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Abstract: Nowadays, solid waste management is a problem of major relevance for all societies. Finding acceptable strategies to cope with such a problem is becoming a quite hard task, owing to the increasing awareness of environmental issues by population and authorities. In general, this awareness has led to the development of enhanced pollution control technologies and to a more rigorous legislation on waste handling and disposal, to minimize the related environmental impact. Solid waste management is a problem that is even more felt at the municipal level, where decision makers should plan an effective strategy, taking simultaneously into account conflicting objectives (e.g. economic, technical, normative, environmental). In addition, the problem is characterized by an intrinsic uncertainty of the estimates of costs and environmental impacts. These reasons have led several authors to propose multi-criteria decision approaches. In this paper, a Municipal Solid Waste (MSW) management system, including one separator, one plant for production of Refuse Derived Fuel (RDF), one incinerator with energy recovery, one plant for treatment of organic material coming out from one separator and one landfill, has been considered. Decisions concern optimal flows of solid waste to be sent to the different plants and to recycling, as well as the sizing of the different treatment plants. A multiobjective approach to support municipal decision makers in the planning of their MSW management system is described. Four main objectives have been proposed, reflecting the most important and conflicting aspects of the decision, specifically: minimizing economical costs (installation, maintenance, transport, and separate collection costs), minimizing incinerator emissions (such as SO_2, HCl, HF, NO_x, dust, and heavy metals emissions coming out the incinerator plants), minimizing the filling time of the sanitary landfill, and maximizing material recovery. Finally, the proposed approach is applied to a specific case study and results are reported.

Keywords: decision support systems, multiobjective decisions, optimization problems, waste treatment, environmental engineering

1. INTRODUCTION

Nowadays, waste management is one of the main environmental problems. At the municipal level, there is an increasing pressure on waste managers, planners and regulators to develop a sustainable approach to waste management and to integrate strategies aiming at producing the best practicable, and environmentally sustainable option. This is a hard task since it is necessary to take into account economic, technical, normative aspects, paying particular attention to environmental problems. A fundamental difficulty in planning a Municipal Solid Waste (MSW) management system is the necessity of taking simultaneously into account conflicting objectives (which usually cannot be dealt with by economical quantifications only). Such reasons have led several authors to propose multi-criteria decision approaches that in some cases allow a formal representation of uncertainty or imprecise information. Recently, several authors have proposed a number of models and tools based on outranking approaches for multiple criteria decision making (MCDM) and multiattribute rating techniques applied to MSW management. Such approaches have paid a special attention to the different aspects (economic, technical, normative, environmental) of the decision process. Among others, the following methodologies have been proposed: Electre III

[Hokkanen and Salminen, 1997], and DEA ranking techniques [Sarkis, 2000]. Other works have proposed a multiobjective formalization [Chang N.B. et al., 1997; Chang N.B. et al., 2000].

In this paper, a waste management system, including one separator, one plant for production of Refuse Derived Fuel (RDF), one incinerator with energy recovery, one plant for treatment of organic material coming out from the separator and one landfill, has been considered. Decisions are taken about optimal flows of solid waste to be sent to the different plants and to recycling, and about the sizing of the different treatment plans. The aim of this work is to present the structure and the application of a decision support system (DSS) designed to help decision makers (DMs) of a municipality in the development integrated programs for solid waste management. To achieve this goal, the DMs are involved in the decision process, which is formalized as a multiobjective problem and faced by means of an interactive decision method.

2. FORMULATION OF THE DECISION MODEL

A DM would like to receive support on decisions related to MSW system planning. Specifically, while the DM has already decided on the MSW configuration, that is, on the number of plants in the MSW, he/she would like to receive support about the sizing of the plant, thus deciding on the optimal flows within the MSW system.

