problem. For instance, inequalities (16), (17) and (18) concern treatment plants. If the configuration of the network and the waste flows are such that treatment plants are not established, these inequalities have little or no effect in computation time. On the other hand, if treatment plants are located these inequalities are very effective.

4.2 Solving the problem heuristically

In larger instances of the problem, with more than 50 candidate locations for each type of facility, computation times tend to increase dramatically even after the introduction of the valid inequalities mentioned earlier. Consequently, heuristic techniques are necessary in order to experiment with different values of the parameters and to produce alternative network configurations in reasonable computation time. On the heuristic side, we modified a heuristic described in ReVelle (2000) for a two level network with transfer stations and disposal sites. This is a heuristic that optimizes each level separately with a cycling procedure between the two levels. However, to the best of our knowledge there are no reports for the quality as well as the computational efforts required for this heuristic. In our case this heuristic is modified as follows:

Step 1: Select at random an initial set of p open sanitary landfills. Initialize minimum total cost ($C_{\min} = +\infty$).

Step 2: With the set of p landfills pre-specified as open, solve model (M1) and determine the temporary optimal set of intermediate facilities (i.e. transfer stations, treatment plants).
Step 3: With the intermediate facilities opened (as per the previous step), solve model (M1) and determine the temporary optimal set of landfills.
Step 4: If $C < C_{\min}$ then update minimum cost (set $C_{\min} = C$) and return to Step 2. Otherwise, stop.

More simply, the process terminates when no improvement is achieved in Steps 2 and 3.

The final solution provided by this heuristic depends on the initial choice of landfills in Step 1. Hence, in this process multiple starting points should be used in order to identify good final solutions. Furthermore, experimenting with multiple starting points is also useful from a purely practical point of view. In this way planners may examine the robustness of the solutions in terms of the intermediate facilities i.e. transfer stations and treatment plants, according to the potential changes in the location of the landfills. In general, transfer stations and treatment plants can be regarded as permanent facilities as opposed to sanitary landfills which have a known life cycle that ranges from 10 to 30 years. Therefore, it is important to identify candidate sites where transfer stations and treatment plants are located in multiple iterations of the algorithm, each based on a different initial solution.

4.3 Computational results

In order to determine the relative effectiveness of our solution methods, 15 test problems[1] were generated in networks with 50 population centers and 50 candidate sites for each type of the facilities to be located (i.e. transfer stations, treatment plants and landfills). We generated these problems considering the values of costs and capacities that were relevant in the realistic application of the design of the municipal waste management system in western Greece. The five technologies for the treatment plants that are described in the next section were randomly assigned over the candidate sites. The distances between sites were randomly generated in the range of 1–200 km. The daily waste production of each of the population centers was also randomly generated in the range of 1–30 tons. Given the costs and capacities that are relevant, the model would result in an excessive number of landfills since they appear to be the cheapest option. This is certainly not desirable, since the main point of our analysis is to keep the number of landfills at a minimum and revert to more environmentally friendly options. Hence, the allowable number of landfills varied between 2 and 4.

The starting points for the initial location for the landfill sites were generated randomly whereas the algorithm was applied five times in every problem. The MIP problems were solved using Premium solver with XPRESS solver engine (Version

[1] Test problems are available from the authors upon request.

7.1). All experiments were performed on a Pentium IV processor with 2.6 GHz and 1 GB RAM memory, running the Windows XP operation system.

To validate the heuristic we define ΔZ as the percentage gap between the heuristic solutions and the best available solutions for each test problem (%gap = ((solution value-best available solution)/(best available solution)) $\times$ 100). Similarly, $\Delta Z^{\max}$ ($\Delta Z^{\min}$) indicates the worst (best) case behavior for the algorithm and $\sigma^2(\Delta Z)$ represents the variance of the obtained solutions. We also define CPU-VI to be the time to optimality using the best combination of valid inequalities described above. In the same way, $\overline{CPU}$ is the average CPU time over all iterations of the algorithm in the same set, $\text{CPU}^{\min}$ ($\text{CPU}^{\max}$) is the minimum (maximum) CPU time, and σ^2(CPU) is the variance in CPU time. Table 1 presents a brief summary of the fifteen test problems and computational results.

