Waste management system optimisation for Southern Italy with MARKAL model

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Abstract

The MARKAL models generator was utilised to build up a comprehensive model of the anthropogenic activities system which points out the linkages between productive processes and waste disposal technologies. The aim of such a study is to determine the optimal configuration of the waste management system for the Basilicata region (Southern Italy), in order to support the definition of the regional waste management plan in compliance with the Italian laws. A sensitivity analysis was performed to evaluate the influence of landfilling fees on the choice of waste processing technologies, in order to foster waste management strategies which are environmentally sustainable, economically affordable and highly efficient. The results show the key role of separate collection and mechanical pre-treatments in the achievement of the legislative targets. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Integrated waste management; MARKAL model; Regional planning; Atmospheric emissions

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1. Introduction

An optimal resources management requires the development of a comprehensive methodology to take into account the entire life-cycle of products, processes and activities, including resources consumption, costs and environmental burdens. Environmental costs must be included in the total costs of commodities to perform a correct cost–benefit evaluation and to properly assess the impact of economic activities on the environment.

The modelling environment must be [1]:

- **comprehensive**, to take into account the physical constraints and to exploit the feedback among different productive sectors and the waste management system;
- **optimising**, to find the most effective solutions either from an environmental or from an economical point of view;
- **driven by the demand** of goods and services, to allow a better optimisation of welfare, avoiding an over-exploitation of supply;
- **multi-period and dynamic**, to take into account technology development, depreciation times and costs and to catch the main technological and socio-economic changes;
- **technology and energy oriented**, to find for each considered time period, the processes and fuels that can satisfy the end uses demand with the lowest environmental impact.

Such requirements are successfully met by the MARKAL models generator, developed in the late 1970s by a consortium of 14 countries under the aegis of an IEA committee (Energy Technology Systems Analysis Development Programme, ETSAP). The original model has been subject to further implementation to take into account different purposes and nowadays, it is widely used by most of OECD member countries to support energy-environmental planning at national and local scale [2–7].

The recent developments of MARKAL regard the integration of energy and material flows [8], broadening the possible utilisation of the methodology to life-cycle analysis [9].

This paper focuses on an implementation of MARKAL to analytically represent the waste management system [10,11]. The waste management MARKAL model (WAMMM) was developed to support the definition of the waste management plan of Basilicata region (Southern Italy). It represents a first step for the implementation of a comprehensive model capable of performing an integrated optimisation of energy and materials flows at regional scale.

The advantage of using MARKAL is to have a source of models capable of describing in detail, energy supply and energy demand, allowing users to analyse and exploit the relationships among the different macroeconomic sectors. In particular, the WAMMM deals with the modelling of the local waste management system, which plays a key-role in the framework of the overall optimisation of the anthropogenic activities system, allowing further extensions of the basic to fulfil future requirements.
2. The planning framework

2.1. The waste issue: problems and normative

In the last decade, waste management issues have gained importance. The main problems that must be considered are the following:

- **A remarkable increase in the amount and variety of wastes.** The production of municipal solid waste (MSW) in Italy has increased considerably: between 1991 and 1994, the volume of MSW increased by 13.5%, whereas the per capita waste production rose from 350 to 398 kg. In the last 25 years, the organic waste fraction has halved from 53 to nearly 23% and the ‘synthetic’ fraction (mainly plastics and card/cardboard) has doubled from 21 to 53% [12,13];

- **A growing demand for waste disposal, not satisfied by an efficient and environmental compatible system.** Some 67.7% of the waste produced is deposited in landfills. In particular, this percentage rises to 88% with regard to municipal solid waste (a percentage among the highest in Europe), whereas the remaining 6.9% of the total waste is recycled and only 5.1% is incinerated, a figure far below that of other countries in Europe (e.g. France 37.1%, Germany 27.9%, UK 14.3%) [14]. As a matter of fact, a considerable amount of the total landfilled waste is dumped in uncontrolled conditions causing many environmental troubles: mineral and organic pollution of ground and surface water, soil and sub-soil contamination, emission of air pollutants, especially during waste fires, etc.;

- **The increasing environmental impact of the anthropogenic activities.** Economic and demographic growth induce an increasing demand for commodities, which causes a depletion of natural resources and an increase of environmental pollution. Such a development is unsustainable. A more rational use of resources is required, based on energy and material recovery [15];

- **The prejudices of the population about the utilisation of the incinerators and the lack of information.** As a matter of fact, most of the incinerators operating in Italy in the 1970s were closed down after a few years due to public concerns regarding the emission of highly dangerous pollutants (mainly dioxins and furans). Modern technology can be provided with a great variety of air pollution control equipment assuring high performances and reliability. Therefore, the public opposition may be overcome by promoting information campaigns on the pros and cons of different waste processing technologies, which could help people to face the ‘waste problem’ in a more correct way.