2.1 Detailed description of the model

The formulation of the decision model proposed here is a simplified version of a previous formulation that appeared in [Costi et al., 2001]. Eleven typologies of materials have been taken into account (1- paper, 2- plastic, 3- plastic bags, 4- plastic bottles, 5- glass, 6- organic, 7- wood, 8- metals, 9- textiles, 10- scraps, 11- inert matter). The total daily MSW production is R; r_i is the daily quantity of material of type i. A detailed representation of the model is shown in Figure 1. The components of the decision vector $\underline{x}$ are those related to the flows of material, and specifically:

- α_i, which represents the percentage of material of type i sent to recycling ($i=1..11$). In particular, note that $\alpha_{10}=0$ and $\alpha_{11}=0$, because scraps and inert matter are not recyclable
- ψ_C, ψ_I, ψ_L correspond to the fractions of dry material coming from separator and sent, respectively, to RDF-plant, to incinerator, and to the landfill.
- λ_L and λ_I represent fractions of scraps coming from RDF-plant and sent, respectively, to the landfill and to the incinerator;
- θ_M, θ_I represent fraction of RDF produced that are, respectively, sold and sent to incinerator;
- $\gamma_L, \gamma_I, \gamma_M$ represent the fractions of stabilized organic material coming from organic material plant and sent to landfill, to incinerator or sold.

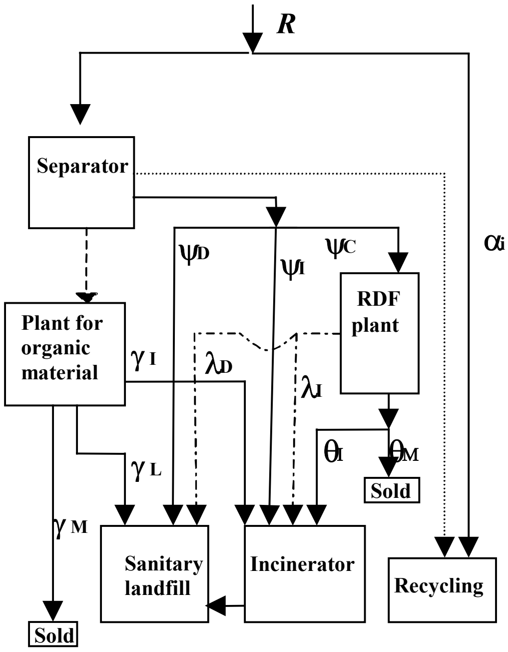

Figure 1. Decision variables

2.2 The problem objectives

Four objective functions, which can be affected by changes of the decision variable vector $\underline{x}$ are considered. Apart from the first objective function, which represents the whole cost, for the other three ones a constraint imposing an acceptability level has been specified in order to satisfy the relevant normatives; in addition, the latter objectives are assumed to have been ordered by the DM according to their importance.

Minimizing economic costs

The first objective function $f_1(\underline{x})$ is related to economic costs only. This function is supposed to be made of two main components: recycling cost and benefits related to either energy or RDF production. Recycling can take place through different techniques $j=1,...,4$ (1 is referred to collection directly at home, 2 through ecological island, 3

through special holders and *4* using small holders). The general parameter ω_{ij} represents the fraction of material *i* collected by method *j*. Let C_{ij}^{r} be the unit costs and C_i the unit benefits gained by selling recycled materials. The annual recycling costs are:

$$C^{r}(\underline{\mathbf{x}}) = \sum_{i=1}^{11}((\sum_{j=1}^{4} C_{ij}^{r} \cdot r_i \cdot \boldsymbol{\alpha}_i \cdot \omega_{ij}) - C_i \cdot r_i \cdot \boldsymbol{\alpha}_i) \qquad \textbf{(1)}$$

The overall cost (per year) related to the management and maintenance of the five plants (the incinerator, the separator, the RDF-plant, the organic material plant, and the sanitary landfill) may be written as

$$C^{g}(\underline{\mathbf{x}}) = \sum_{z=1}^{N} \overline{C}_z \cdot \overline{Q}_z(\underline{\mathbf{x}}) + C_{F\,z} \qquad \textbf{(2)}$$

where $\overline{Q}_z(\underline{\mathbf{x}})$ is the annual refuse mass treated in plant *z*, which can be expressed as a function of the decision variables, C_z represents the unit cost (per mass) for treatment plant *z*, C_{F_z} represents the fixed cost (per year) for plant *z*.
Possible benefits either as a result of electric energy production or of RDF selling are finally taken into account. The possible benefits can be expressed as:

$$B(\underline{\mathbf{x}}) = \widetilde{C}_C \cdot RDF(\underline{\mathbf{x}}) + (\frac{\eta_E \cdot HV(\underline{\mathbf{x}})}{0.86} - E_c) \cdot \overline{Q}_2(\underline{\mathbf{x}}) \cdot \widetilde{c}_I \qquad \textbf{(3)}$$

where:

