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Abstract: A multi-objective approach to sustainable Municipal Solid Waste (MSW) management is presented, with the aim of supporting the decisions about the optimal flows of solid waste to be sent to landfill, recycling and to the different treatment plants. To achieve this goal, an approach is proposed in which the decision makers (DMs) are interactively involved in the decision process, following the reference point methodology [Wierzbicki et al, 2002]. The method can be viewed as an integration/modification of techniques already introduced in the literature. The purpose of the DMs is to determine the various flows of the different materials in the whole MSW management system in order to satisfy a number of technological and normative constraints and minimizing four main objectives: the economic cost of material treatment, the quantity of unrecycled waste, the quantity of waste sent to the landfill, and the emissions of the incinerator. The model proposed has been applied to a case study concerning the municipality of Genova. The case has been analysed assuming the presence of two different decision makers, characterized by different attitudes in selecting the initial reference solution and in interacting with the methodology. Results and final comments are reported.

Keywords: Waste management, Optimization, Multi Objective Decision Model.

1.   INTRODUCTION

The complexity of planning a Municipal Solid Waste (MSW) management system depends on the necessity of taking simultaneously into account conflicting objectives. It is really difficult for planners to develop a sustainable approach to waste management and to integrate strategies aiming at producing the best practicable and environmentally sustainable option. To formalize these strategies, in the last two decades, considerable research efforts have been directed towards the development of optimization models for MSW flow allocation. Several examples of mathematical programming models have been developed for MSW management planning, such as, for example, in Chang and Chang [1998], Fiorucci et al. [2003], Costi et al. [2003]. The necessity of taking into account economic, technical, and normative aspects, paying particular attention to environmental problems (which usually cannot be dealt with by economic

quantifications only) is more and more felt. Such a reason has led several authors to propose multi-criteria decision approaches. Recently, several authors have proposed a number of models and tools based on outranking approaches for multiple criteria decision making (MCDM) and multi-attribute 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, Electre III [Hokkanen and Salminen, 1997], and DEA (Data Envelopment Analysis) ranking techniques [Sarkis, 2000] have been presented. Shekdar and Mistry [2001] have proposed an interactive goal programming model of multi-objective planning of the overall system. The considered objectives are the maximization of energy recovery and material recovery, the minimization of expenditure, and the limitation on the landfilling capacity. Generally speaking, different procedures of interactive multiple objective programming are available.

Gardiner and Steuer [1994] showed how these procedures can be unified into a single algorithm. As concerns environmental management, which is often formulated as a multi-objective problem, the reference point methodology [Wierzbicki et al, 2002] has been proposed as an appropriate approach.

In this paper, a multi-objective decision making (MODM) approach to sustainable MSW management is presented, with the aim to support the decision on the optimal flows of solid waste to be sent to landfill, recycling and to the different treatment plants. To achieve this goal, in the proposed approach the decision makers (DM) are interactively involved in the decision process, following the reference point methodology. The fundamental improvements with respect to previous approaches to MSW, such as Shekdar and Mistry [2001], the possibility to take into account important environmental aspects, such as the ones due to emissions, by means of non-linear objectives and constraints. In fact, the use of reference point methodology can be considered a more effective method than goal programming and it is widely recognized as an effective approach to non-linear multi-objective optimization problems.

2. THE MSW DECISION PROBLEM

Consider a decision framework in which a DM needs support in facing a MSW planning problem. Specifically, given a MSW configuration (that is that the number and type of plants in the MSW system is fixed *a priori*), the DM aims at establishing the optimal waste flows, and the plants size. The model of such a system is similar to the one in Costi et al., [2001 and 2004], where the decisional variables also include the sizes of the plants and the flows among them, but only a single objective, the economic cost, is taken into account. In the municipality, the total daily MSW production can be partitioned into eleven typologies of materials, namely, paper, plastic, plastic bags, plastic bottles, glass, organic, wood, metals, textiles, scraps, and inert matter. The structure of the overall MSW system is depicted in Figure 1, where five types of plants are represented and the flows among them are indicated. Apart from *R*, which represents the total daily MSW production, all symbols represent flow percentages. More specifically, for every branching point, the following convention is adopted: the symbol associated with an outgoing link represents the percentage of the flow corresponding to the unique incoming link.
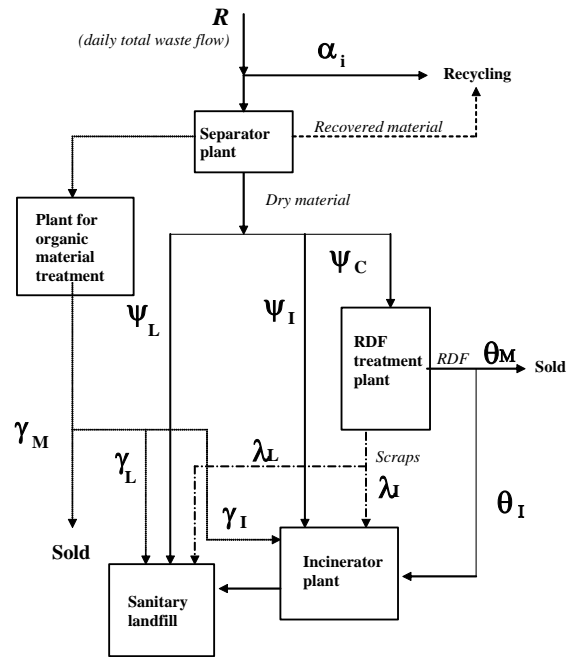

