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DECISION SUPPORT SYSTEMS IN SOLID WASTE MANAGEMENT: A CASE STUDY AT THE NATIONAL AND LOCAL LEVEL IN GREECE

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ABSTRACT

Decision support systems (DSS) are used to aid at solid waste management, a tedious problem with many technical, economic and social constraints. The main DSS available are briefly presented and the development of a novel system, ReFlows, is described. The novelty of the developed DSS consists of the detailed analysis of the collection subsystem and in particular the source separation and collection programs for recyclables materials. ReFlows utilises mathematical equations for material and financial flows, organised in several subroutines, to simulate the various sub-systems of an integrated solid waste management system and may be applied to any geographical scale, from the local to the national. The model, currently developed in MATLAB, is applied on recycling scenarios based on the degree of expansion of the different source collection schemes currently operating in Greece. Results are presented at a national (Greece) and a local level (Municipality of Athens). The main outcome of the study is that full expansion of the existing schemes may not fulfil the recovery goals for packaging waste in Greece. Improved collection schemes are required, based on more pilot programs in order to investigate the optimum recycling strategy.

KEYWORDS: solid waste, DSS, ReFlows, packaging recycling, Athens Municipality.

1. DECISION SUPPORT SYSTEMS (DSS) IN SOLID WASTE MANAGEMENT

The total amount of solid waste in the EU is expected to increase by about 45% between 1995 and 2020 (Hischier *et al.*, 2005). Nowadays, solid waste is a potential source of secondary raw materials. In 2001 the EU packaging directive was incorporated into the Greek national law. This directive regulates the recovery and recycling of packaging waste aiming at improved generation of secondary raw materials.

Solid waste management is a very complex issue. Several technical, financial and social problems have to be resolved simultaneously. Computer-aided approaches help the decision makers reach their final decision. Any computer-based system supporting decision making is defined as a DSS (Finlay, 1989). DSS incorporate computer-based models of real life biophysical and economic systems.

There are two main categories of DSS applied to solid waste management (SWM): the first one, based on applied mathematics, emphasises application of statistical, optimisation or simulation modelling. Contreras *et al.* (2008) utilise the analytical hierarchy process to analyse stakeholders preferences for SWM in Boston, USA. Sufian and Bala (2006) developed a dynamic computer model to predict solid waste generation, collection and electricity generation from solid waste with application in the urban city of Daka, Bangladesh. Ghose *et al.* (2006) propose a GIS optimal routing problem for the collection of municipal waste in India. Fiorucci *et al.* (2003) present a DSS based on the solution of a constrained non-linear optimization problem for application in urban areas. Karavezyris *et al.* (2002) present a