In order to solve the specific problems at national and local scale, several laws were promulgated in Italy. In particular, in 1997 the Dlgs. n°22/97 (the so-called ‘Ronchi Law’ from the name of the Minister of Environment) tried to resume and organise these rules in the framework of the EU directives (in particular, with reference to 91/156/CEE, 91/157/CEE, 91/689/CEE, 94/62/CE), serving as a comprehensive framework for waste management.

The most relevant features regard waste valorisation (by energy recovery and materials recycling) and a change in the service tariffs, at present calculated on the
basis of the house areas, which will be turned into a rate, split up in a fixed part (related to the number of persons belonging to the same family) and in a variable part, correlated to the actual amount of waste disposed.

In particular, by 16th July, 2001 only inert, pre-treated or otherwise specified waste can be landfilled, whereas new incinerators must be equipped with energy recovery devices. Moreover, 35% of separate collection is mandatory in 2003, with intermediate targets of 15 and 25%.

In the new regulations, according to the ‘proximity principle’, the waste produced in a region must be dealt with inside that region. Waste management plans will be defined by regional authorities and carried out in the territorial areas identified as optimal basins.

Concerning the end-life phase of vehicles and durable domestic goods (television sets, washing machines, refrigerators, etc.), appropriate recovery systems have to be set up. In the case of durable domestic goods, these systems must cover the take back phase.

Moreover, in line with the EU packaging directive, six management consortia have been established, one for each packaging material (glass, plastics, aluminium, steel, paper) and one overall co-ordination structure [16]. Representatives of all the life cycle stages (production, distribution, use) must take part in the consortia, according to the ‘principle of shared responsibility’.

2.2. The local system

The planning problems of Basilicata region are mainly related to the low density of population (≈ 61 inhabitants/km²), the inadequate road network and the lack of adequate waste processing facilities.

More than 50% of the 131 municipalities is populated by < 3000 inhabitants, as shown in Table 1 [17]. Most of them use small and often uncontrolled landfills. At this moment, the only operating waste treatment facility technology is a small composting plant near Matera town (the second administrative centre of Basilicata region), whereas a new incinerator will treat wastes produced by a mechanical industry (FIAT) and the MSW of a small group of towns around the industrial area.

<table>
<thead>
<tr>
<th>Classes of inhabitants (No.)</th>
<th>Municipalities (No.)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–1000</td>
<td>15</td>
<td>11.5</td>
</tr>
<tr>
<td>1000–3000</td>
<td>57</td>
<td>43.5</td>
</tr>
<tr>
<td>3000–6000</td>
<td>32</td>
<td>24.4</td>
</tr>
<tr>
<td>6000–15 000</td>
<td>22</td>
<td>16.8</td>
</tr>
<tr>
<td>15 000–100 000</td>
<td>5</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Table 2
MSW composition for Basilicata region and Italy

<table>
<thead>
<tr>
<th>Components</th>
<th>Basilicata region 1997 (%)</th>
<th>Italy 1995 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermentable and others</td>
<td>51.7</td>
<td>34</td>
</tr>
<tr>
<td>Card and cardboard</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Plastic and rubber</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Textile, wood and leather</td>
<td>5.3</td>
<td>4</td>
</tr>
<tr>
<td>Metals</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Glass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

In order to meet the legislative objectives, the regional waste management plan has to define solutions which must be affordable for small to mid-size districts. The Basilicata region authority has attempted to analyse these questions in great depth in the framework of the definition of the regional plan for waste management [18]. A preliminary study was carried out to collect, make uniform and compare data on waste generation, collection, delivery and treatment [19]. The analysis has revealed that the average pro-capita MSW production ranges between 0.86 (1995) and 0.89 (1997) kilograms per day, with a 4% annual average increase. Therefore, the estimated annual total MSW production at 2001 (the basis year for the planning process) is 226,000 tonnes. The regional MSW average composition is shown in Table 2 compared with the national values [19].

The amounts of secondary raw materials (card and cardboard, plastics, glass, metals) recovered are still low (~ 3000 tonnes per year, in 1997) even though they have an increasing trend due to better organisation of the separate collection system (in 1995, only 1000 t were collected).