Figure 1. The MSW management system

The total waste flow is partly gathered (percentage α_i) by a separate collection and then sent to recycling. Note that recycling is not possible for three kinds of the above materials, that is, heavy plastics, scraps and inert matter, whereas the other eight materials can be separately collected by different methods. Besides to separate collection, material recovery is also possible by dividing the various materials in a separator plant. From such a plant, three flows may come out:

- the metals that can be sent to recycling;
- the organic material that must be sent to a treatment plant (*humid material*);
- a fraction of material, with low humidity and high heating value (*dry material*), that can be burnt (percentage ψ_I), or sent to the plant for Refuse Derived Fuel (RDF) production (percentage ψ_C), or disposed in the sanitary landfill (percentage ψ_L).

The RDF plant produces fuel, which can be sold to industries (percentage θ_M) or burnt in the incinerator (percentage θ_I), and scraps, which can be sent either to the incinerator (percentage λ_I) or to the landfill (percentage λ_L).

The organic material collected for recycling can be directly sent to a composting plant because it is pure enough to produce compost for agricultural use. The *humid material* is treated in the organic material treatment plant, which produces Stabilized Organic Material (SOM). SOM can be sold (percentage γ_M), burnt in the incinerator (percentage γ_I), or sent to the landfill (percentage γ_L). Clearly, material recovery takes place not only

through recycling but also through the various treatment plants which provide SOM, RDF and metals. Energy recovery by MSW combustion has to be taken into account as well. As recycling modifies the composition of the refuse sent to incineration, it influences the heating value of the refuse that has to be burnt, and hence energy recovery. The purpose of the DM is to determine the various flows of the different materials in the whole MSW management system in order to satisfy a number of technological and normative constraints and minimizing four main objectives: the economic cost of material treatment, the quantity of unrecycled waste, the quantity of waste sent to the landfill, and the emissions of the incinerator. In the following sections the details of the mathematical formulation and of the approach of the multi-objective decision problem (MODM) are illustrated.

3. THE MODM APPROACH

In the considered context, the multi-objective problem can be in general expressed as a vector optimization problem (VOP):

$$\min_{\underline{x} \in X} \underline{F}(\underline{x}) \qquad (1)$$

where $\underline{F}(\underline{x}) = [f_j(\underline{x}), \quad j \in J = \{1, \dots, m\}]^T$ and X represents the feasible decision space.

The MODM approach used in this work follows the Reference Point Analysis [Wierzbicki et al., 2002], adapted to the case study, and an iterative solution for the interaction with the DMs, following the experience of the Satisficing Trade-Off Method (STOM) developed by Nakayama [Wierzbicki et al., 2002].

The kind of information required by the procedure proposed in this paper is different from the one used in STOM: the reason of this choice is the necessity of making the meaning of the evaluation quite clear for the DMs involved in the specific application context considered, so that they can easily provide the information needed.

The first step is to define the utopia solution $\underline{q}^u \in Q$ for all the objectives. This can be found solving the following problems:

$$q_j^u = f_j(\underline{x}_{(j)}^u) = \min_{x \in X \cap X^a} f_j(\underline{x}) \quad j \in J \qquad (2)$$

where $Xa = \{f_j(x) \le q_{ja} \ \forall j \in A\}$, being A the subset of objectives for which a level has been provided by the DM.

