Sixth Joint Conference on

Food, Agriculture and the Environment

(in honor of Professor Emeritus Philip M. Raup)

Minneapolis, Minnesota

August 31 - September 2, 1998

Hosted by the

Center for International Food and Agricultural Policy
University of Minnesota
Department of Applied Economics
1994 Buford Avenue\332 ClaOff Building
St. Paul, Minnesota 55108-6040 U.S.A.

INTEGRATED SOLID WASTE MANAGEMENT: A MULTICRITERIA APPROACH

Guido Maria Bazzani

University of Minnesota

University of Bologna **University of Padova**

University of Perugia **University of Firenze**

University of Piacenza **University of Wisconsin**

University of Siena **University of Alberta**

Title:	Integrated Solid Waste Management: a Multicriteria Approach

Author Guido Maria BAZZANI

Affiliation: *Centro di Studio sulla Gestione dei Sistemi Agricoli e Territoriali (CNR)*

Tel.: (39) 51-243204

Fax: (39) 51-252187

Email: bazzani@area.bo.cnr.it

Keywords Integrated solid waste management; Modelling; Integer programming, Multi Objective, Optimisation

Abstract:

The paper presents the first results of a long term research aimed at producing a decision support system to deal with the integrated solid waste management planning at regional level.

In the last years urban waste management has received a strong attention from the public authority in Italy culminating in a new national law, which has priorities such as waste prevention (waste avoidance and reduction) reuse and recycling. Italian Legislation requires to consider not only a series of waste management options aimed at source reduction but also to integrate the environmental soundness with economical viability and social equity. To support this integrated solid waste management it is necessary to ascertain the environmental, economic and social impacts associated with various waste management options so that decision makers can trade them off to achieve a better waste management strategy. To deal with the problem a three level process is suggested: zoning of the territory, implementation of the waste plan, Environmental Impact Assessment (EIA) on the new facilities.

The paper focuses, in a non technical way, on a dynamic mixed integer linear programming model to be used in the second phase of the previous process. A multicriteria approach has been adopted to manage waste as an integrated system of recollection, transportation, recovery and disposal activities. At the moment four objective functions have been defined: total cumulative distance, total discounted net cost, total cumulative impact on traffic due to waste transportation, total cumulative landfilling. The model includes different types of collection, as well as different technologies. The model gives the possibility to locate in the same site more facilities. In this way it is possible to construct waste integrated platforms which permit to reduce costs and impacts. The model chooses the sites to be developed, the types of technology that will be installed on such sites, and the schedule of activity. In accordance with the input concentration for each technology it is possible to specify the appropriate output coefficients. The model computes the yields of the intermediate technologies directly from the model parameters, such parameters are exogenously determined, case by case, on the basis of the technical information; all the yields are automatically recomputed by the model when they

vary. In this way high flexibility is introduced into the model. According to the preference of the decision maker specific constraints can be introduced in order to limit the admitted technologies; such restrictions have yearly validity. In this way a good representation of a dynamic situation can be reached. The main aspects that can be studied in space and time are: waste recollection at municipality, destination of each type of waste, technologies operating at facilities, landfilling, material and energy recovering, cost, traffic impact due to waste transportation. The results of a first application referred to the Province of Ravenna, in Emilia Romagna Region, Northern Italy are presented in the final section.

Introduction

The aim of this paper is to present in a non-technical way the first result of a long term research aimed at producing a decision support system (DSS) to deal with the integrated solid waste management planning problem at territorial level.

The paper is organised as follows. First a short economic analysis of waste management in Italy is introduced and an overview of the problem addressed is presented. The following section deals with the implementation of the DSS and offers same details on the characteristics of the model. The final section presents a first application to the Ravenna Province in Italy.

The Italian situation and public intervention in waste management

In Italy in recent years urban waste management has received the public authority’s attention, which culminated in a new national law, known as Decreto Ronchi (Dlgs 22/97), which, together with its following modifications, redefined the entire sector widely accepting that solid waste management options should be selected based on a waste management hierarchy. The hierarchy puts waste prevention (avoidance and reduction) as the most preferred option, followed by re-use, recycling, waste treatment and disposal.

The main principles *of self-sufficiency* at State Level and *proximity* between production and disposal, introduced by the EEC Directive 156/91, has been reinforced and lowered to the infra-regional dimension in Italy[1].

Another important innovation is the emphasis on the *market approach* in waste management. Previously c*ommand and control* policy was the main approach adopted as derived from the earlier law (Dpr. 915/92). This law requested the Regions to plan and manage the waste treatment and disposal, leaving to the local authorities, the Municipalities (MUs) to organise collection and transportation. As a consequence the treatment and disposal markets are characterised by a monopolistic control of public companies, while collection is more competitive since many private subjects are also present.

Waste management and disposal are often visualised as a *merit* good. According to this view citizens don’t fully understand the real utility of the service; this wrong estimate determines a willingness to pay too low to make the service profitable to private operators. The market failure is corrected by the public action which covers the costs incurred with its own funds.

---

[1] This choice, confirmed by Dlgs 22/97, creates close local markets which could be inefficient but permit a closer control on the real destination of waste.

This approach could be correct if the citizens were really the counterparts, but this is not the case. In fact citizens are represented by the local authorities (MUs) which must take care of the disposal; they represent the demand not the citizens. In this case the wrong estimate cannot be justified any more. It should be also mentioned that at present in Italy the firms offering these services receive high profits.