3. The method of analysis

Let us first recall the structure of the MARKAL models generator, to point out the fundamental features which gave rise to the WAMMM model.

3.1. The MARKAL models generator

MARKAL (an acronym for MARket Allocation), is a models generator based on linear programming (LP) techniques [20,21]. It represents a comprehensive tool for energy system analysis, allowing the user to combine and take simultaneously into account energy, social–economic and environmental constraints in determining the optimal configuration of the anthropogenic activities system. Moreover, it is possible to perform a medium to long term analysis, splitting the time period into several time periods of fixed length (typically 3 or 5 years). The user can thus define a different data input for each period in order to represent the subsequent
developments of the analysed system. This feature is of fundamental importance to follow technology development and to compare different energy–technology scenarios.

Analytically, the linear programming methodology requires the definition of an objective function and a representation of the relationships among supply and demand sectors by means of a set of linear inequalities.

In the MARKAL environment, the primal objective function is represented by the total discounted system costs. In particular, investments, operations and maintenance costs of the technologies are included and have a fundamental importance in determining the optimal solution.

A least cost solution is then determined by minimising the total system cost in compliance with the constraints defined by the model user.

Technologies are described by two kinds of tables. Economic parameters include the investment and maintenance costs, the life duration, the date of availability of new technologies and the residual capacity of existing technologies. Technical parameters include the efficiency of the technology (expressed as input/output ratio). Emission factors are introduced in relation to each fossil fuel and/or technology. Additional constraints can be set on the atmospheric pollutant emissions [22].

Among the actual available versions, the M-MARKAL (where M stands for material) was chosen in the WAMMM. In particular, the structure of M-MARKAL allows the user to utilise a new set of balance equations specific for material flows, which substitute the inequalities typically used for energy flows. Therefore, waste generation can be treated as mining of waste flows.

3.2. The REMS

The reference energy and materials system (REMS) represents the basic technological configuration of the analysed system, defining the fundamental parameters of the model database. The REMS is usually represented by a flow diagram, to emphasise energy and materials flows from supply to demand through the network of technologies.

The definition of the reference set of technologies is of fundamental importance to meet the planning objectives, assuring the model a flexible choice which is compatible with the local resources availability in the considered time horizon.

Concerning the waste management plans, they must be operative in the short term, whereas the effects of the waste management re-organisation on economic and environment can be appreciated over a medium time horizon. This implies that in this case, the reference energy and materials system should include only consolidated and already marketable technologies, to allow the planners a short-term actuation of the new system configuration.

Moreover, both Italian and European directives on waste management promote action programmes based on the following topics:

- diminution of waste volume;
- valorisation of waste (energy and materials recovery);
optimisation of waste disposal and minimisation of its impact on environment (reduction of waste transfer, landfilling of only non valuable waste) [23].

As a consequence, the proposed reference waste management system is based on an integrated technological set-up which takes into account the existing resources and the geomorphology of territory, allowing the planners to make better use of resources, exploiting the synergies between productive processes and waste processing technologies. Fig. 1 shows the Basilicata region REMS, which includes screening operations, composting plants, incinerators, aerobic stabilisation processes and landfills. In the model database, each process has been characterised by consumption, average life, efficiency, investment costs, operating and maintenance expenditures and delivery costs according to the MARKAL features.

As shown in Fig. 1, besides separate collection, the unseparated waste may be further split by a rotary drum in two different flows, which can be advantageously processed by subsequent treatments:

- a **dry** flow, which can be incinerated with energy recovery,
- a **moist** flow, suitable for biological treatments: in particular, the aerobic stabilisation is appropriate to avoid the unpleasant production of biogas in landfill due to anaerobic degradation.

The screening mesh dimension influences the ratio among the two streams produced and, in general, their average composition. Experimental tests carried out on waste in standard conditions with five different wire mesh dimensions (40, 60, 80, 100 and 120 mm) show that the larger the screening dimension is, the more moist flow is produced [19]. At the same time, the pre-selection process based on large wire meshes produces smaller amounts of dry flow but with a higher energy content.

A more effective bring network for glass, plastic, metals and card/cardboard and the recovery of fermentable waste (mainly kitchen waste) is also provided to achieve the law targets. This choice is funded on the following considerations:

- Fermentable waste potentially represents 50% of the waste (as reported in Table 2) and is the main nuisance for landfill management and biogas production [23];
- Repeated failures associated with unsorted MSW composting operations throughout the last 40 years [24] suggest the adoption of two different biological treatments for the valorisation of the moist fraction (composting for selected food scraps from refectories, pruning residuals, etc. and aerobic stabilisation for unsorted fermentable waste);
- The separation of the moist fraction allows better use of the incinerators, burning only the dry fraction of the waste (with a higher energy content);
- Local markets exist for high quality compost.