- $\widetilde{C}_C$ is the price at which RDF can be sold [€/t],
- $RDF(\underline{\mathbf{x}})$ represents sold Refuse Derived Fuel, in t/y, is a function of the decision variables,
- η_E is the global efficiency for incinerator,
- $HV(\underline{\mathbf{x}})$ is the heating value of the refuse entering the incinerator plant
- E_c is electric energy consume for every ton of treated refuse,
- $\overline{Q}_2(\underline{\mathbf{x}})$ is the annual refuse quantity that enters the incinerator.
- $\widetilde{c}_I$ is the price at which produced electric energy can be sold [€/kwh], and

$$f_1(\underline{\mathbf{x}}) = C^{\mathbf{r}}(\underline{\mathbf{x}}) + C^{g}(\underline{\mathbf{x}}) - B(\underline{\mathbf{x}}) \qquad \textbf{(4)}$$

Minimizing unrecycled waste

The unrecycled material, in this model, is the total waste produced in mass (*R*) minus the waste separately collected.

$$f_2(\underline{\mathbf{x}}) = R - \sum_{i=1}^{9} \boldsymbol{\alpha}_i r_i \qquad \textbf{(5)}$$

Minimizing the quantity of waste sent to sanitary landfill

Solutions for MSW management problems that are heavily based on sanitary landfill exploitation are not environmentally sustainable over a long time horizon. For this reason, it is necessary to introduce in our model a specific objective, which has the function of preventing a too rapid saturation of the available sanitary landfill.

$$f_3(\underline{x}) = \overline{Q}_5(\underline{\mathbf{x}}) \qquad \textbf{(6)}$$

where $\overline{Q}_5(\underline{\mathbf{x}})$ is the quantity of waste per year coming to the landfill.

Minimizing incinerator emissions

An incinerator produces different kinds of emissions. It is important to quantify such emission and to minimize them. Emission concentrations and quantities depend on the chemical reactions which take place among the various elements present in the entering refuse. Specifically, every material present in the refuse has a specific percentage of S, Cl, C, N, O, H, F, that can give the following compounds: CO_2, H_2O, HCl, O_2, N_2, SO_2, HF. The quantities depend on the mole numbers and on the efficiency of fumes purification. In this simplified approach, only HCL emissions have been taken into account. It is possible to show [Costi et al., 2001] that such emissions can be expressed as

$$f_4(\mathbf{x}) = \sum_{i=1}^{11}(1-\boldsymbol{\alpha}_i)\cdot r_i \cdot (1-k_i)\cdot\{[\beta_1 \cdot \psi_I + \beta_2 \cdot \psi_C \cdot \boldsymbol{\theta}_\mathbf{I} + \beta_3 \cdot \psi_C \cdot \boldsymbol{\lambda}_I]\cdot Cl_i + \gamma_I \cdot \delta \cdot Cl_{f,i}\} \qquad \textbf{(7)}$$

where $\beta_{1,2,3}$ and δ can be computed on the basis of the characteristics of the various plants, Cl_i is the chlorine percentage for every collected material, and $Cl_{f,i}$ is the chlorine percentage of the refuse outgoing the organic material plant.

2.3 Technical and normative constraints

Mass balance equations

Mass conservation equations are needed for each branching point at which a flow can be split. Such equations are:

$$\boldsymbol{\theta}_{\mathbf{M}} + \boldsymbol{\theta}_{\mathbf{I}} = 1 \quad \textbf{(8)}$$

$$\boldsymbol{\lambda}_{\mathbf{I}} + \boldsymbol{\lambda}_{\mathbf{D}} = 1 \quad \textbf{(9)}$$

$$\boldsymbol{\gamma}_{\mathbf{I}} + \boldsymbol{\gamma}_{\mathbf{L}} + \boldsymbol{\gamma}_{\mathbf{M}} = 1 \quad \textbf{(10)}$$

$$\boldsymbol{\psi}_{\mathbf{C}} + \boldsymbol{\psi}_{\mathbf{I}} + \boldsymbol{\psi}_{\mathbf{D}} = 1 \quad \textbf{(11)}$$