conceptual model for waste management systems which is based on system dynamics and fuzzy logic. Karagiannidis and Moussiopoulos (1997) utilise the ELECTRE III approach for the integrated SWM in Athens, Greece. Wang *et al.* (1996) presented SWIM, a simulation package based on Excel which follows the integrated waste management approach.
The second category of DSS provides specific problem-solving expertise stored as facts, rules and procedures. In addition, there are also hybrid approaches. De Oliveira Simonetto and Borestein (2007) developed SCOLDSS, a decision support system for the planning of solid waste collection. It is a hybrid system that utilise discrete-event simulation and algorithms/heuristics. The developed system is validated in the city of Porto Alegre, Brazil. Tsiliyannis (2005) uses a hybrid mathematical/heuristic approach to assess different reuse/recycle packaging waste schemes. Amponsah and Salhi (2004) use a heuristic approach to solve the problem of collection, transport and disposal of solid waste in developing countries. Jayawardhana *et al.* (2003) developed a rule-based expert system with application on organic waste composting in Sri Lanka.
Recently, there has been a major shift towards LCA computer-aided tools. LCA is a holistic approach that is increasingly utilised for solid waste management, especially in the decision-making process and in strategy-planning. LCA can be categorised as a hybrid approach since it utilises equations for inventory analysis and recycling loops on the one hand, while on the other it requires expertise input for impact assessment and characterisation. Riber *et al.* (2008) utilise EASEWASTE (Christensen *et al.*, 2007) for the environmental assessment of waste incineration. Liamsanguan and Gheewala (2008) calculate the inventory for the solid waste management system in Phuket, Thailand. The same research group (Wanichpongpan and Gheewala, 2007) examine the life cycle feasibility of a landfill gas-to-energy project. Buttol *et al.* (2007) apply the commercially available WISARD software to examine the LCA of the solid management system in Bologna, Italy. Özeler et. al. (2006), utilising the IWM-1 software, examine 5 different scenarios for the management of solid waste in Ankara, Turkey. Güereca et. al. (2006) analyse two alternatives for the management of the organic fraction of solid waste in Barcelona while Hischier *et al.* (2005) utilise LCA to compare two electrical and electronic equipment waste management schemes in Switzerland. Skordilis (2004) utilised a hybrid model based on worth benefit utility analysis and LCA to analyse integrated solid waste management in Corfu, Greece. Björklund *et. al.* (1999) utilise an early version of ORWARE (Eriksson *et al.*, 2002) to assess the solid waste management system in Uppsala, Sweden.
The scope of this paper is the presentation of the main features of ReFlows, a computer-aided decision support system for solid waste management. ReFlows, developed in MATLAB, is applied on recycling scenarios based on the degree of expansion of the different source collection schemes currently operating in Greece.

2. DESCRIPTION OF THE DEVELOPED MODEL

The ReFlows model simulates physical and financial flows in an integrated solid waste management system (Figure 1). It can calculate recycling and recovery performances achieved by different source separation schemes applied at local, regional and national level. The model aims to evaluate the performance of existing or planned waste management systems and configurations under different scenarios as compared to the quantitative targets defined by the solid waste management policies. Its original version was a spreadsheet module, which allowed high transparency of the system's complex calculations (Togia, 2003). In order to standardise and automate data input and accelerate the analysis of many different scenarios, a second version was developed by transcribing the spreadsheet rules and calculations into MATLAB (Karaiskou, 2006).

2.1 ReFlows model structure

ReFlows accounts for all the principal processes which constitute an integrated solid waste management system. It includes modules for waste generation, source separation, collection, alternative treatment methods (composting, incineration w/energy recovery) and final disposal (landfilling). Each process can be isolated in modular form with waste flows as inputs and outputs, incorporating in each module the corresponding financial flows (costs, subsidies and revenues from the sale of the recovered material and energy). Moreover, it can be interconnected with a common data structure and adaptable user interface modules (Figure

1). The user can thus work with the model at either the detailed level of each individual module or interact with the model to a higher level.