A frequent justification for public intervention is the high incidence of fixed costs on variable costs which determines economy of scale, it's the case of *natural monopoly*. When the good or the service has the characteristic of being public, like water, electric power, telecommunication, … and citizens have a right to it, intervention is admitted in order to guarantee its supply. The high cost of building waste disposal facilities was one of the main reasons for maintaining public intervention. It should be noted that such costs are different according to the type of facilities and technology innovation reducing cost reduces also the reason for public intervention. Furthermore, the possibility to recover secondary inputs or to produce energy, compost, biogas from waste, determines new chances of profitability which also reduce the urban waste natural monopoly strength.

Waste management is often described as a network activity. It should be noted that this network does not require fixed infrastructures, such as water tubes, gasoline pipes, or electric lines, but only vehicles to transport the waste from the many production points to the facilities. Vehicles are mainly *ad hoc* trucks, which run on normal roads. This makes it easy to give the full control of the transportation phase to the waste producer, the municipality.

The previous elements seem to suggest that more and more waste management should be treated as a private good in more open markets. The Dlgs 22/97 goes in this direction. In fact, it changes the citizens' imposition from a tax to a tariff which must be linked to clear quali-quantitative parameters. The tax was based upon apartment size, regardless of the number of people living there, with this approach the household's have a marginal or incremental cost of waste disposal equal to zero. The weigh/volume based pricing aims to provide a direct incentive to reduce waste production. In this way citizens are encouraged to play a positive role by reducing waste production at the source.

A multicriteria approach to waste planning

General awareness of our environmental problems has led to the development of new technologies to minimise the environmental impact associated with solid wastes and has shifted the main concern of waste management from disposal to waste prevention, minimisation, and recycling. Nowadays, waste management involves considering an interrelated series of options aiming at waste source reduction, recycling, treatment and finally disposal. If properly managed many waste can be re-used or transformed into useful materials or energy, and different waste management options have been proposed and implemented during the last few years.

However, the control of environmental impact is just one of the goals that decision makers have to consider. Economic viability and social equity must also be taken into account. Efficiency must be introduced in the allocation of economic resources if we really want to pursue a sustainable development in the long-term. Social equity is concerned with how the benefits and costs of waste management are distributed among different groups within society. In fact, in nearly all public interventions there are winners and losers. Although a regional waste treatment or disposal facility may achieve the economics of scale required for economic viability, the siting of the facility is a difficult issue because the local community generally opposes the choice, the NIMBY "Not in my backyard" syndrome is always present; in this case, the local community is the loser while the regional community is the winner. This equity issue can be resolved by compensating the loser, and past experience have showed that the compensation cannot be only potential.

Italian Legislation requires to consider a series of waste management options aimed at source reduction and environmentally sound practices, and also to integrate the environmental soundness with economical viability and social equity. According to Dlgs 22/97 different points of view must be taken into account, but environmental soundness, economic efficiency, social equity are not necessarily consistent. In this multicriteria framework no optima solution exists *a priori* any more. The cheapest solution seldom is the best one environmentally. The best option in terms of environmental impact may not be the best according to social equity issue.

To support the integrated solid waste management which is now requested it is necessary to ascertain the environmental, economic and social impacts associated with various waste management options before decision makers can trade them off to achieve a better waste management strategy. In this context the lack of information on waste generation and composition, inadequate pricing of waste management practices and a lack of systems analysis (Pearce and Turner, 1993) represent serious hindrances which must be considered also in the analysis phase.

To cope with the previous problem a three level strategy is suggested [2] as illustrated in Figure 1:

1. zoning of the territory,
2. implementation of the waste plan,
3. Environmental Impact Assessment (EIA) on the proposed new facilities.

The three phases are subsequent.

In the first phase a multicriteria analysis is undertaken to zone all the territory in homogeneous areas according to their environmental and social characteristics. The zoning process ends classifying units as suitable or unsuitable for waste facilities[3]. Such a study has just been realised by many Italian regions which have classified their territory taking into account the different sectorial plans existing.

The second phase concerns the definition of the waste plan. At this level operations research models are particularly well suited for the description of complex systems involving many variables and constraints. These models may be used as DSS to help understand the complexity of the systems as well as assess the long-term role and impacts of new technological options.

In the third phase, according to the law, EIA studies are requested to verify case by case the environmental compatibility of the new facilities identified in the previous phase.

---

[2] The suggested approach is strictly related to the Italian situation even if with the requested modifications could be applied to many different realities.

[3] The same territorial unit could be classified as unsuitable for an incinerator but suitable for a material recover facility, but in Italy zoning is aimed at identify all the unsuitable area with a *ad excludendum* approach.

Operations research and waste planning

The focus will be now on a multi-objective dynamic mixed integer programming model (MODMIP) which applies at territorial level in the second phase of the previous scheme.

The first applications of operations research models to waste management were mainly concerned with specific problems (i.e.: vehicle routing, assignment of generating sources to landfills, transfer stations siting, site selection for landfills, etc.), offered a simplified description of the system and were subject to many limiting assumptions (i.e.: weak disaggregation of material flows, one processing option of each type, sites dedicated to one particular processing or landfilling technology, only one time period, recyclable/organic collections rarely taken into account, poor (or no) description of markets for recyclable, a single waste generating source, etc.[4]. In the nineties many studies presenting new and innovative models appeared in the literature. Gottinger [1991] suggested a dynamic network flow model with non linear costs for waste management and facility-siting decisions. Caruso et al. [1993] proposed a multi-objective mixed integer programming model working at regional level over a single time period. Chang et al. [1993] introduced first a dynamic mixed integer programming model and then Chang and Wang [1996] transformed it into a multi-objective one having four different criteria, three of them being environmental functions. Baetz and Neebe [1994] suggested a dynamic mixed integer programming model which considers revenues from sales to markets. Everett and Modak [1996] proposed a multiperiod and multi-regional model. Sundberg et al. [1994] adopted a static non-linear programming model, MIMES/WASTE. Environmental considerations are taken into account. Berger et al. [1988] proposed an integrated model EUGENE which seems able to treat very general real-life systems.

