EXECUTIVE SUMMARY

This paper presents the methodology that has been followed and the results that came up from the elaboration of an EC co-financed LIFE+ project in Greece (LIFE09/ENV/GR/294). The objective of the project is to develop a software tool that enables Waste Management Authorities and other stakeholders to substantially reduce GHG emissions resulting from their waste management (WM) activities. The tool provides "decision support" for the optimization of WM practices, in terms of GHG emissions and financial data through a simulation environment, where an existing or desired regional / local waste management system can be designed by the user. The innovative idea is the incorporation of an optimization function through which the tool will calculate the optimal values for the decision variables using Mathematical Programming (MP). The results of the software tool enabled the identification of procedures for the development of Local Action Plans, which aim to reduce GHG emissions from waste management activities at local level. Each Action Plan sets specific quantitative goals for GHG emissions reductions, specifies the means to attain them, as well as the relevant investments that need to take place and the timing of these investments.

INTRODUCTION

The main objective of the WASTE-C-CONTROL project is to develop a software tool that assists decision-makers to design and evaluate different integrated waste management systems, from the level of waste generation up to the level of waste treatment and disposal, on the basis of overall GHG emissions and management cost. In addition, the evaluation is extended also to ancillary environmental impacts, such as generation of air pollutants.

The investigation of different WM alternatives is performed through mathematical programming, the outcome of which is the identification of those integrated systems where their overall GHG emissions can be reduced only at the expense of management cost. In other words, the tool assists the user to build the so-called ‘Pareto frontier’ in the particular situation faced. In this way, decision-makers...
become aware of trade-offs involved in their waste management problem and are able to select a solution by being aware of the main dilemmas and constraints faced.

The tool has been tested through three case studies in Greece, namely in the Regional Union of Chania, Crete, the Region of Eastern Macedonia-Thrace (north-eastern Greece) and the Region of Western Macedonia (north-central Greece). In this paper, data and results will be presented for the Region of Eastern Macedonia and Thrace (REMTH).

**METHODOLOGY**

The mathematical model that describes the Municipal Solid Waste (MSW) management system is developed using the principles of Mathematical Programming (MP). All the available technologies and paths of the MSW system are expressed in the model with proper relationships (equalities and inequalities). The model consists of the decision variables (the unknowns of the problem), the parameters (the known data), the constraints (the relationships that describe the system) and one or more objective functions (the drivers of the optimization).

Borrowing ideas from the field of process synthesis in chemical engineering, the problem can be formulated as a multi-period structure, design and operational optimization problem (Iyer and Grossmann, 1998). All the available MSW options and their interdependencies can be considered in the superstructure of the system (topology of all the available MSW options) and the MP model proposes the best solution. A simultaneous, structural, design and operational optimization of the MSW system is achieved i.e. the output of the created model is which technology units will be used and which paths are followed for the MSW system (structure), what is the capacity of these units (design) and what are the flows and operating loads to and from the units (operational optimization). MP has already been used for the optimization of MSW systems in various cases (see e.g. Abou Najm and El-Fadel, 2004, Louis and Shih, 2007, Jing et al., 2009).

The model which is developed is a multi-objective mathematical programming model. Specifically it has two objective functions: (1) the Net Present Value of the system over the 20-year horizon and (2) the CO$_2$-equivalent emissions. As the name suggests, multi-objective optimization (or multi-criteria optimization) involves optimisation in the presence of more than one (usually conflicting) objective functions (criteria). The main difference between single and multi-objective optimization is that in the case of the latter, there is usually no single optimal solution, but a set of equally good alternatives with different trade-offs, also known as Pareto-optimal (or non-dominated or efficient) solutions. The Pareto optimal solutions are the feasible solutions that cannot be improved in one objective function without deteriorating their performance in at least one of the rest. In the absence of any other information, none of these solutions can be said to be better than the other. Usually a decision maker is needed to provide additional preference information and to identify the “most preferred” solution (“optimal” according to his/her subjective preferences). Depending on the paradigm used, such knowledge may be introduced before, during or after the optimization process. Multi-objective optimization thus has to combine two aspects: optimization and decision support (Steuer, 1986). In the present study, the generation of the Pareto optimal solutions will be done using a version of the popular epsilon constraint method (Mavrotas, 2009).

**Model Building**

The mathematical model will describe the MSW system as a directed graph. There are nodes that represent the processes and arcs that represent the flows between the processes. The boundaries of the system are defined from the collection phase till the final disposal. The model will represent the
superstructure of the system, i.e. all the available options with their interconnections as shown in Figure 1. In Figure 1, one can see how the bins are connected with the processes, how the processes are interconnected and which the main products of each process are. It must be noted that for each generic technology there are more than one specific type of units that can be utilised which are mutually exclusive. For example, for Composting we have 5 types of units while for MBT we have 18 types of units. The optimal type of unit for each technology will be selected by the model.