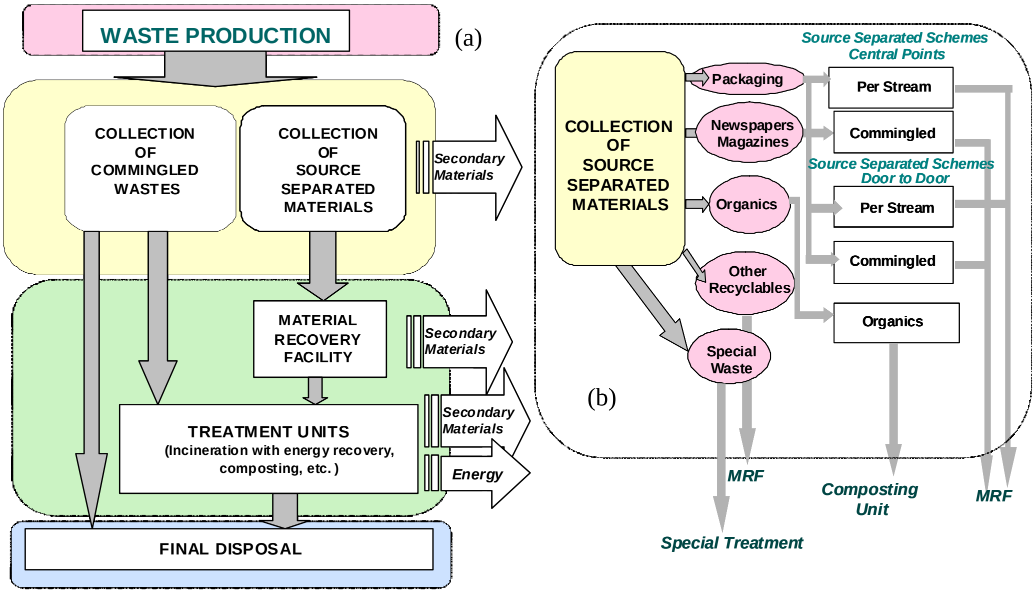

Figure 1. Schematic representation of (a) the model structure and (b) the collection module

The main model inputs and outputs are summarized in Table 1. Numerical specification of basic input data requires the completion of background studies or/and estimations. Default values are available for all the parameters. The user-DSS interface is an Excel spreadsheet. The model does not include any forecasting module for waste generation, which can be developed independently for various scenarios, if needed.

Table 1. Main inputs and outputs of the ReFlows model

Inputs	Outputs
Local parameters	
Annual waste generation per capita	Material flows per waste system
Population size involved in source separation	Financial flows per waste system
Costs per management system	
General parameters	
Physicochemical waste characteristics	
Treatment units performance characteristics	
Costs per treatment	
Taxation and revenues	

2.2 Material and financial flows

The material flows of the model are divided in 4 routines (see Appendix):

- Production routine, which calculates the quantities of municipal solid waste produced in a certain region in each waste category. Inputs to this routine are: a) the annual waste generated per category and capita and b) the population.
- Collection routine, which is made up of two sub-routines: i) mixed-bag collection and ii) collection of source separated recyclables. Inputs to this routine are: the population served by: a) the mixed-bag collection system and b) the recyclables collection system. In addition, the % recyclables collection rate is also needed.
- Treatment routine, which consists of four subroutines: i) the separation of collected materials subroutine ii) the special treatment subroutine for hazardous waste iii) the incineration subroutine with energy recovery, and iv) the mechanical recycling and composting subroutine. Inputs to each subroutine are the recovery performance characteristics per material per treatment method.

- Final disposal routine. Input to this routine is the waste that has not been treated in the treatment subroutines or the remaining output of the treatment subroutines.

The financial flows of the system are described by the following two key equations:

$$C_T = C_C + C_{TRI} + C_{TSP} + C_I + C_{URMC} + C_{CET} \quad (1)$$

$$C_{Tnet} = C_T – S_T – E_T \quad (2)$$

where
C_T: total cost (gross)
C_{Tnet}: net of expenses
C_C: collection cost
C_{TRI}: separation cost
C_{TSP}: special treatment cost
C_I: incineration cost (w/energy recovery)
C_{URMC}: mech. recycling and composting cost
C_{CET}: Final disposal cost
S_T: Subsidies
E_T: income (sale of recovered materials)

Adopting a "system type" based approach, which corresponds to a regrouping of local waste management systems with the same characteristics in terms of physical performances and organisational aspects, the model represents and investigates different scenarios at a national level. More specifically, a national solid waste management system of a country P (SN^P) can be represented as the compilation of a number of different regional or local "system types" (*ST*), as described in equation 3.

$$SN^p = \sum_j STj \quad (3)$$

where *j=1,2,…m* the number of the "system types" which represent the national system.