The first observation is that the original formulation, without the valid inequalities, cannot handle the problem with 50 population centres. After the introduction of the valid inequalities, the problem can be solved to optimality in moderate computation time. In some cases, this computation time exceeds 3 h which is somewhat inconvenient in practical applications. On the other hand, the heuristic is much faster and produces solutions in reasonable time that on average does not exceed 9 min. As far as the quality of the solution is concerned, although the heuristic is very simple, it returns solutions which in most cases are within 2–3% of the optimum. Hence, it may be used by decision makers to produce satisfactory solutions and assess alternative scenarios regarding the structure of the problem.

Table 1 Summary of the computational results

Problem		Optimal solutions (CPU-time in seconds)		Heuristic solutions							
				CPU-time in seconds				Quality of the solutions			
p	No	CPU	CPU-VI	$\overline{\text{CPU}}$	$\text{CPU}^{\max}$	$\text{CPU}^{\min}$	σ^2(CPU)	ΔZ	$\Delta Z^{\max}$	$\Delta Z^{\min}$	$\sigma^2(\Delta Z)$
2	1	–[a]	3,415	493	580	374	6,144	3.14	5.53	0.53	5.84
	2	–	2,992	372	487	260	6,656	4.73	9.47	2.39	16.37
	3	–	12,092	500	735	344	6,382	2.61	4.81	0.00	3.49
	4	–	1,609	411	550	320	9,896	5.10	8.25	2.41	4.92
	5	–	839	376	495	283	22,375	2.62	3.53	0.00	2.17
3	1	–	3,158	525	607	465	2,971	2.39	4.05	0.00	2.35
	2	–	1,882	433	515	336	4,384	2.57	5.52	0.64	3.84
	3	–	2,278	525	710	403	15,783	4.45	7.15	1.22	8.50
	4	–	2,879	357	524	158	25,890	2.62	5.33	0.00	6.99
	5	–	2,647	484	697	272	33,184	6.50	17.40	1.42	39.59
4	1	–	4,436	487	707	333	20,706	3.89	6.19	1.27	5.50
	2	–	4,376	462	627	312	13,656	3.36	4.74	0.79	2.52
	3	–	2,913	346	361	333	110	4.84	5.66	3.32	1.02
	4	–	2,224	339	390	294	1,454	2.73	4.83	0.00	6.27
	5	–	3,901	388	517	312	7,426	4.35	7.54	1.58	6.26

[a] Solver was terminated after 12 h as optimal solution not obtained

5 Application in Achaia Prefecture

Waste management in Achaia is facing a period of rapid and radical change. Driven by European legislation, the need for improved environmental protection and public expectation, local authorities must find ways of reducing the current dependence on landfills and moving towards more sustainable methods of managing waste and resources. The Prefecture of Achaia (Fig. 2) is a region of 3,721 km^2 and it is located in the western part of Greece. The total estimated population of the prefecture is around 339,000 inhabitants and generates more than 360 tons of municipal solid wastes per day. These estimates were based on data of the latest Census (2001) for the population and also on an estimated seasonal population that visits Achaia in the summer season. Achaia is divided in 23 municipalities with the capital city of Patras being the major population center (171,000). In our study we include a total of 228 population centers, with Egio (22,000 inhabitants) being the second largest and Dersinou the smallest community (28 inhabitants). Furthermore, it must be emphasized that the distribution of the population of Achaia is highly inhomogeneous. Although the population is rather stable over the past 20 years, there are shifts from rural central areas to urban coastal areas. More than 80% of the population is assembled in urban and semi-urban centres in the coastal area of north Achaia.