Technical constraints
Every treatment plant must be subject to some restrictions for treated mass.

$$M_a \le \overline{Q}_1 \le M_b \text{ for RDF plant} \quad \textbf{(12)}$$

$$M_a^{'} \le \overline{Q}_2 \le M_b^{'} \text{ for incinerator} \quad \textbf{(13)}$$

$$M_a^{''} \le \overline{Q}_4 \le M_b^{''} \text{ for separator} \quad \textbf{(14)}$$

$$M_a^{'''} \le \overline{Q}_3 \le M_b^{'''} \text{ for organic material plant} \quad \textbf{(15)}$$

where $\overline{Q}_z$ represents mass quantities entering per year the various kinds of plants, which can be expressed as a function of the decision variables.

Constraints on recycling
Italian legislation requires that waste recycling is no less than 35% of the total produced waste in mass (R). That gives rise to the following constraint.

$$\sum_{i=1}^{9} \boldsymbol{\alpha}_{\mathbf{i}} r_i \ge 0.35R \quad \textbf{(16)}$$

Constraints related to the material flows sent to the sanitary landfill

It is necessary to introduce in our model specific constraints, which have the function of preventing a too rapid saturation of the available sanitary landfill. Such constraints may be expressed in terms of the *minimum filling time*, and corresponds to the counterpart of objective function $f_3(\underline{\mathbf{x}})$.

$$\overline{Q}_5(\underline{\mathbf{x}}) \le \frac{M_R}{T_R} \quad \textbf{(17)}$$

where M_R is landfill residual capacity and T_R is filling time.

2.4 Environmental constraints

The environmental constraints are the same as in Costi et al. [2001]. A first set of them is related to:

- *Produced RDF*. Produced RDF must have specific characteristics imposed by law. Specifically, heating value must be greater than 3600 kcal/kg, Cl, S, ashes, and humidity content cannot exceed a fixed quantity. Finally, no more than a certain quantity of RDF can be sold.
- Cl content in produced RDF must be less or equal to 0.9%
- S, ashes, humidity, sold RDF content constraints
- Stabilized organic material (SOM) must also be constrained. Specifically:
  - the organic material content in the SOM must be greater than 40%
  - the glass content in the SOM must be less than 40%
  - the C/N ratio in the SOM must be less than 30
  - the plastic content must be less than 1%
  - a constraint on sold SOM assessing that a superior limit can be acceptable by the market is to be fulfilled.

Incinerator plant
An incinerator produces different kinds of emissions. It is important to quantify such emission and to limit them according to normative indications. Emission concentrations and quantities depend on the chemical reactions among the various elements present in the entering refuse. Specifically, every material present in the refuse has a specific percentage of S, Cl, C, N, O, H, F that can give the following compounds: CO_2, H_2O, HCl, O_2,N_2, SO_2,HF. The quantities depend on the mole numbers and on the efficiency of fumes purification. For instance, the HCl emission constraint can be written as [Costi et al., 2001]

$$\sum_{i=1}^{11} (1-\boldsymbol{\alpha}_i)\cdot r_i \cdot (1-k_i)\cdot \{\, [\beta_1 \cdot \boldsymbol{\psi}_I + \beta_2 \cdot \boldsymbol{\psi}_C \cdot \boldsymbol{\theta}_{\mathbf{I}} + \beta_3 \cdot \boldsymbol{\psi}_C \cdot \boldsymbol{\lambda}_I]\cdot (\xi_i - Cl_i) + \beta_4 \cdot \boldsymbol{\gamma}_I \cdot (\xi_i^{'} - Cl_{f,i}) \,\} \ge 0 \quad \textbf{(18)}$$

where ξ_i and $\xi_i^{'}$ can be easily computed.

Similar constraints can be given SO_x, HF, heavy metals, NO_x, and dust emissions. They are reported in Costi et al. [2001] too, and are omitted here for the sake of brevity.