The novelty of the ReFlows model, compared to other available approaches, consists of the detailed analysis and description of the collection subsystem and in particular the source separation and collection programs for recyclable materials. The proposed model allows for the examination of the effects of different source separation schemes and configurations (definition of target-materials; number of recyclables' streams/flows, i.e. one stream of mixed recyclables or one stream per material; and, source separation, storage and collection methods, i.e. door to door, central collection or drop off sites), on the collected and recovered materials, as a function of: a) the population participating and served by the programs; b) the obtained per capita performances; and c) the corresponding costs. The efficiency of the different schemes examined in the model is always compared with the targets set by the relevant (local, national etc) policies.

3. MODEL APPLICATION AT THE NATIONAL LEVEL

In Greece, there are 3 waste recovery and recycling programs for packaging waste and newsprint paper. The first one (program A) is widespread throughout Greece, while the other 2 have been implemented in the Municipality of Athens, as pilot programs since 2005 and are gradually adopted by other municipalities.

More specifically, the characteristics of each program are:

- Program A: This program is the most widespread throughout Greece. It is a single stream system, i.e. the citizens place all the dry recyclable materials in bins (coloured blue). The contents of the bins are then transported to central material recovery facilities (MRF) and the materials are separated. The recovery rate for this program in Athens is 69% while the national recovery rate is assumed as 65%.
- Program B: It is a pilot program run by the municipality of Athens. It is a 3-stream source separation system: i) newsprint and paper, ii) aluminium and iii) the rest of dry recyclables (plastics and glass). For the implementation of this system, there are stainless steel bins with three compartments, placed along the central road infrastructure of the city. For this pilot study 100 bins were placed, serving approximately 12,000 people. Based on data of the Municipality of Athens, the recovery rate for program B is 88.1%.
- Program C: It is also a pilot program run by the Municipality of Athens. It is a 5-stream source separation program: i) paper, ii) metals, iii) glass, iv) plastics and v) printed paper. For the implementation of this program, four deposit refund centres were placed in central

squares in the city of Athens, serving 4,000 citizens each. The recovery rate for program C is 100% (no foreign materials accepted by the centre).

The total per capita recovery rate from each program is given in Table 2. Data are from Athens Municipality, in which all three programs run simultaneously. The overall EU and national target set for packaging waste recovery and recycling for 31/12/2011 is 55-80%. This is itemised as 60% for packaging paper and glass, 50% for metals and 22.5% for plastics. There is currently no national target set for the print paper, but for this study the target adopted by the Municipality of Athens (30%) is also used at the national level.

The ReFlows model was applied for the estimation of the recovered materials in 2011 in Greece. The population of Greece in 2011 is projected to be 11,298,620 people. However, due to the geographical constrains of the Greek space (mountainous areas and small isolated islands) the model runs on the assumption that 90% of the population will be served. Waste generation in Greece is increasing with an annual rate of 1.5%. In 2003, 4,710,000 tons of municipal solid waste were generated. It is projected that, with the abovementioned increase rate, in 2011 the waste generated will amount to 5,305,780 tons. The per capita waste generation for 2011 is projected to be 469.6 kg cap^{-1} y^{-1}. Due to lack of reliable data that would allow credible waste composition predictions, the waste composition in 2011 is assumed to be identical to the present one (2003), i.e.: 47% organics, 10% packaging paper, 10% printed paper, 8.5% plastic, 4.5% metals, 4.5% glass while 15.5% is termed as other (rubber, textile, wood, inters, household hazardous waste, etc.). This composition is utilised for all the simulation purposes of the current work.

Table 2. Recovery rate per material for each recycling program in Athens

	Recovery (kg cap^{-1} y^{-1})		
	Program A	Program B	Program C
Packaging paper	11.57	0.05	5.28*
PET	0.72	0.09	
PE	0.69	0.02	
Film	0.20	0.01	
Other plastic	0.22	0.01	5.69**
Aluminium	0.12	0.04	1.64
Tin	0.97	0.02	8.01
Glass	1.98	0.30	7.73
Print paper	16.10	2.26	5.28*
Total	32.57	2.80	33.63

*Total paper recovered in program C includes both packaging paper and print paper at an assumed 50-50 rate.