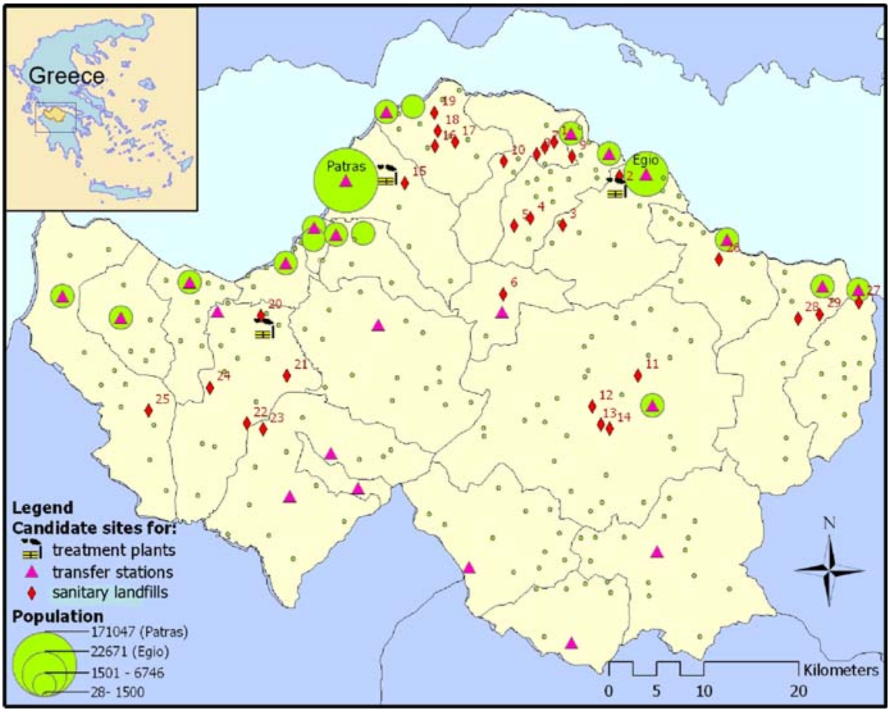


Fig. 2 Prefecture of Achaia

Future plans for waste management should be based on sound understanding of waste sources, quantities and composition, and existing transport and management infrastructure. However, there was only one organized sanitary landfill site that served the city of Patras and its suburban areas processing 53% percent of the total waste generated in the whole region. Moreover, the present SWM system does not include other treatment facilities or transfer stations. The other communities use non-monitored and non-staffed open air dump sites, which imply huge risks for releasing pollutants and causing fires especially in the summer season. The existence of these illegal dumps is a particular problem for the Greek authorities if we consider that in 2005, more than 2,200 illegal dump sites operated for waste disposal in the whole of the country. According to European Union instructions these sites have to be closed down by 2008. Due to the fact that the unique landfill is approaching the end of its life-cycle, the process for finding new locations should start without any further delay. In this situation, planners and decision makers need to consider a methodology for obtaining a holistic solution to the problem.

The treatment method that was adopted in the initial plans of the planning authorities was the operation of sanitary landfills along with a network of transfer stations that will be constructed in order to reduce the transportation costs. However preliminary studies in the region show a reluctance to create new sanitary landfills due to the opposition that is raised when some of the proposed sites become known. Further details about SWM in Achaia and the first stages of the decision process can be found in Adamides et al. (2008). At the same time the costs associated with sanitary landfills have rapidly increased during the last few years due to decreasing availability of land. Therefore rather than relying solely on sanitary landfills for waste disposal, it has become necessary to adopt other kinds of processing methods that in the first place seem rather expensive. In practice the treatment of solid waste is mainly done to reduce the volume that is transferred to the sanitary landfills. Consequently the incorporation of treatment plants into the system considerably affects the lifetime of the landfills and hence the time when new landfills have to be constructed. Therefore the local administrators are eventually forced to examine more systematically options that reduce this dependency on sanitary landfills through the increase of the proportion of waste managed using alternative treatment methods.