The model is properly formulated in order to perform structural, design and operational optimization. In other words, the major questions that will be answered with the optimization process are: which processes (structure), what will be their capacity (design) and what will be there annual operational load (operation). All these figures will be computed in period-wise basis. In technical terms the model is a Multi-Objective Mixed Integer Linear Programming (MO-MILP) model, which means it contains continuous and integer (mostly binary) variables. The basic elements of the multi-objective mathematical programming model are briefly described below:

Objective functions
Two are the objective functions of the problem: (1) the minimization of the Net Present Value (NPV) of the MSW system over a period of 20 y, which represents the economic objective and (2) the minimization of total CO\textsubscript{2}-eq emissions of the MSW system, which represents the environmental objective. The NPV incorporates the investment and operational costs, as well as the income from recyclables, electricity and other products over a 20-year period.
**Decision variables**
The decision variables of the model are actually the unknowns of the problems, i.e. those variables for which we are trying to find their optimal values. In our case we have discrete (binary or integer) and continuous decision variables. The discrete variables are mostly associated with the structural characteristics (is i-th technology present in the optimized MSW system? how many units will be needed?). The continuous variables are mostly associated with the design and operational characteristics (what is the capacity of i-th unit in period t? Which is the amount of waste transported from i-th unit to j-th unit?).

**Constraints**
The main constraints of the model are the mass balances that have to be satisfied between nodes (equality constraints) and the capacity constraints that have to be satisfied (“less than” constraints). There can be policy constraints (e.g. the recycling rate or the amount of waste sent to landfill). Logical constraints are also present in order to apply conditions for mutually exclusive alternatives. Auxiliary constraints may also be present (e.g. linearization of non-linear terms). Special reference should be made to the modeling of the landfill and the associated CH$_4$ emissions. It has been done using the IPCC guidelines and takes into account five waste categories (food, garden, paper, textile and wood) and the different behavior of treated – untreated material. The calculation of the CH$_4$ emissions (and therefore the CO$_2$ – equivalent) takes into account in a flexible manner the possibility of flaring, as well as the ongoing process of CH$_4$ emissions after the expiration of the study horizon. These ex-post emissions are explicitly calculated and participate in the minimization of CO$_2$-eq. objective function.

**Parameters**
The parameters of the model are the known data. These data are the economic and technological characteristics of the processes, the prices of the recycled materials and produced energy, and the conversion factor of every ingredient in each one of the candidate technologies. The original waste is classified in 34 ingredients and its composition is considered known for the model based on representative past data. The scheme of the bin configuration is also considered as given (which types of bins are used) in the model. The different bin schemes can be examined as different scenarios.

**Modes of Operation and Expected Results**
The model can be used as an optimization tool or just as a simple calculation tool. The user can adjust the extent of optimization by controlling the degrees of freedom of the model. Instead of performing a full optimization (with all the degrees of freedom), he/she can consider some technologies as given and the system will be optimized given this information. In this case the corresponding decision variables will have fixed values in the optimization and will not be altered. Moreover, the user can impose constraints (user defined constraints) on the flows (e.g. no more than 30,000 tn/year can be sent from the mixed waste bin to the MBT units). The full model includes approximately 24,445 continuous variables, 210 integer variables and 12,399 constraints.

The optimization of the multi-objective model provides a representative set of the Pareto optimal solutions for the MSW management problem. With the term “solution” we mean the structural characteristics (which units will be constructed in each period), the design characteristics (the capacity of the units, what capacity expansions will be required) and the operational characteristics (annual waste flows between the units). All these amounts are expressed with appropriate decision variables and their values will be the main output of the system, of course along with the value of the objective function(s).
The model is multiperiod and has a dynamic evolving element over time, following the scenario for the quantity of produced MSW (20y horizon divided into four periods). The results of the optimization will refer to each period of time and there will be inter-period constraints quantifying the relevant linking relationships. The model has been implemented and solved using the widely known modeling language GAMS / General Algebraic Modeling System (Brooke et al., 1998).

SOFTWARE TOOL

The Waste-C-Control tool is a decision support software (DSS) targeted to experts and/or practitioners in the field of MSW management. The user is able to examine various scenarios by designing conceptual architectures of MSW systems by selecting among the component technologies. Depending on the selected component technologies the system creates the conceptual architecture by adding in the graphical map the respective type of bins in the collection system, the types of landfills for disposal following the superstructure constraints illustrated in Figure 1 and the links among the component technologies (Figure 2). Note that for the disposal we use two types of landfill, with the hazardous connected only with the Waste to Energy component. For each technology (i.e. composting, anaerobic, WtE, etc.), many types of processes have been incorporated. Therefore, the software contains an extensive library with cost data (capex, opex) and environmental data (emissions, fuel consumption, etc.), for each technology type. Data has been drawn from literature, but also from questionnaires distributed to operating plants in Greece and Europe.