A DSS for solid waste management

In Italy data on waste production are only available for arbitrarily determined spatial units, the municipalities (MUs), representing an aggregated level which makes the problem manageable; MUs are the lower level of the system. Different MUs are grouped in a aggregate administrative unit, the Province, which according to the legislation represents the area to be considered in the waste management plan. The waste basin represents the higher level of the system and it can be subdivided in smaller areas, each grouping same MUs on the basis of their location in the territory and always characterised by the presence of landfilling facilities. These sub basins are strictly interrelated and represent the intermediate level of the system. Such an administrative territorial subdivision can be integrated to take into account specific situations such as the proximity of municipalities which are not included in the administrative border even if they are really integrated with the basin, as well as facilities located very close to the border or, even if far away, with some peculiar characteristics which require consideration in the study.

Different options exist for waste collections at MUs level. According to the Dlgs 22/97 three different alternatives, not mutually exclusive, are considered:

- undifferentiated waste,
- monomaterial recovery,

---

[4] One example of such a model is LAWMAN (Local Authority Waste Management) by the CSIRO (Crawford et al., 1988).

- inorganic/organic fraction.

In Italy, up to now most of the collection has taken the form of undifferentiated waste[5]. The cited law requires a minimal percentage of recovery starting from 2000[6] and suggests a separate collection for the organic/inorganic fraction of the urban waste. Therefore, the three options must be all contemporarily present in the model, even if with different importance in different MUs and years. The model permits to specify all these parameters. For instance, it is possible to define that a particular recyclable/organic collection is only available for some MUs, or define a different undifferentiated waste collection percentage in different MUs. The total waste generated at each source and time period is an exogenous parameter; such data must be estimated on the basis of the data collected by MUs according to previous legislation[7]. The quantity of materials collected in a given MU depends on the participation rate of the households and the capture rates of each of the collected materials. All these parameters can be treated as variables with lower bound predetermined varying along the time horizon considered, Figure 2.

Once the waste is collected, it must be transported to one or more sites to be processed or landfilled. Different vehicles can be used each characterised by its own cost. Specific relations trucks/materials can be easily introduced.

The model adopts, like most transportation models, a network approach to the problem which can be represented by nodes and arcs, Figure. 3.

Four types of node can be identified:

1. waste generating sources,
2. processing locations,
3. landfilling locations,
4. transport nodes.

The number and location of nodes for each category is controlled by the user.

These four types of node are linked together using flows which can represent aggregated flows (i.e., those associated with waste, recyclables and organic collections) as well as disaggregated flows (RDF, paper, plastic, …).

In fact, just two types of node can be distinguished: the transport nodes and all the others. The first permits to describe the territorial situation of the study area. Municipalities, existing and proposed location for facilities of any kind, as well as points of interest, can be individually identified. If a connection is allowed among them, which means that a possible route is recognised, then an arc can be quantified according to the distance existing. In this way a complete network of the area can be depicted. Only this network is considered to quantify the distance travelled and the relative impacts. This network represents the infrastructure upon which all the other nodes can be located. In this way it’s possible to link many other nodes to one trasportation node. For instance, a node can be identified as the location for a MU, a waste processing and a waste landfilling facilities[8].

---

[5] Nearly 90% of the waste produced go directly to landfilling.

[6] The recovered materials must reach 40% of the total urban waste production within 4 years from the adoption of the waste territorial plan.

[7] It should be mentioned that not all the municipalities have collected such data.

[8] The arc existing between the transport node and the municipality or a facility is never considered in the estimate of the different indexes adopted.

It should be mentioned that the waste generating sources can also be external to the area defined as the waste basin. In many cases contractual agreements or technical reasons can suggest to import into the system such external production. In the same way the model permits to send to external locations waste for processing and or landfilling. This introduces a great reality into the model. Examples are importation of urban waste from MUs which, even external to the administrative basin border, are located very near to one of the existing facilities which often are located right at the border of the basin.

Figure 4 presents a schematic illustration of the network of the municipal/provincial solid waste system handled by the DSS.

The basic facilities considered in the model are: material recovery, selection, composting, RDF, burning, landfilling, each characterised by technical and economical coefficients.

The complete waste disposal cycle can require more than one treatment according to the technologies adopted. This requires a complete description in terms of flows at the processing/landfilling nodes. In the model, waste collections, like inorganic fraction or undifferentiated which represent aggregated flows, are treated as individual products represented as disaggregated flows of a specific waste/material. In this way it is easy to verify the balance of the material from the generation points to the final destinations and the transportation problem can be completely described at territorial level quantifying the flow generated for each arc and node in every year.