Our research is based on a preliminary study (technical report) that was completed by the prefecture administrators in order to determine the treatment technologies that are suitable for the SWM system. The effort in that study was to propose complete units for the central treatment of solid wastes. Although some of the alternatives may require multiple processes, all of these processes must be included in the same unit. It is also recognized in that study that the best practices will adopt the "waste to energy" principle and the use of recycling materials (Haley 1990). Five options are proposed for consideration determining also the cost and capacities for each unit (Table 2). The cost figures shown in Table 2 were estimated following the guidelines suggested by Li et al. (2008) and the results of a detailed study commissioned by the Prefecture of Achaia (2003) concerning the management of solid wastes in the area. Therefore, the figures of the potential treatment plants relative to the size, technologies and technical characteristics have already

Table 2 Technological alternatives of the SWM system in Achaia

	Technological alternative	Waste reduction (%)	Energy-material production	Cost (€/ton)
0	Landfilling	–	–	35
1	Anaerobic digestion	60	11 GW and compost	53
2	Aerobic digestion	68.3	37 GW and material recovery	120
3	Biological drying	39.4	Material recovery	64
4	Biological drying with energy utilization	75	44 GW and material recovery	73
5	Mass-burn	84	63 GW	88

Alternatives 1–5 are in respect to the total processing wastes of 150,000 ton/year

been fixed, so that all parameters in the cost function can be assumed as known. Finally, costs for waste collection and transportation were estimated based on existing conditions in the residential sector.

6 Implementation and results

Due to the different nature of SWM system facilities (i.e. treatment plants, transfer stations and sanitary landfills) the candidate sites for each facility type were obtained through different approaches.

Landfill siting should take into account a wide range of territorial and legal issues in order to reduce negative impacts on the environment. In this study several important factors and criteria were considered in order to arrive at this initial sitting decision including the pre-existing land use, location of sensitive sites, soil conditions and topography, climatological conditions, surface water hydrology, geological and hydrogeological conditions, local environmental conditions (Frantzis 1993, Kungolos et al. 2006, Tchobanoglous et al. 1993). Under the above considerations and restrictions for developing sanitary landfills, a GIS-based constraint mapping technique was employed for the entire study area (Siddiqui et al. 1996, Sumathi et al. 2008). Subsequently, 29 potential sites within the Achaia region were identified as candidates for sanitary landfill development on the basis of the selected criteria. Most of them are former dumpsites satisfying the exclusionary criteria for environmentally and geologically safe operation.

In the case of the treatment plants, which are considered as heavy industrial facilities, access to required utilities provided the selection of three candidate sites according to European Union regulations (European Union 2000). Specifically the two locations for potential plants considered in the industrial zones of the region, nearby Egio and 20 km southwest from Patras respectively, whereas the third location was in the greater area of the current landfill.

Finally, the candidate sites for transfer stations were also obtained through a different process. Transfer stations are usually located within city limits since their undesirable effects are less severe than the effects of treatment facilities (US EPA

2002). In the existing 228 population centers, 25 sites were considered as candidates for the location of transfer stations. These alternative sites are mainly the largest cities/towns through the prefecture.

In order to determine the physical distances for the waste flow shipments within the SWM network, we used geographic information systems (GIS). With a GIS software we determined the real distances in kilometres of the shortest path along the existing road network, between every population center and each candidate site. The proposed MIP model has 17.336 variables, 69 of which are zero-one variables. More specifically these figures result from having 228 Population centers, 29 candidate sites for landfill location, 25 candidate sites for transfer stations and 3 sites for possible treatment plants that will adopt one of the five options considered. Model (M1) could not be solved within reasonable computation time on a Pentium IV machine with 2.6 GHz and 1 GB RAM with Premium solver and XPRESS solver engine (Version 7.1) software. With the use of valid inequalities (14–18) the problem was solved to exact optimality in 206–464 s computational time for each run.