Figure 2 Conceptual map of an MSW system

Subsequently, the user has to define the parameters of the MSW system: (a) the composition of the MSW generated, (b) the collection system parameters, i.e. bin models, collection frequency, etc., (c) the component technologies parameters, e.g. min/max capacities of units in tonnes per year, etc., and (d) the transportation parameters, e.g. truck models of each link, average distances, etc. Next, the user may define constraints to be considered in the optimization problem, e.g. recycling targets, restrictions on the number of units, or in the flows between component technologies and run the optimization. The outcome of the optimization is the “Pareto frontier”; in this case a curve with the x-axis representing the net present cost for the 20y horizon and the y-axis the environmental impact of each solution, thus tons of CO_{2}-eq. (Figure 3). The user may select a point on the Pareto curve and see the parameters and outcomes of the respective solution analysed in the four 5-year periods (Figure 4).
Figure 3 Pareto curve for the feasible solutions of an MSW system

Figure 4 Summary of the outcomes of a feasible solution
CASE STUDY: THE REGION OF EASTERN MACEDONIA-THRACE (REMTH)

Background Information
REMTH lies in the North-East part of Greece and is divided in five Regional Unions with a total of 22 Municipalities, with the main urban centres being Drama, Kavala, Xanthi, Komotini and Alexandroupolis. The rest of the municipalities are rural based. Also, the two islands / municipalities of Thasos and Samothrace are included. The total population is approximately 610,000 inhabitants.

Waste quantities are estimated based on the daily production rate of MSW per inhabitant. This rate is estimated as 1.40 kg/(inh.*d) for the urban areas and as 1.14 kg/(inh.*d) for the rest municipalities. This estimation results in a quantity of 320,000 tpa MSW, with an annual increase of 1.5%. The estimation is verified by sample weighing of the MSW collection vehicles.

REMTH has an officially approved Regional Waste Management Plan (RWMP, 2009), as dictated by the relevant Greek legislation. The RWMP sets key issues for MSW management:

- Utilization of transfer stations (TS) to efficiently (in environmental and cost terms) transfer waste to the dedicated facilities
- Achievement of the Packaging Directive targets by use of dedicated bins for dry recyclables and Material Recycling Facilities (MRF)
- Achievement of the Landfill Directive targets (Dir. 99/31/EC) by: a. Recycling of the organic fraction of MSW (separate collection and biological treatment) and b. Treatment of the rest of MSW in Integrated Waste Management Units (IWMU), incorporating mechanical –biological treatment in two central facilities with energy and material recovery and landfill of the residue.

So far, not all of the planned facilities have been constructed and MSW management is based mainly on landfill. Currently, the use of two (2) transfer stations has been initiated and one Material Recycling Facilities (MRF) (six are foreseen by the RWMP). As a result, the recycling of waste packaging material (“blue bin”) is practised only in three municipalities. The recycling of special types of solid wastes, such as ELVs, tyres, WEEE, batteries, etc., is extensively practiced in the whole Region.

Tool Application in REMTH
DIAAMATH, the formal Waste Management Body of REMTH, participates as a beneficiary in the LIFE 2009+ project. DIAAMATH has used the Waste-C-Control Tool to examine several waste management options (scenarios) with the aim to propose improvements to the MSW management plan (as applied so far, but also as planned in the official RWMP), in order to reduce GHG emissions and costs. The results (improvements) of this application will be incorporated in a Local Action Plan (LAP) that DIAAMATH is determined to apply.

Seven (7) scenarios were formulated using the software tool. The rationale behind the scenarios development was that from scenario 1 to scenario 7, there is a gradual improvement of waste treatment options, from only landfilling to more sophisticated options:

1. One – bin system for the total MSW – Landfilling. (Blank scenario).
2. Two – bin system/6 spots: packaging material (“blue bin”) and the rest MSW. Packaging Material recycling in six MRFs - landfilling of the rest MSW. The software “decides” the MRF technology, their capacity and the mass flow in the respective 5-y period.
3. Two – bin system/2 spots: Like scenario 2, but 2 MRFs, 2 composting facilities. The software “decides” also for the composting technology, capacity and mass flow.
4. Three – bin system/6 spots: packaging material (“blue bin”), organic fraction of MSW (OFMSW) and rest MSW. Recycling in 6 MRFs, composting of OFMSW in 6 composting facilities and landfilling of the rest MSW. The software “decides” for the MRF and composting technology, capacity and mass flow.