4. Scenarios hypothesis

In order to investigate the requirements of waste processing technologies at short- and medium-term, a fundamental step in the analysis is the definition of the scenarios and cases hypothesis. Therefore, several scenarios were defined, taking in
Fig. 1. The REMS of the WAMMM model.
the normative issues (limited use of landfilling and increasing separate collection) and the size of grid for screening to apply on the remaining waste. Moreover, for each one of them, the model was run for a series of cases in which the landfill fees were varied parametrically (Table 3).

In particular, the actual situation is represented by the base scenario (separate collection target: 5%), whereas the medium-term conditions are characterised by the 35% separate collection target (as imposed by Ronchi Law in 2003). Between them, a 15% separate collection case adds only the recovery of selected fermentable waste to the base case.

This choice enables the identification and comparison of different strategies in terms of total discounted system cost, energy and materials recovered, landfills volume variations, pointing out the important role of the separate collection and the pre-selection process (screening) on the amounts and characteristics of the waste management streams. On the other hand, it is also possible to evaluate the influence of the disposal fees on the choice of the waste disposal system configuration.

5. Results

A first step to assess the best configuration of the waste disposal system consists in the evaluation of the landfill volume required in the different scenarios (Fig. 2). This volume can be compared with the actual regional landfill availability (that is \( \approx 700000 \text{ m}^3 \)) in order to determine the landfill exhaustion time relative to each

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Wire mesh dimensions (mm)</th>
<th>Cases: landfilling fees (EUR/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>No screening (only landfilling)</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>SC: 5%</td>
<td>C1</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>D1</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>E1</td>
<td>120</td>
</tr>
<tr>
<td>SC: 15%</td>
<td>C2</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>E2</td>
<td>120</td>
</tr>
<tr>
<td>SC: 35%</td>
<td>C3</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>D3</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>E3</td>
<td>120</td>
</tr>
</tbody>
</table>
examined scenario (Fig. 3). In particular, if no waste is diverted towards other technologies, the existing landfills will be exhausted in only 2 years at the actual separate collection target (5%). The achievement of the 35% separate collection target fixed by law does not represent a remarkable improvement: the total volume of existing landfills can last for \( \approx 3 \) years (saving only an extra year compared to the actual situation). The use and dimension of the screening wire mesh allows a more significant reduction of landfill requirements. The smaller the wire meshes are

![Figure 2. Requirement of landfill volume.](image2)

![Figure 3. Exhaustion time for existing landfills.](image3)
the lower the required landfill volumes become (because of a larger use of incinerators, which causes an 80–90% reduction in volume of the input waste). In particular, with a 35% separate collection target, the required landfill volume decreases from 64 to 82% depending on the screening wire mesh (120–40 mm).

As concerns the greenhouse gases emissions, Fig. 4 shows for each scenario the amounts of carbon dioxide equivalent (CO₂eq) released in the atmosphere by the regional waste management system. According to the concept of global warming potential (GWP) the ‘carbon dioxide equivalent’ measures the possible warming effect on the atmosphere from the emission of each gas in relation to carbon dioxide. In particular, the contribution of methane (CH₄) as a greenhouse gas was calculated considering that 1 ton of CH₄ has a GWP 21 times larger than the CO₂ one on a 100-year basis, as suggested by the International Panel for Climate Change [25]. Comparing the different waste management strategies, it can be noted that a disposal system based only on landfilling is characterised by the highest amount of carbon dioxide equivalent which is reduced 13%, increasing the separate collection of secondary raw material from the actual 5% up to 35%. To achieve a more effective reduction of CO₂ and CH₄ emissions, it is necessary to pass to an integrated system based on waste separation. The screening wire mesh dimension plays an important role: reducing it from 120 to 40 mm, the CO₂eq emission reduction percentage spans from 54 to 59% (58% at 80 mm).

Table 4 shows the contribution of different waste processing technologies at the total emission of carbon dioxide equivalent and the credits from electric energy recovery (separate collection target: 35%): the minimum value can be achieved using an 80 mm screening mesh (−46%).
To evaluate the effects of landfilling fees on the waste management system configuration, a sensitivity analysis was performed for each separate collection target.