3. THE MULTIOBJECTIVE APPROACH

Planning a MSW can be structured as a MCDM problem, as several conflicting criteria should be taken into account to identify an acceptable compromise alternative. A difficulty in modeling the decision process is also given by the nonlinear constraints which arise whenever a MSW system component behaves as a splitter of material (such as for example, the output of the separator and the related flows $\boldsymbol{\psi}_{\mathbf{C}}$, $\boldsymbol{\psi}_{\mathbf{I}}$, $\boldsymbol{\psi}_{\mathbf{L}}$), thus introducing bilinear constraints as described in [Quesada and Grossmann, 1995].

In addition, since the decision variables in the considered context can assume real values within their respective feasibility ranges, the MCDM problem becomes more specifically a multiobjective one, which can be generally expressed as the following vector optimization problem (VOP):

$$\min \underline{F}(\underline{\mathbf{x}}) = [f_1(\underline{\mathbf{x}}), ..., f_n(\underline{\mathbf{x}})]^T \qquad \underline{x} \in X \qquad \textbf{(19)}$$

where $\underline{x}$ represents the decision variable vector, X the set of feasible values for $\underline{\mathbf{x}}$ defined in section 2.3 and 2.4, and $\underline{F}(\underline{\mathbf{x}})$ is the vector objective whose components are the single objective functions $f_h(\underline{\mathbf{x}})$, h=1,...,n. For some of the considered objective functions, acceptability bounds have been introduced in order to satisfy a set of norms imposed by the community and local laws. Then the *feasible and acceptable* (FA) values for the decision variables are defined as

$\underline{\mathbf{x}} \in X \cap X_R$

where $X_R=\{\underline{\mathbf{x}}: f_h(\underline{\mathbf{x}}) \leq b_h, h \in F_R\}$ and $F_R \subseteq \{1,...,n\}$ represents the subset of the objective functions for which an acceptability bound b_h has been specified.

In such a context an ideal decision could correspond to a feasible and acceptable solution that simultaneously minimizes all the objective functions. Since these solutions very rarely exist, a multiobjective decision method can be used to lead the DM to assess a FA compromise solution. The method that is here proposed originates from the following considerations:

– the method must be easily understood by DMs; DMs should not be required to provide judgments on unclear possible scenarios as, for example, it could happen when asking preferences on complex multidimensional trade-offs among objectives;

– the output of the method should be accepted by DMs; DMs do not consider as a reliable support solutions that come from a black box method, and they usually prefer to be directly involved in the procedure leading to the decisions.

For these reasons a multiobjective decision method that, similarly to the Step Method (STEM) used in the multiobjective linear programming (Benayoun et al., 1971), progressively acquires preference information from the DM has been adopted. At each step the DM is provided with (one of) the FA solution that better satisfy her preference judgments corresponding to implicit trade-offs among the objectives. In more detail, the method solves at the initial step the following (nonlinear) optimization problem.

(Step 1) $\min f_1(\underline{\mathbf{x}}) \qquad \underline{\mathbf{x}} \in X \cap X_R$

being $F_R=\{2,...,n\}$. Note that in the considered MSW problem, n=4 and $f_1(\underline{\mathbf{x}})$ corresponds to the global economic cost objective, whereas for the other $f_h(\underline{\mathbf{x}})$, h=2,3,4, a legislation bound b_h has been given *a priori*. However, the method can be extended to general cases by including in the first step a lexicographic ordering phase among objectives $f_h(\underline{\mathbf{x}})$ with $h \notin F_R$, and specifying acceptability bounds for all the objectives but the one ranked first. The solution of Step 1 achieves the best level for $f_1(\underline{\mathbf{x}})$, say f_1^*, associated with a FA solution $\underline{x}^*_{(1)}$. Note that if no solution can be found at Step 1, no FA solution can be found for the whole problem. The DM is asked to evaluate solution $\underline{x}^*_{(1)}$, in particular to judge a possible trade-off between the level f_1^*, achieved for $f_1(\underline{\mathbf{x}})$ and the level obtained for one of the other objectives, in particular, for the ones satisfying the acceptability constraints as equalities. In the MSW context, this trade-off corresponds to considering if a possible increase in the economic costs is worth for improving, for example, an environmental objective beyond its minimum standard level. If the DM accepts an increase Δ_1 for $f_1(\underline{\mathbf{x}})$ in order to improve the level of another objective, say $f_2(\underline{\mathbf{x}})$, selected according to her local priority, a new step is performed solving