Instead, the nadir solution can be appropriately fixed by selecting the maximum values assumed by the objectives:

$$q_j^n = \max_{h=1,\dots,m} f_j(\underline{x}_{(h)}^u) \qquad j \in J \qquad (3)$$

Then, the objective functions are normalized by means of the following substitution

$$q_j \leftarrow \frac{q_j - q_j^u}{q_j^n - q_j^u} \qquad\qquad j \in J \qquad (4)$$

The achievement function to be maximized is:

$$\sigma(\underline{q}, \overline{q}) = \min_{j=1,\dots,m}(\overline{q}_j - q_j) + \varepsilon \sum_{j=1}^{m}(\overline{q}_j - q_j) \qquad (5)$$

subject to the set of constraint X^{ea}. As theoretically justified in [Wierzbicki, 2002], the parameter ε can be computed as $\varepsilon = 1/(M-1)$, being M a suitable upper bound on the trade-offs among the objectives. The initial efficient solution is identified by maximizing the achievement function $\sigma(\underline{q}, \overline{q}^0)$ defined in (5), being $\overline{q}^0$ the initial aspiration levels either fixed at the utopia solution or directly provided by the DM, and q_j. The results of the maximization regard the optimal value of each objective function, to which corresponds the normalized solution that is comparable with the pre-defined reference point. Then, the DM evaluates if the levels of the objectives associated with the current solution are satisfying, and, in the affirmative case, the procedure is terminated. If none of the objective levels is satisfying the DM, the procedure can be either terminated, not being able to provide any support, or re-initialised by setting a different set of aspiration levels. Actually, in such a case it could seem appropriate to revise some of the constraints that specify X^{ea}, in particular relaxing some of the acceptability conditions. Finally, let U^k the set of indexes of the objectives whose level is considered not satisfying and S^k the complementary set of indexes of the objectives considered satisfying at the *k-th* iteration. The procedure aims at identifying a trade-off in an implicit way asking the DM to indicate for at least one of the objective $j \in S^k$ an increase (recall that a minimization is considered) Δq_j^k that the DM is willing to accept in order to possibly improve the objectives in U^k.

The procedure then computes a new reference point from the objective levels of the current efficient solution as $\overline{q}_j^{k+1} = \overline{q}_j^k + \Delta q_j^k$ $\forall j \in S_{TO}^k \subseteq S^k$, where S_{TO}^k is the set of the objectives in S^k for which the DM is willing to accept an implicit trade-off, and $\overline{q}_j^{k+1} = \overline{q}_j^k \quad \forall j \in J \backslash S_{TO}^k$.

Then, a new candidate efficient and acceptable solution $(\underline{x}^{k+1}, \underline{q}^{k+1})$ is found by maximizing the order consistent achievement function as follows

$$\max_{x \in X^k} \sigma(\underline{q}, \overline{q}^{k+1}) \qquad (6)$$

being $X^k = X^{k-1} \cup \{ q_j \le \overline{q}_j^k + \Delta q_j^k, \forall j \in S_{TO}^k \}$. In this way the new reference points are taken into account in (6) and a relevant set of new constraints

are added which impose the maximum worsening level accepted by the DM. This interaction continues till the DM is satisfied for all the objectives. As recent approaches to MODM have pointed out [Wierzbicki et al., 2002], information provided during the decision making process (also called "progressive" information), generally lead to identify decisions that are easily recognized to be consistent with the DM's preference and then finally accepted. In addition, the use of progressive information does not require that the DM expresses definitive and accurate preference judgements only once, but lets the DM free to revise the preference at each step of the decision process, taking into account the current solution point at which the judgements previously provided have led to.

4. THE FORMALIZATION OF THE MODM DECISION PROBLEM

The primary decision variables correspond to the flows of materials and represent the components of the decision vector $\underline{x}$. The following decision variables, described in section 2. are considered: $\alpha_i \ (i=1,...,11)$, ψ_C, ψ_I, ψ_L, λ_L, λ_I θ_M, θ_I $\gamma_L, \gamma_I, \gamma_M$ (see Figure 1).

4.1 Objectives

Four objective functions are considered: minimizing economic costs, minimizing unrecycled waste, minimizing waste sent to landfill, and minimizing incinerator emissions. For brevity, the complete formalization of these functions is not reported. Further information can be found in [Fiorucci et al., 2003, Costi et al., 2004]. The first objective function $f_1(\underline{x})$ is related to economic costs. Three main components are assumed for $f_1(\underline{x})$, that are, recycling cost $C^r(\underline{x})$, maintenance costs $C^g(\underline{x})$, and benefits $B(\underline{x})$ related to either energy or RDF production, leading to the following expression:

$$f_1(\underline{x}) = C^r(\underline{x}) + C^g(\underline{x}) - B(\underline{x}) \qquad (7)$$

All these costs are function of the previously defined decision variables.