Fig. 5 shows that at the actual fees (20 EUR/m³) landfilling is the cheapest option, whereas increasing the landfilling fee up to 70 EUR/m³, the integrated configuration with an 80 mm screening mesh becomes the minimum cost solution for all three separate collection targets. Moreover, the comparison among the three sets of the 70 EUR/m³ curves points out an overall decrease of the total discounted system cost due to the increase of the separate collection targets (−21% at 80 mm).

This implies that the optimal screening mesh dimension is 80 mm, both from an environmental and economical point of view. In particular, the CO₂eq reduction is ≈139 Kt, with an average unit cost of 64 ECU/t.

6. Experiences in policy support

In Basilicata region (Southern Italy), a working group was set up in order to draw up a waste management plan (Regional Council Decision No. 732, 10th March, 1998), in compliance with the laws in force and the existing sector plans.

The regional waste management plan (WMP), is aimed at regulating the activities of waste collection, transportation and disposal of waste collection, encouraging the reduction of waste production and their valorisation.

The main steps involved in the definition of the Basilicata region WMP are:
1. Analysis of the normative framework;
2. Characterisation of the main territorial and geographical features;
3. Survey on the amounts and composition of the regional waste streams;

<table>
<thead>
<tr>
<th>Emissions (ton per year)</th>
<th>Screening wire meshes dimension</th>
<th>BASE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 mm</td>
<td>60 mm</td>
</tr>
<tr>
<td>Total CO₂</td>
<td>99 051</td>
<td>91 410</td>
</tr>
<tr>
<td>Landfilling</td>
<td>8027</td>
<td>9235</td>
</tr>
<tr>
<td>Composting</td>
<td>15 086</td>
<td>15 086</td>
</tr>
<tr>
<td>Aerobic stabilisation</td>
<td>12 732</td>
<td>17 665</td>
</tr>
<tr>
<td><em>Incineration</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste burning</td>
<td>88 447</td>
<td>73 559</td>
</tr>
<tr>
<td>Energy recovery</td>
<td>−25 240</td>
<td>−24 135</td>
</tr>
<tr>
<td>Total CH₄</td>
<td>2887</td>
<td>3322</td>
</tr>
<tr>
<td>Total CO₂eq</td>
<td>159 684</td>
<td>161 170</td>
</tr>
</tbody>
</table>
Fig. 5. Effects of an increase of landfilling fees on the total system costs for different separate collection targets: 5% (a), 15% (b), 35% (c).

4. Preliminary selection of the waste processing technologies suited to the local case, taking into account the best available technologies as well as the best examples of waste management systems existing at national scale;
5. Implementation of a comprehensive optimising model (WAMMM) for analysing energy and material flows;
6. Definition of the optimal waste management system configuration.
The working group has supported decision-makers in all the above mentioned phases, individuating the waste management system configuration discussed in previous paragraphs as the best suited one.

In order to make effective the strategies outlined by the working group, regional authorities have to define the following operative tools:

- **Normative and economic**: incentives, taxes, environmental restrictions, etc., to foster correct public behaviour in the achievement of planning priorities;
- **Information and training**: to promote environmental information and the participation of the population.
- **Control tools**: to verify the effectiveness and the public response to the proposed strategies;
- **Up-dating**: to guarantee a dynamic up-dating of the operative tools, eventually checking again the initial goals.

### 7. Conclusions

The complexity and uncertainties which affect the planning process make necessary the definition of a comprehensive methodology to support decision makers, taking into account different issues (technical, legislative, social-economic).

Moreover, the waste-to-energy and waste-to-materials issues are becoming more and more important in the scientific as well as in the normative debate, requiring a new approach which overcomes the traditional sectorial planning.

In this context, the MARKAL model generators represents a versatile and powerful tool, capable of following the evolution of the planning process. This work presents an innovative application of such a model, which extend the typical applications in the energy sector to the waste management system.

The MARKAL-based WAMMM represents the first step to afford the problem of an overall optimisation of the anthropogenic activities system, maintaining a sector level of detail. This feature is useful, in particular, to exploit the feedback among the commodities demand side and the supply system, evaluating separately the contribution of each sector to the fulfilment of the planning goals.

The results show that the key-parameters for the actuation of the proposed integrated system are: boundaries on land use (limits on the annual volumes landfilled), environmental constraints on greenhouse gases and waste disposal fees.

In any case, the success of a waste management plan is strongly dependent on the involved ‘human factor’, therefore, particular attention has to be paid to training, organisation and information promotion for increasing public concern and participation.

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