5. Three – bin system/2 spots: Like scenario 4, but 2 MRFs, 2 composting facilities

6. Three – bin system/2 spots/MBTs. Like scenario 5, but treatment of rest MSW in 2 MBTs producing RDF and in situ thermal utilization of the RDF. The software “decides” respectively for the MRF, composting, MBT and RDF thermal treatment technology, capacity and mass flow.

7. Three – bin system/2 spots/MBTs. Like scenario 5, but treatment of rest MSW in 2 MBTs producing RDF. Ex situ thermal utilization of the RDF (sale to end user). The software “decides” respectively for the MRF, composting and MBT technology, capacity and mass flow.

**Results - Local Action Plan**

Each scenario was a different “run” of the software and one Pareto front with 11 feasible solutions was produced for each scenario (see Figure 5). Based on the tool’s results, the most favoured scenario is 7.

![Figure 5 Pareto “fronts” or curves, for each scenario in REMTH](image)

One can see from the curves that Scenario 7 results in lower emissions and costs. The points of each curve are the 11 feasible solutions that the tool produces. Each solution consists of different structural, design and operational characteristics. The decision-maker may choose the least costly one or (usually), the one in the middle of the curve.

By examining the scenarios and the feasible solutions of the preferable scenario, DIAAMATH has formulated a Local Action Plan (LAP), for the short-term, mid-term and long-term, with policies and measures regarding recycling of materials, collection and transport of wastes, waste treatment and disposal. The relative cost for the application of the LAP can be obtained by the software tool, while the reduction of GHG has been quantified, as well. As such, the environmental and cost “impact” of the plan is transparent to all involved stakeholders and can be communicated to the public.
Transfer of waste
The operation of all planned transfer stations should begin as soon as possible (short-term target), since, according to the tool, this results in lower GHG emissions (compared to current fuel consumption data), regardless the scenario examined.

Recycling of materials
In a mid-term period, the recycling of packaging materials by the “blue bin” system should be expanded to most of the municipalities in REMTH. Also in a mid-term horizon period the initiation of the operation of a second MRF should be considered.

Additionally, the introduction of a 3rd bin (organic bin) should apply, with the respective composting facilities. The tool indicated that two simple open-windrow composting plants would be sustainable for the case of REMTH.

Waste treatment
In the long-term the treatment of waste should be a reality by the utilization of appropriate treatment facilities. The solution positioned in the middle of the curve for scenario 7 (light purple curve, Figure 5), consists of two MBTs with the “B” part being dry anaerobic digestion and the “M” being high intensity mechanical pretreatment to supplement packaging waste recycling and to produce RDF. It is preferable to utilise the RDF in ex-situ installations (even though a negative selling price was used). These suggestions will be taken into account when the realization of the MBT plants is due.

Waste disposal
Also, in a long-term horizon period the waste heading towards disposal and landfilling should be the minimum. This means that in a long-term horizon period the IWMU should be constructed and operational.

Expected results
The expected results, in respect to the foreseen improvements of the waste management system can be summarized in the following:

- **Short-term results (2012-2013):** Utilization of Transfer Stations with respective saving of fuel, time and money.
- **Mid-term results (until 2015):** Covering more municipalities with the blue bin system and respectively increasing the recycling levels. The increased recycling levels means less amounts of waste heading for landfilling, saving in this way valuable space-volume in landfills. Treatment of the OFMSW by saving and reducing the GHG emissions (especially CH₄) from landfills.
- **Long-term results (2016-2017):** Treatment of mixed MSW in MBTs will result in the minimization of landfilling, increase of recycling and recovery of renewable energy.

CONCLUSIONS
Mathematical Programming proved to be a reliable tool for the multi-objective optimization of the MSW management system. The developed model is flexible and can be customized to any case, as the main key parameters are determined by the user. The synthesis (which units), design (which capacity) and operational (annual flows) optimization provides the Pareto optimal solutions based on two criteria: (1) the net present cost over the 20 years period and (2) the cumulative CO₂-eq emissions over the 20-year period. The obtained Pareto fronts from different scenarios can be compared and the
tradeoffs among the Pareto optimal solutions within each one Pareto front can be also investigated by
the user. The dynamic evolution within the 20-year period of the corresponding technologies associated
with each solution is also calculated.

The application of the software tool in REMTH enabled the development of a Local Action Plan,
which aims to reduce GHG emissions from waste management activities at local level. Through the use
of the tool, DIAAMATH was able to answer questions like “what is the necessary number of
installations”, “what is the impact of adding OFMWS recycling in terms of costs and emissions”, “is it
necessary to use transfer stations”, etc. The answers to these questions, which could not be materialised
in the past, are now provided through an integrated solution that has been formulated and can be easily
communicated by DIAAMATH’s waste experts to decisions-makers and the broader public, by using
two comprehensive indicators: cost (NPV in million euros) and emissions (in CO$_2$-eq.), over a 20y
period.

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