Unrecycled material, in this model, is simply the total waste produced R minus the waste separately collected, namely:

$$f_2(\underline{x}) = R - \sum_{i=1}^{9} \alpha_i r_i \qquad (8)$$

The quantity of waste per year sent to the landfill (called $\overline{Q}_5(\underline{x})$ in this work) is function of the decision variables (and of the different parameters

that characterize each treatment plant efficiency). The third objective is:

$$f_3(\underline{x}) = \overline{Q}_5(\underline{x}) \qquad (9)$$

Finally, emission concentrations and quantities depend on the chemical reactions, which take place among the various elements present in the entering refuse. Every material present in the wastehas 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 produced depend on the mole numbers, on the flows entering the incinerator plant, and on the efficiency of exhaust gas treatment. In the proposed approach, only HCL emissions have been taken into account.

The fourth objective is:

$$f_4(\underline{x}) = M_{HCl}(\underline{x}) \qquad (10)$$

where $M_{HCl}(\underline{x})$ is the overall amount of chlorine entering daily the incinerator plant.

4.2 Constraints

Different classes of constraints have been included in the formalization of the mathematical optimization problem: minimum recycling constraints, treatment plants' size constraints, flow conservation constraints, RDF and SOM composition constraints, incineration emissions constraints, landfill saturation constraints.

5. THE CASE STUDY

The model proposed in this paper has been applied to a case study concerning the municipality of Genova where refuse disposal is a very critical problem. With a daily waste production of 1355 t, the current solution is the disposal in a unique landfill, whose residual capacity is rapidly decreasing. For the sake of brevity the data relevant to the case under concern are not reported here, but they can be found in Fiorucci et al. [2003], where the MSW management problem was faced without introducing a multi-objective formulation.

The preliminary step that must be performed in order to apply the MODM approach to the MSW case study is to identify for each objective function f_j both the utopia q_j^u, and the nadir q_j^n solutions and to normalise the function with respect to the interval $[q_j^u, q_j^n]$. Table 1 reports the four objective functions considered together with their dimensions and the computed utopia and nadir solutions.

f_j	Dim.	q_j^u	q_j^n
f_1	M€	45.732	64.027

f_2	Tons	376.616	880.750
f_3	Tons	0.020	0.100
f_4	Mg/m3	3.392	10.000

Table 1. Utopia and Nadir computation

The case has been analyzed by two different decision makers, DM_1 and DM_2, showing different attitudes in selecting the initial reference solution and in interacting with the methodology. The first decision maker, DM_1, is not able to initially identify a feasible satisfying reference point. So, DM_1 simply accepts to start the method from the (unfeasible) utopia point. Then, the method computes the first solution from this reference and presents it to DM_1. Table 2 reports the iteration sequence characterizing DM_1. The first column of the table denotes the iteration, the other eight columns respectively reports first the references used and the objective values obtained by the method from such references. Note that the values reported for both the references and the objective have been normalized with respect to the interval $[q_j^u, q_j^n]$ for j=1,...,4.

	Reference Point				Objective Values			
k	$\overline{q}_1$	$\overline{q}_2$	$\overline{q}_3$	$\overline{q}_4$	q_1	q_2	q_3	q_4
1	0	0	0	0	0.34	0.34	0.34	0.16
2	0.5	0	0	0	0.65	0.15	0.05	0.00
3	0.5	0.45	0	0	0.56	0.23	0.06	0.00
4	0.5	0.45	0.06	0	0.52	0.30	0.08	0.00

Table 2. Iteration sequence for DM1

After having analyzed the results obtained in the first iteration, DM_1 is willing to accept a worsening for the satisfying objective 1, accepting costs that are in the middle between the normalized utopia and nadir ($\overline{q}_1 = 0.5$, see Table 2), with the aim to achieve a possible improvement in at least one of the not satisfying objectives. Then, DM_1 proceeds with the other iterations as summarized in table 2. The objective values obtained at the iteration 2 are quite good for q_j, j=2,3,4, but the projection on the efficient frontier provided by minimizing $\sigma(\underline{q}, \overline{\underline{q}})$ leads to a cost value that is considered too high. Then, instead of reducing the reference variation introduced for the objective 1, i.e., performing again the first iteration, DM_1 tries to exploit the improved consciousness about the objective levels that can be actually achieved, and fixes a new reference variation for the objective 2. This kind of behaviour continues until the iteration 4. As a matter of fact, this last iteration is considered a worsening by DM_1 and, also in view of other steps, DM_1 feels quite satisfied with the solution given by iteration 4. To transform the subjective satisfaction into an objective evaluation of the quality of the solution is quite a hard task in a multi-objective problem. In the proposed decision problem, where the objectives are normalized, a star coordinate system representation may help both the DM to view the solution with respect to the reference, the nadir and the utopia points, and the DSS specialist to have a more objective evaluation of the quality of results. Figure 2 shows the solution at the iteration 4 and the related reference point; the nadir coordinates are the end points of the star, whereas the utopia ones are in the centre of the star. The solution can be assessed as adequate also since it is almost included in the area delimited by the convex hull of the reference points and because its objectives are lower than the mean of the solutions obtained.
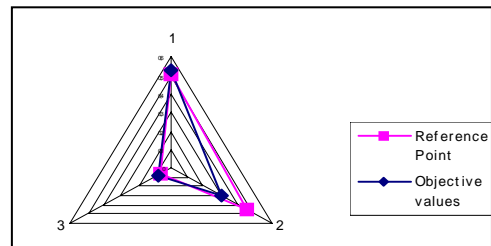