At the processing facilities transformations take place. Each facility can be characterised by one or more operating modes. The main facilities considered are as follows:

- the material recovery facility (MRF) receives collections of recyclables (aggregated flows) and separates them into flows of individual marketable products (like papers, plastics, metals, glass) and rejects (disaggregated flows) which must be taken to the landfilling locations. Different types of MRF, each characterised by proper coefficients and relations, can be introduced. Waste, if not already dense, may be compacted in many of them. MRF operate also as transfer stations where waste is unloaded from smaller collection vehicles and re-loaded into larger vehicles for transport to a disposal or processing site[9]. Drawbacks to transfer stations include the additional capital costs of purchasing trailers and building transfer stations, and the extra time, labour, and energy needed for transferring waste from collection trucks to transfer trailers.
- the refuse derived fuel (RDF) is produced through waste separation and size reduction of inorganic waste at a specific facility; the combustibles can also be pelletized and stored. Up to now RDF have been limited in application due to the need to have large industrial areas in close proximity to market the fuel to, or another burning facility where energy will be produced. Both facilities, RDF producing and burning with energy recovery, have been considered.
- composting plants (CP) may process organic collections (aggregated flows) which act as input for the facility and produce compost, humidity and waste. According to Dlgs 22/97 organic fraction cannot be landfilled starting from 2000 but must be taken to composting

---

[9] Transfer represents sound practice when there is a need for vehicles servicing a collection route to travel a shorter distance, unload, and return quickly to their primary task of collecting the waste. They are particularly suggested when facilities are designed to serve a large region, with the result that they are sited at a considerable distance from the collection service areas; in this circumstance, since transporting waste from the MUs to the facility takes longer and uses more fuel, transfer stations can be very useful.

plants. Two different composting facilities are introduced into the model, high quality and low quality composting. The former receives basically organic waste collected as separated fraction, the latter transforms organic separated in a previous processing. The different quality of inputs determines different output. The high quality compost is supposed to be an organic fertiliser to be used in agriculture[10], the low quality compost is supposed to be used for public purposes, for instance to fill abandoned surface pits.

- landfilling (LF) facilities represent the final destination of the waste; different types of LF are introduced according to the toxicity of the materials stored in accordance with the existing legislation.

For each facility it is possible to define the complete list of waste and material that can be allowed to be processed at the site, such a definition can be modified on a yearly basis. According to the preference of the decision maker specific filters can be introduced in order to limit the admitted technologies (processing or landfilling are both technologies) for some waste. In this way it’s possible to reproduce in the model real situations which, even if inefficient, represent the existing reality, for instance as consequence of operating agreements or changed law requirements. The restrictions have yearly validity, in this way a good representation of a dynamic situation can be reached. For example consider the undifferentiated waste case: until 2000 it can be sent directly to landfilling, from 2001 this will not be possible any more and undifferentiated waste will be sent to other destinations basically MRFs.

Specific restraints allow the user to define the maximum processing capacity of a technology on a specific location in each time period. Only for land filling facilities total capacity are considered. If requested, other restraints can control the minimum and maximum number of installed facilities for each technology at each time period.

The model gives the possibility to locate in the same site more facilities to the user, in this way it’s possible to construct waste integrated platform which permit to reduce cost and impacts. Instead in literature it is very common to have only one technology available for a particular processing/landfilling location. According to the model, a given site may eventually be developed for any of the uses implied by the list of alternatives defined by the user who is not forced to an *a priori* decision on the use of the sites. In other words, the model chooses if the site needs to be developed, the type of technology that will be installed in it, and the schedule of activity on the basis of the options which the user has previously identified.

According to the input concentration and quality, for each operating mode it’s possible to specify the appropriate output coefficients. In this way high flexibility is introduced into the model which permits to describe many different technologies also for the same facilities. The model computes directly the yields of the intermediate technologies (i.e. MRF, CP, RDF, LF) from the model parameters. Parameters are exogenously determined, case by case, on the basis of the technical information offered by engineers and waste facilities experts. For instance, the amount of energy produced from the burning of one ton of waste depends on the heating values and shares of the individual waste components in the waste collection. In the same way, the yields of an MRF depends on the processed items. The user can easily change the values of these parameters, all the yields will be automatically recomputed by the model. This feature

---

[10] The feasibility of the agricultural use of the high quality compost is a strong assumption which require severe control on the quality of the product and possibly incentive to create a private convenience to use it.

offers a great deal of new information which permits to evaluate different technologies for many facilities.

Modelling the cost of technologies represents one of the most difficult tasks because of the difficulty of data collection. The cost is a concave function of capacity which exhibits economies of scale. We assume that a facility requires capital cost to be built and same annual operating cost for each year of activity. The model permits to consider the enlargement of existing facilities as well as the construction of new ones. For any new investment construction cost is introduced into the model as a fixed reintegration cost, higher as the facility capacity increases, operating costs are instead decreasing according to the capacity, Figure 5. To model this situation requires the introduction of binary (integer) variables. The number of options considered for each facility increases the complexity of the model and for this reason only few options are considered.

In most cases the economic life of the facility is longer than the time period considered by the plan, in these cases the residual values are quantified and both values, total discounted investment cost and discounted residual cost, are presented in the final report.

The model permits to specify different costs for different materials, in this way it’s possible to study ex-ante the impacts of regulatory policies. Other options introduced into the model permit to investigate the effect of new taxes on waste that can be landfilled or the effect of price support to recovered material.

Appropriate markets can be defined for many materials, like energy, collections of recyclable and compost. However, market prices of most of these materials are highly uncertain and variable. In response to this situation the model may be used to study the sensitivity of the system to price variations.

An overview of the model

The model is process oriented and based on the mixed-integer programming paradigm. As stated by Wilson [1977], the merit of such an approach "is that large numbers of strategies may be evaluated against several criteria on a routine and consistent basis, giving the planner better information on which to base his recommendations."