In Table 3, the results obtained for each alternative technology are shown. We also examine the effects on the SWM system of the maximum number of landfills allowed to be located in the region in question. The results of our analysis indicate that in the cases where up to three landfills were allowed ($p \leq 3$), the introduction of a treatment plant keeps the number of landfills required down to two. More simply, as shown in Table 3, the solution for $p \leq 3$ is identical to the solution for $p \leq 2$.

Obviously, the optimal annual cost obtained with three landfills and no treatment plants, is lower than the annual costs obtained with two and one landfill as the transportation costs considerably grow. In general, reducing p increases the total cost of the system. On the other hand reducing the maximum number of landfills from two to one implies that more waste will be processed at the treatment plants and consequently less waste will be deposited at the landfills. Consequently, the difference in cost between landfilling and the other available technologies declines when treatment plants are in operation until eventually some of the alternative waste management technologies become equally cost effective as landfills with the added benefit of being more sustainable and more environmentally friendly (see Fig. 3).

As the analysis concerns the treatment technology that will be adapted into the system, type-1 plant seems as the economical solution, in contrast to type-2 plant

Table 3 Total annual cost (€) of SWM system

Technological alternative	Number of sanitary landfills allowed (p)		
	1	2	3
Type 1	16,359,536	15,067,359	–
Type 2	25,767,385	24,709,666	–
Type 3	19,613,194	17,725,224	–
Type 4	18,155,120	17,302,712	–
Type 5	19,682,138	19,091,534	–
Landfilling	16,362,103	13,759,068	12,326,992

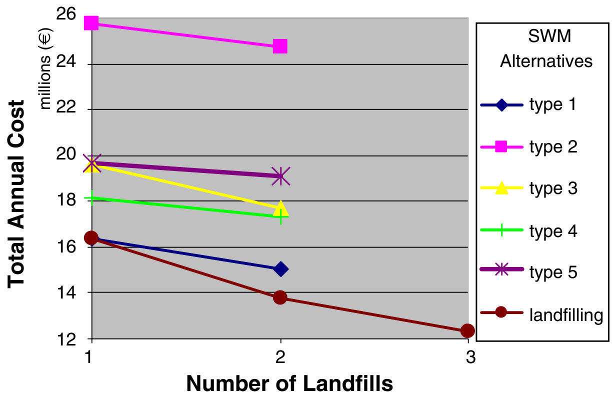


Fig. 3 Distribution of solutions

that is the most expensive SWM alternative to be implemented. For the other three technologies, if we assume that the system will operate with two landfills, then type-5 alternative has higher total cost compared with the almost similar costs of type-3 and 4 technologies. On the other hand, with only one plant in operation, type-3 technology implies a larger increase in cost than type-4 technology. As a result, the system cost is now comparable to the cost when type-5 technology is adopted. In our results, the relevant site selected for the placement of the treatment plants does not vary in any of the alternatives. The proposed location is in the area of the current landfill that actually is the closest site to the main waste generator in the region, the city of Patras. Moreover the landfills locations are not affected by the alternative types of treatment plants. Therefore our solutions indicate site number-2 when one landfill is allowed, plus site number-20 when more landfills may be located (see Map 1 and Map 2, in Fig. 4, respectively). Additionally in all of the above cases there is no need for transfer stations.

Much different results are observed in cases without treatment plants. If the SWM administrators choose to construct three sanitary landfills, our solutions indicate the sites number-2, 15 and 20 for their locations (Fig. 4, Map 3). Moreover if the decision is to develop of two landfills then the sites number-2 and 20 are the most economical locations along with a transfer station that will serve the city of Patras (Fig. 4, Map 4). Finally the solution with one landfill indicates the site number 15 and one transfer station in Egio (Fig. 4, Map 5).

7 Conclusions

In this study, a MIP model has been developed and applied to the planning of an integrated regional SWM system. Cost effective development of these systems requires comprehensive planning in order to account for the various system facility interactions. In particular we emphasize on the decreasing availability of landfill sites and the corresponding increasing development costs of these sites over time.