Figure 2. The star representation of the result of the iteration process for DM1

A similar process characterizes the iterations performed by DM_2. However in this case, the behavior of DM_2 in the decision process has some important differences with respect to DM_1. While DM_1 has started from the unfeasible utopia as reference point, DM_2, who shows some awareness about the possible outcomes that one can expect for the considered MSW management problem, starts from a reference point that, satisfying all the problem constraints, results to be feasible. The attitude by DM_2 in the iterations of decision algorithm is different with respect to DM_1. While DM_1 relaxed the reference point according to ideas suggested from the solution obtained in the current iteration, DM_2 needs to firm up on improving the amount of recycled waste (objective q_2), taking into account the effects on the other objectives.
The iteration of the decision process is summarized by the values in the Table 3.

	Reference Point				Objective Values			
k	$\overline{q}_1$	$\overline{q}_2$	$\overline{q}_3$	$\overline{q}_4$	q_1	q_2	q_3	q_4
1	0.50	0.50	0.03	0.10	0.54	0.26	0.07	0.00
2	0.50	0.20	0.03	0.10	0.54	0.24	0.07	0.04
3	0.50	0.10	0.03	0.10	0.59	0.19	0.06	0.00
4	0.45	0.10	0.03	0.10	0.56	0.21	0.08	0.00

Table 3. Iteration sequence for DM2

Moving from iteration 1 to 2, q_1 and q_3 remain the same while q_2 is lowered and q_4 is increased. From iteration 2 to 3, q_1 rises while the other objectives decrease. However, DM_2 is not very satisfied by q_1 and wants to lower it. At iteration 4, q_1 is lowered,

and q_2 and q_3 increase a bit. DM2 is satisfied by this iteration. Figure 3 reports the star representation for the result of the DM2 iteration process.
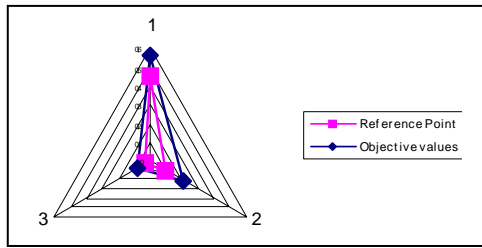

Figure 3. The star representation of the result of the iteration process for DM2

To reach the final decision, DM_1 and DM_2 should discuss their two solutions in order to agree upon a compromise. To solve the decision the following questions have to be answered: is it worthwhile to spend additional 0.54M€ a year (moving costs from 55.18M€ to 55.56€, corresponding to the gap from q_1=0.52 for DM_1 to q_1=0.56 for DM2), in order to reduce of 25.21 tons per year the amount of unrecycled waste (moving from 525.7€ to 501.8 tons per year corresponding to the gap from q_2=0.30 for DM_1 to q_2=0.21 for DM_2)? Which solution is most feasible and robust according to the decisional variables?

6.   CONCLUSIONS

The proposed multi-objective 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. The MODM procedure allows different DMs to participate interactively with the decision process, obtaining, at each iteration, a solution that is optimal from different points of view (economic, environmental, legislative, etc.) and that they have to decide if they want this solution or if they prefer to have another "option", adjusting their reference goals. This process seems to be particularly suitable for MSW because of the different DMs and the different political/social aspect involved in the real decisional process. The case study has been analyzed assuming the presence of two different decision maker, DM1 and DM2, showing different attitude in selecting the initial reference solution. This choice is justified by the fact that the test aims at showing the capability of the method of identifying, under the control of the decision maker, a satisfying solution even when starting from quite different initial reference points.

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