The problem addressed by the model can be stated as follows:

given:

- the locations of sources and the generation of each type of waste from each source,
- the various types of collections of waste,
- a set of sites where facilities can be located,
- a set of existing or potential processing (like composting, material recovery, etc.) and landfilling technologies,
- a set of markets for energy, materials and compost,
- the distances between the sources and locations,
- a number of time periods and their length,
- same scenario parameters;

determine:

- the percentage of organic/inorganic collection to adopt,
- the assignment at each time period of each collection from each source to each processing/landfilling location,
- the activity of each technology for each operating mode at each location and time period,
- the assignment of the materials generated at each site to other sites,
- the vehicles to use in the transportation phase.

The minimisation of an objective function determines the result under the constraint that all the waste produced must be collected, processed and landfilled according to the allowed technologies.

At the moment four objective functions have been defined, others may follow,

1. total cumulative distance;
2. total cumulative landfilling;
3. total cumulative traffic impact;
4. total discounted net cost.

The first is the total distance requested to transport waste and collect materials from production locations[11] to processing and landfilling facilities and to markets.

The second is an index which quantifies the total cumulative landfilling, the less waste is taken to landfilling, the more materials are recovered through monomaterial collection at municipality level and/or during processing at recovering facilities. Reducing such a quantity reduces also the social impact connected with the requirement of new landfilling facilities which are highly opposed by citizens. Reducing waste going to landfill becomes very much the measurement of performance in waste management at the local government level.

The third is an index which quantifies the total cumulative traffic impact; each arc is characterised by an appropriate index related to road traffic. Minimisation of such an objective implies minimisation of the impact on traffic due to waste transportation, which in Italy is completely realised by trucks running on public roads.

The fourth is the discounted total net cost, which is the discounted summation of all the cost and revenues each with its right sign. Costs, with plus sign, include annual collection and transportation costs, annual operating costs, investment costs, as well as the costs paid to external facilities in case of waste transferred outside the basin. Revenues, with a minus sign, include annual revenues from sales to the markets and the revenues deriving from importing waste from the external sources. Taxes and price support are also included with their proper sign.

The model is multi-period with the number of the time periods, each of one year’s length, defined by the user.

Almost all data can be varied with time.

The model was implemented using the highly flexible and powerful General Algebraic Modelling System (GAMS). Model is described in concise algebraic statements while all data are entered only once in list and table form saved in ASCII files. Results are also saved in this form.

---

[11] They can be municipalities or intermediate facilities.

The case study: Ravenna waste management system

A first application is referred to the Province of Ravenna, in the Region of Emilia Romagna, Northern Eastern Italy. The study was realised on the basis of a convention with the Regional Agency for the Environment (ARPA) in a preparatory phase of the new waste management plan. The case study considers a 5 year period 1999-2003.

The Province, which represents the basin, was segmented into 3 sub-basins (lughese, ravennate, faentino), each grouping several MUs (i.d production areas). In detail, 18 MUs are present distributed as follows: 9 lughese, 3 ravennate, 6 faentino[12], Figure 6.

The complete description of the existing road network required about 50 transport nodes.

Processing/landfilling facilities are divided into developed and potential: 11 facilities of 6 different types are already developed, some of which grouped in a multifunctional platform near Ravenna, while 5 others are only potential.

A yearly working capacity has been estimated for each facility, only for landfilling also total capacity has been included.

The application considers 36 different materials (including waste components, recyclables, organics, recovered materials).

Different scenarios have been examined considering changes in demand (such as waste generation rate, participation and set-out rates); changes to service (i.e. types of recyclables collected, change in collection methods); changes in infrastructure (such as availability and location of facilities), changes in policies (such as incentive programmes for waste minimisation and user-pay program).

In the basic case scenario, the present Municipal Solid Waste (MSW) generation rate of the Ravenna residential sector is approximately 201 376 tons per year. Since the population is not increasing, this figure is not expected to change in the next future. An additional source is represented by the Special Assimilate Waste (SAW), whose production 79 458 tons is expected to remain constant in time. Therefore 280 834 tons represent the total year's production. The complete situation is represented in Table 1. The table shows that sub-basin 1 produces 2/3 of the total waste. This is due to the presence of the town of Ravenna, with its high concentration of population.

The urban waste fraction can be separated into seven categories according to the composition which is differentiated at the sub-basin level. Table 2 indicates that nearly 2/3 represent the inorganic fraction, and only 1/3 the organic one. The previous data are introduced into the model in a more disaggregate way, i.e. at MUs level.

Even if the total quantity and composition does not change in time, the interception rate of the monomaterial collection does. Table 3 shows that better results are reached for glass and paper. The interception rate for the latter will go from to 20% to 50% in the next five years as required by the Dlgs 22/97.

The remaining waste is partly collected through a differentiated collection, which maintains separate the organic and inorganic fractions, and the rest as undifferentiated. Since organic collection is very costly it should apply only to those households that are willing to participate.

---

[12] It should be mentioned that in fact some flows are generated in the imolese sub-basin and imported following existing waste treatment agreements. Such MUs are easily identified on the basis of the assigned node code

The previously described basic scenario emerged from the ARPA estimates and it must be emphasised that up to now the study is conducted according to the Agency's preferences. In the optimal solution, waste is sent to the processing facilities according to the schedule in tons presented in Table 4.

Table 5 quantifies the recoveries at the processing facilities in tons. The previous materials add to the ones collected at the MUs. The 121 784 tons of low quality compost are supposed to be used to fill abandoned urface pits at zero cost, instead an agricultural market, not existing yet, is visualised for the high quality compost. The revenue deriving from the previous recovered materials and energy adds to the reduction of the waste mass to be landfilled. Arrivals at the existing landfilling facilities in this scenario determine a quite high residual capacity of landfilling sites which can satisfy a demand deriving even from a less satisfactory material recovery scenario.