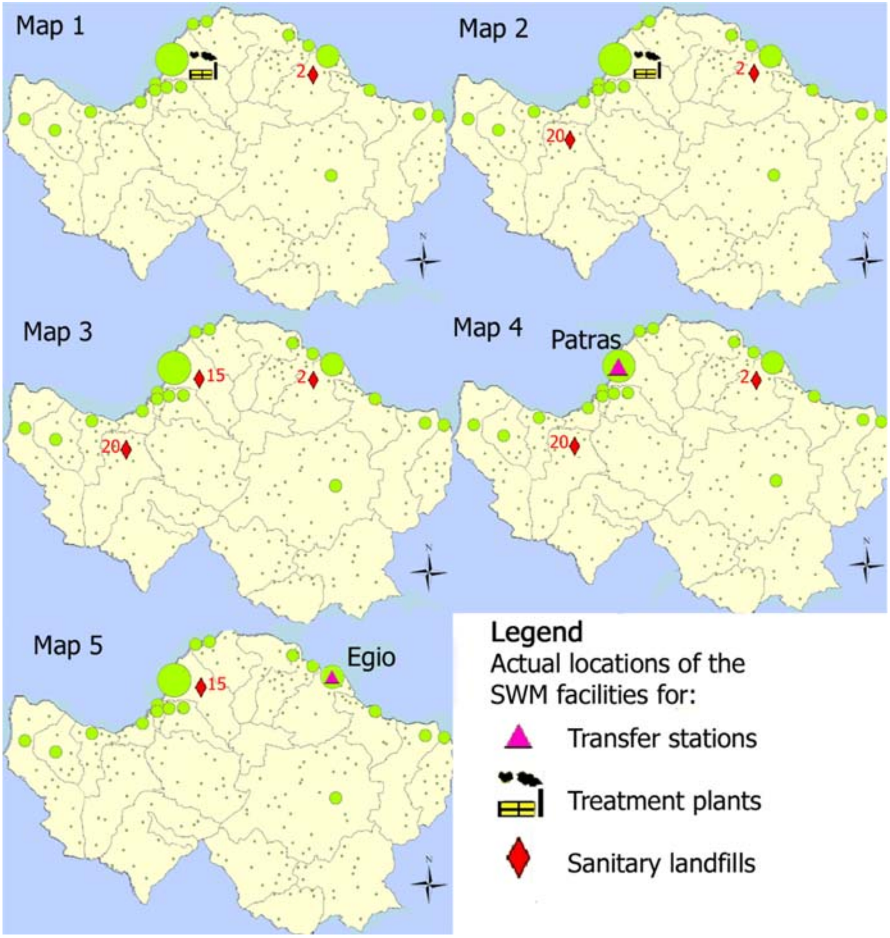


Fig. 4 Actual locations of SWM facilities in Achaia indicated by the alternative scenarios

One of the main problems in the decision making process for developing an integrated SWM system is the choice between: (a) a treatment technology with relatively high cost that reduces considerably the solid waste stream for disposal and the resultant landfilling costs and (b) a technology with no treatment process, where the total stream of wastes is disposed of in landfills with a consequent increase in landfilling costs. Our model takes into account in the best possible way the trade offs between these two options. In contrast to the majority of the models in the literature that consider fixed costs for the landfills, we used variable costs depending on the amount of waste that is disposed of in these sites until they reach design capacity, including also the relevant costs for closure, post-closure and for replacement landfill development. We also impose minimum capacity constraints for the landfills according to the local regulations that also ensure an efficient operation of these sites. Computational experience indicates that the problem is not integer friendly. Therefore we propose a set of valid inequalities and a heuristic to solve this combinatorial problem. Finally, we demonstrate our model in a realistic problem in a case study in Greece, adopting five alternative technologies for the treatment of the solid wastes. Although the case study itself can be tackled with the valid inequalities, the proposed heuristic would be the only way forward in larger problem instances. Our model can easily be generalized to examine whatever technologies are proposed for implementation. Future research topics include the development of a methodology that will combine the location model with system dynamic simulations. This multi-methodological approach may be employed for understanding the dynamics of agreed interventions at meso-temporal level and for developing dynamic coherence of the problem.