(Step2) $\min f_2(\underline{\mathbf{x}}) \qquad \underline{\mathbf{x}} \in X \cap X'_R$

where $X'_R= X_R \cap \{\underline{\mathbf{x}}: f_1(\underline{\mathbf{x}}) \leq f_1^*+\Delta_1\}$. Note that $\underline{x}^*_{(1)}$ is also a FA solution to problem at step 2.The method iterates asking again the DM to evaluate the possibly new solution $\underline{x}^*_{(2)}$; in case this latter is not satisfying, the DM should consider a new compromise, i.e., the possibility of a further increase in the first objective (the global cost) or an increase of Δ_2 worsening (within its FA bounds) the optimal value of the second objective f_2^* achieved at Step2. If the DM accepts any trade-off a new step is performed optimizing $f_3(\underline{x})$ with the set of constraints as, for example $X''_R= X'_R \cap \{\underline{x}: f_1(\underline{x}) \leq f_1^*+\Delta_1+\Delta'_1\}$. The method yields a sequence of FA solutions until the DM evaluates the current solution as a globally satisfying compromise, or all the objective functions have been singularly optimized. Finally, it can been observed that, due to the nonlinear nature of the MSW problem, it could be significant even to perform steps with null objective increase (i.e., Δ_1=0) as the optimal solution achieved at each step is in general a local optimum.

4. RESULTS

The multiobjective method described in section 3 has been applied to the MSW system shown in Figure1. In the first step, the following problem has been solved:

(Step1) $\min f_1(\underline{\mathbf{x}}) \quad \mathbf{x} \in X$

$$f_2(\underline{\mathbf{x}}) \leq 0.65R \quad \textbf{(20)}$$

$$f_3(\underline{\mathbf{x}}) \leq 0.2R \quad \textbf{(21)}$$

$$f_4(\underline{\mathbf{x}}) \leq E^* \quad \textbf{(22)}$$

where R and X have been previously defined, and E* represents the HCl emission level allowed by law.
Step 2 is characterized by the minimization of function $f_2(\mathbf{x})$ and the additional following constraint:

$$f_1(\underline{\mathbf{x}}) \leq C^* \quad \textbf{(23)}$$

where C^* is a cost that decision makers can accept. In Step 3, function $f_3(\mathbf{x})$ is minimized, and constraint **(20)** is transformed according to the procedure described in section 3. Similarly, Step 4 is performed. Table 1 shows the results obtained. Evidently, Step1 presents a lower cost (44 M€ instead of 50 M€), but a low quantity of material is recovered (in Step 1, 820 t/d of waste is not recycled while in the other Steps recovered material is much more) and landfill rapidly saturates (because a great quantity of material, 260 t/d, is sent to the landfill). Step 2 and Step 3 yield a compromise among the first three objectives. Specifically, in Step 3, the quantity of material sent to landfill is minimized and unrecycled waste and the overall costs have acceptable values. Finally, Step4 yields a lower value of the fourth objective function, at the price of raising the value of the third objective.

Table 1. Results obtained for each step

	Step1	Step2	Step 3	Step 4
$f_1(\underline{x})$	44	50	50	50
$f_2(\underline{x})$	820	617	660	660
$f_3(\underline{x})$	260	167	101	140
$f_4(\underline{x})$	10	10	10	8.5

5. CONCLUSIONS AND FUTURE DIRECTIONS

The proposed comprehensive DSS model allows municipal decision makers to plan the treatment plants that must be used in an optimal MSW management system and defines how to organize recycling and waste disposal in a integrated approach. A MSW management system is formalized in a constrained non-linear optimization problem, where decision variables are both integer and continuous. As in many environmental related problems, the decision problem is multiobjective [Wierzbicki et al., 2000]. Then, a suitable technique can be applied interactively with the decision maker to obtain a solution which represents a compromise acceptable to decision maker.

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