Another result of the analysis conducted is the estimate of the unsatisfied processing capacity. Three different facilities are requested: an incinerator for RDF with energy recovery from the first year of activity as well as a low quality compost facility. The need to open a new high quality composting facility appears instead only from the forth year of the plan and it could be overcome if the existing agreement with the society which is managing the existing one could be increased.

The impacts on traffic were also quantified since for each arc it has been possible to quantify the yearly flow due to the transportation phase.

All the previous results have be condensed in the new Ravenna Waste Plan adopted by the Province in October 1998.

Future developments and conclusion

In this paper a three level strategy is suggested to deal with the integrated planning of regional solid waste management at territorial level. The approach has been adopted by public authorities in Italy.

The opportunity to generate and evaluate *ex ante* different scenarios suggested to create a highly flexible model which could be used as a decision support system for the regional decision makers to cope with the new Italian waste legislation.

A mixed integer dynamic programming model permitted to study in space and time:

- waste production at municipalities,
- collection choices,
- destination options for each type of waste,
- technologies operating at facilities through the input/output coefficients and the maximum capacity constraint,
- cost and benefit,
- effects of policy,
- traffic impact.

The model has been applied to the Province of Ravenna in a preparatory study of the new Urban Waste Plan. Different scenarios have been examined considering changes in demand (such as waste generation rate, participation and set-out rates); changes of service (i.e. types of recyclables collected, change in collection methods); changes in infrastructure (such as availability and location of facilities), changes in policies (such as incentive programmes for waste minimisation and user-pay program). The study has showed that the introduction of organic-inorganic collection represents a necessary option to reach the target fixed by Dlgs 22/97. According to the new plan, emission of methane at landfilling facilities will be reduced with positive effect on greenhouse effect. It should also be noted that recycling has highly positive environmental effect reducing the net emissions in manufacturing relative to a system based on virgin manufacturing.

This first experience has confirmed the utility of the DSS adopted and created the conditions for future developments and improvements which should occur in the next future. The most important among these are:

- the quantification of environmental indexes which will permit a multi objective analysis of the waste plan offering new insight on the trade-off existing between the different objectives considered;
- the construction of a friendly environment to insert data based on a geographic information system (GIS).

The DSS will hopefully be soon applied to others realities, we are now working on this.

References

Ambiente S.P.A. (a cura di), “Smaltimento RSU – Alternative a confronto”, Pubblicazione AUSITRA – Assoambiente, 1996.

Baetz, B.W., and A.W. Neebe, "A Planning Model for the Development of Waste Material Recycling Programmes", Journal of the Operational Research Society, Vol. 45, No. 12, 1994, pp. 1374-1384.

Berger, C., G. Savard, and A. Wizere, "the model: An Optimization Model for Integrated Regional Solid Waste Management Planning", to appear in International Journal of Environment and Pollution, 1998.

Bianchi D., “Dalla raccolta alla riduzione dei rifiuti: fondamenti ecologici ed economici e strumenti per una politica di gestione dei rifiuti dal lato della domanda”, Prima Conferenza Nazionale sui Rifiuti Solidi Urbani, Legambiente, Roma, 4-5 maggio 1995.

Caruso, C., A. Colorni, and M. Paruccini, "The Regional Urban Solid Waste Management System: A Modelling Approach", European Journal of Operational Research, Vol. 70, No. 1, 1993, pp. 16-30.

Chang, N.B., and S.F. Wang, "Solid Waste Management System Analysis by Multiobjective Mixed Integer Programming Model", Journal of Environmental Management, Vol. 48, No. 1, September 1996, pp. 17-43.

Chang, N.B., R.E. Schuler, and C.A. Shoemaker, "Environmental and Economic Optimization of an Integrated Solid Waste Management System", The Journal of Resource Management and Technology, Vol. 21, No. 2, June 1993, pp. 87-100.

Crawford, J. R., Mashford, J. S., Newton, P. W. and Sharpe R. (1988). "A planning model for solid waste disposal". In P.W. Newton, M.A.P. Taylor and R.Sharpe (eds.), Desktop Planning: microcomputer applications for infrastructure and services planning and management, Hargreen Publisher Co., Melbourne, Chapter 16.

Decreto legislativo 5 febbraio 1997, n. 22 “Attuazione delle direttive 91/156/CEE sui rifiuti, 91/689/CEE sui rifiuti pericoli e 94/62/CEE sugli imballaggi e sui rifiuti di imballaggio”.

Everett, J.W., and A.R. Modak, "Optimal Regional Scheduling of Solid Waste Systems. I: Model Development", Journal of Environmental Engineering, Vol. 122, No. 9, September 1996, pp. 785-792.

Gerelli E., “Società post-industriale ed ambiente”, Ed. La Terza, 1994

Gottinger, H.W., Economic Models and Applications of Solid Waste Management, Gordon and Breach Science Publishers, New York, 1991.

Istituto di Ricerche Ambiente Italia: “Vantaggi ambientali dei diversi sistemi di smaltimento dei rifiuti e rassegna internazionale tecnologie”, Milano , 1994.

Legge regionale della Regione Emilia Romagna 12 luglio 1994, n. 27, “Disciplina dello smaltimento dei rifiuti”.

Merzagora W., and S. P. Ferrari, “Impianti di trattamento dei rifiuti solidi urbani e assimilati – Indagine 1995”, Pubblicazione AUSITRA – Assoambiente, 1996.