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References

Aardal K (1998) Capacitated facility location problems: separation algorithms and computational experience. Math Program 81:149–175

Adamides E, Mitropoulos P, Giannikos I, Mitropoulos I (2009) A multi-methodological approach to the development of a regional solid waste management system. J Oper Res Soc 60:758–770

Antunes AP (1999) Location analysis helps manage solid waste in central Portugal. Interfaces 29(4):32–43

Antunes AP, Teixeira JC, Coutinho MS (2008) Managing solid waste through discrete location analysis: a case study in central Portugal. J Oper Res Soc 59(8):1038–1046

Barros A, Dekker R, Scholten V (1998) A two-level network for recycling sand: a case study. Eur J Oper Res 110:199–214

Bloemhof-Ruwaard JM, Salomon M, Van Wassenhove LN (1996) The capacitated distribution and waste disposal problem. Eur J Oper Res 88:490–503

DoE (1995) Making waste work: a national strategy for waste. HMSO, London

Eiselt HA (2007) Locating landfills-optimization vs reality. Eur J Oper Res 179:1040–1049

Erkut E, Karagiannidis A, Perkoulidis G, Tjandra SA (2008) A multicriteria facility location model for municipal solid waste management in North Greece. Eur J Oper Res 187:1402–1421

European Union (2000) Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste. Off J Eur Communities L 332:91–111

Frantzis I (1993) Methodology for municipal landfill sites selection. Waste Manag Res 11:441–451

Galvao R, Espejo L, Boffey B (2002) A hierarchical model for the location of perinatal facilities in the municipality of Rio de Janeiro. Eur J Oper Res 138:495–517

Gottinger HW (1988) A Computational model for solid waste management with application. Eur J Oper Res 35:350–364

Haley C (1990) Energy recovery from Bunning municipal wastes. Resour Conserv Recycl 4:77–103

Hamacher HW, Nickel S (1998) Classification of location models. Locat Sci 6:229–242

Kungolos A, Bakopoulou S, Papaoikonomou K, Haidarlis M (2006) Planning of solid waste management in Attica prefecture, Greece. Fresenius Environ Bull 15(8A):811–815

Li YP, Huang GH, Yang ZF, Nie SL (2008) An integrated two-stage optimization model for the development of long-term waste-management strategies. Sci Total Environ 392:175–186

Melachrinoudis E, Min H, Wu X (1995) A multiobjective model for the dynamic location of landfills. Locat Sci 3:143–146

Mitropoulos P, Giannikos I, Mitropoulos I, Adamides E (2009) Developing an integrated solid waste management system in western Greece: a dynamic location analysis. Int Trans Oper Res 16:391–407

Narula (1986) Minisum Hierarchical location–allocation models on a network: a survey. Ann Oper Res 25:7–272

Narula S, Ogbu U (1979) A hierarchical location–allocation problem. Omega 7:139–143

Prefecture of Achaia (2003) Solid waste management plan (In Greek)
ReVelle C (2000) Research challenges in environmental management. Eur J Oper Res 121:218–231
Sahin G, Sural H (2007) A review of hierarchical facility location models. Comput Oper Res 34(8):2310–2331
Siddiqui M, Everett J, Baxter V (1996) Landfill siting using geographic information systems: a demonstration. J Environ Eng 122(6):515–523
Sumathi VR, Natesan U, Sarkar C (2008) GIS-based approach for optimized sitting of municipal solid waste landfill. Waste Manag 28:2146–2160
Tchobanoglous G, Theisen H, Vigil S (1993) Integrated solid waste management: engineering principles and management issues. McGraw-Hill, USA
US EPA (2002) Waste transfer stations: a manual for decision-making (EPA530-R-02-002). Washington, DC