Ministero dell’Ambiente, “Relazione sullo stato dell’ambiente”, Istituto Poligrafico e Zecca dello Stato, 1997.

Pearce, D.W. and Turner, R.K. (1993). "Market-based approaches to solid waste management". Resources, Conservation and Recycling, 8, 63-90.

Provincia di Ravenna (1998), “Piano Provinciale di Gestione dei Rifiuti Urbani e Speciali della Provincia di Ravenna”, Ravenna

Regione Emilia Romagna (1997), “L’incenerimento dei Rifiuti. Ricognizione sulla Realtà Regionale”, L. Morselli ed., Bologna.

Richardson, A. J. And Wang, F. S. (1994). "Domestic Solid Waste Management: the Forgotten End of the Urban Goods Movement Chain". Forum Papers, 19th Australasian Transport Research Forum, 583-601.

Riva A., and E. Tiezzi, “I rifiuti come risorsa sostenibile”, RICICLA, 1997

Sundberg, J., P. Gipperth, and C.-O. Wene, "A Systems Approach to Municipal Solid Waste Management : A Pilot Study of Göteborg", Waste Management and Research, Vol. 12, No. 1, February 1994, pp. 73-91.

Wang, F. S., Richardson, A. J., and Roddick, F. A. (1994). "SWIM - An Interactive Model for Solid Waste Integrated Management". 2nd National Hazardous & Solid Waste Convention, Melbourne, pp. 134-140.

Wang, F.S., Richardson, A.J. and Roddick F.A. (1996). "Development and Application of the SWIM Model". 3rd National Hazardous and Solid Waste Convention, Sydney, Australia. May.

Wang, F.S., Richardson, A.J., Roddick, F.A. and Curnow, R.C. (1994). "SWIM - Interactive Software for Continuous Improvement of Solid Waste Management". Journal of Resource Management and Technology, 22 (2), 63-72.

Wilson, D.C., "Strategy Evaluation in Planning of Waste Management to Land - A Critical Review of the Literature", Applied Mathematical Modelling, Vol. 1, March 1977, pp. 205-217.

Tab. 1 Waste production

	MSW	SAW	TOT.
1 RA	126762	55962	182724
2 LU	51027	16820	67847
3 FA	23587	6676	30263
Tot.	201376	79458	280834

Tab. 1 Waste composition

	1 RAVENNA	**2 LUGO**	**3 FAENZA**
PAP	26.9	19.0	30
PLA	14.3	5.0	17.1
MET	2.0	3.0	2.0
GLA	4.6	13.0	4.7
ODW	16.0	23.0	14.5
ONW	18.2	24.0	14.5
OTH	16.8	13.0	14.0

where:
PAP paper, PLA plastic, Met metal, GLA glass, ODW domestic organic,
ONW non domestic organic, OTH other.
ODW and ONW together determine the organic fraction.

Tab. 3 Monomaterial recovery at MUs

Material	**Year**				
	1	**2**	**3**	**4**	**5**
PAP	0.200	0.275	0.350	0.425	0.500
PLA	0.100	0.112	0.125	0.137	0.150
MET	0.050	0.055	0.060	0.065	0.070
GLA	0.400	0.450	0.500	0.550	0.600
OTH	0.070	0.077	0.085	0.092	0.100

Tab. 4 Recovery at the facilities

Output	**1**	**2**	**3**	**4**	**5**	**TOT.**
PAP	3407	4541	4800	5010	5168	22926
PLA	1704	2270	2400	2505	2584	11463
MET	4900	6064	5854	5638	5418	27874
GLA	2555	3406	3600	3757	3876	17194
OTH	3407	4541	4800	5010	5168	22926
CHQ	11691	14027	16362	18697	21033	81810
CLQ	22267	27109	25595	24122	22691	121784

Fig. 1 Multicriteria approach to waste management

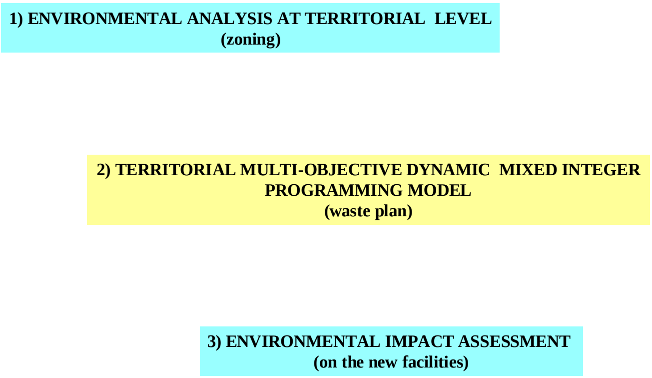
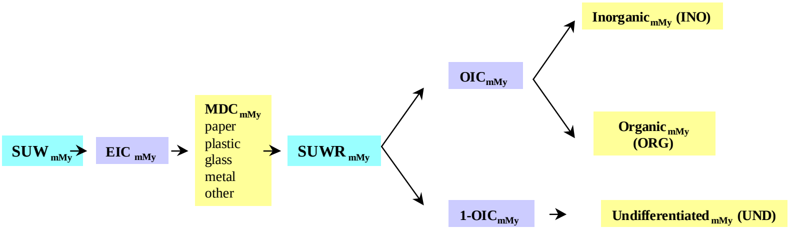


Fig. 2 Waste collection



SUW_{mMy}	**Solid Urban Waste production(for: material, Municipality, year)**
EIC_{mMy}	**Expected Interception Coefficient (for: material, Municipality, year)**
MDC_{mMy}	**Monomaterial Differentiated Collection (for: material, Municipality, year)**
$SUWR_{mMy}$	**Solid Urban Waste Residual after MDC (for: material Municipality, year)**
OIC_{mMy}	**Organic/Inorganic Coefficient (for: material Municipality, year)**

Where: m = material; M = Municipality; y=year

Fig. 3 Flowchart of waste collection, recovering, processing and landfilling

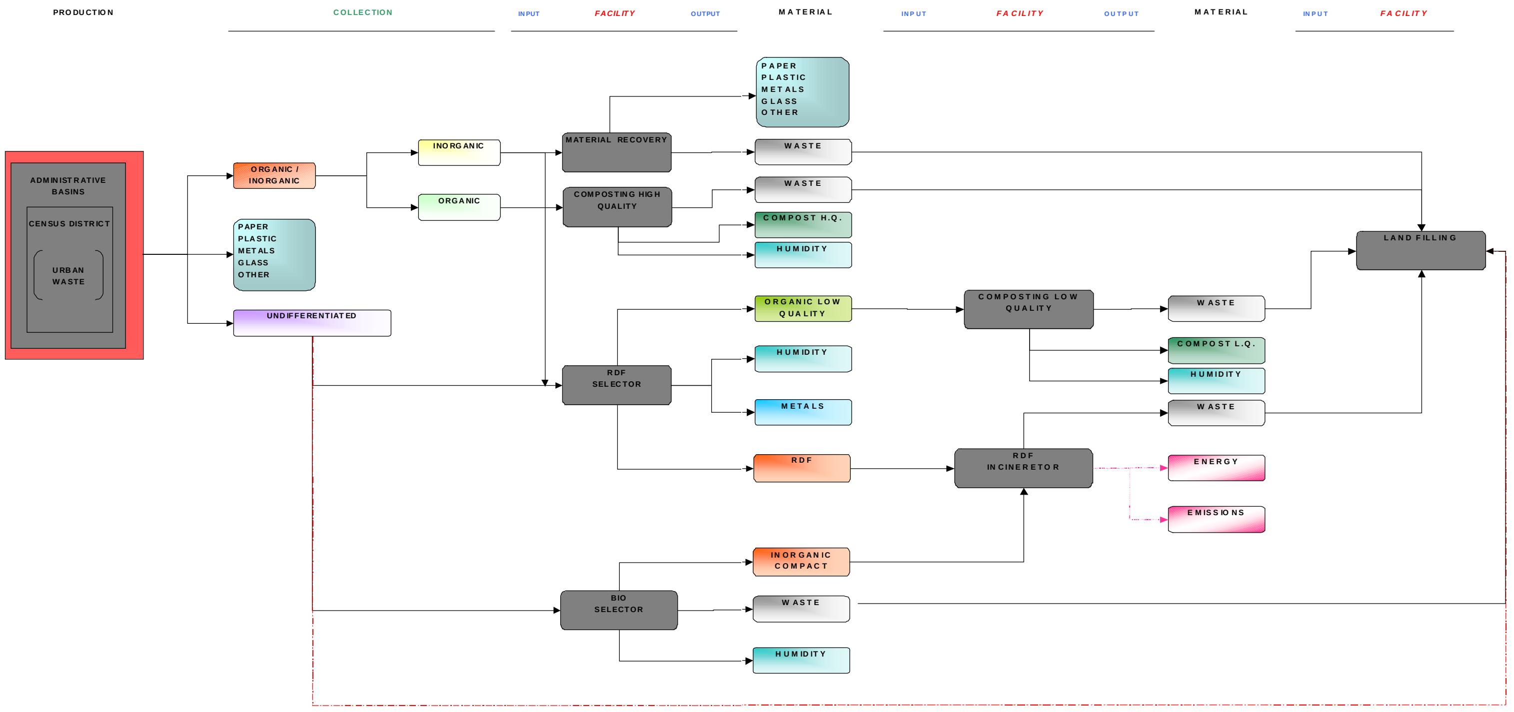


Fig. 4 Network of nodes and arcs with internal and external flows

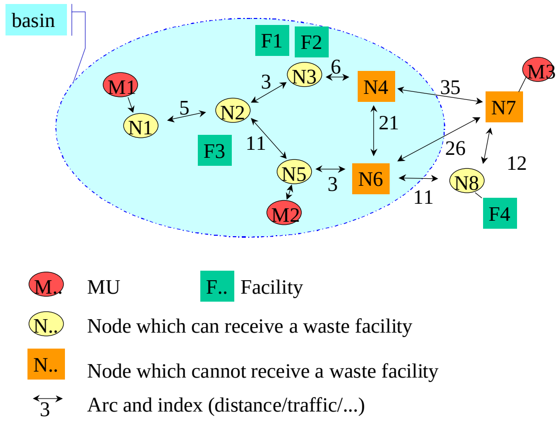


Fig. 5 Total facility cost function

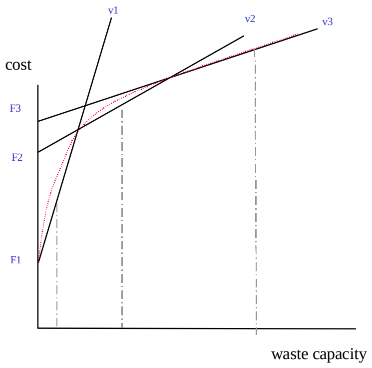


Fig. 6 Ravenna basin and sub-basins