** In program C there are no specific values for the various types of plastic (PET, PE, film).

Based on the aforementioned assumptions, the first scenario examined was that until 2011, program A will cover 90% of the population of Greece. Results presented in Figure 2 indicate that the application of just program A with a recovery rate of 65% is not sufficient to achieve the national targets, especially regarding the packaging waste. The second option simulated is that until 2011, program C will cover 90% of the population of Greece. The application of program C alone, even with a recovery rate of 100%, also fails to achieve the national targets. However, this scenario gives better results for packaging waste (Fig. 2). The application of program B alone gives even lower outputs, therefore its results are not included in Figure 2.

Results indicate that a combination of programs A and C is required if Greece has to achieve its recycling targets. Program A offers a more geographically extended coverage while program C offers better material recovery. The success of any recycling scheme depends on the achievement of a high level of citizen participation and a low level of material contamination. It requires the provision of clearly communicated, simple instructions, adequate supporting advice to the public and regular feedback. Therefore, further development of the recycling programs in the country should not only focus on increased geographic coverage but also on improved participation.

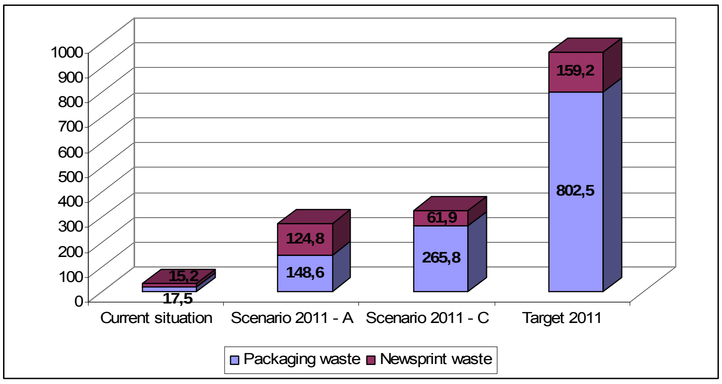

Figure 2. National recycling targets and simulation results for 2011

4. MODEL APPLICATION AT THE MUNICIPALITY OF ATHENS

The Municipality of Athens is the largest in Greece with a population of 754,000 inhabitants rising daily to over 2,200,000 persons with commuters and tourists, a surface of 37,953,568 m^2 and 959,434 km of road network, many narrow roads and pedestrian alleys, traffic problems and urban planning oddities. These characteristics pose many restrictions in the implementation of a source separation program. Aiming at a full-scale implementation of the recycling program, the Municipality of Athens has set internal recovery-recycling targets for packaging and newsprint waste, although national legislation in Greece does not set any geographical distribution of the national targets, at municipal, prefecture or regional level. More specifically, in the first phase of the full-scale implementation of the recycling programme, the Municipality has set recycling targets of at least 25% of the produced packaging waste (the same as the national target to be achieved by the end of the year 2005) and 30% of the newsprint waste produced within its boundaries. The estimated waste generation in the Municipality of Athens is 1,300 t day^{-1}, of which 533 t day^{-1} and 211 t day^{-1} is packaging waste and newsprint waste, respectively. Because of lack of accurate data concerning the composition of municipal solid waste in Athens, the official estimates for the solid waste composition in large Greek cities were used as input to the model (as presented earlier).

Data from the pilot projects (Table 2) are inputs to the “Current Situation” run (i.e. 2006) of the model and provide the basis of the assumptions used in the other two scenarios investigated in the context of this research. “Scenario 1” represents the full-scale implementation of the recycling programme, as anticipated by the Municipality (Table 3). Results of scenario 1 indicate that full-scale implementation of these pilot programs does not satisfy the recycling targets of the Municipality, therefore “Scenario 2” was explored (Figure 3). In “Scenario 2”, additional actions (Program D) are proposed in order to achieve a better physical convergence of the system with the quantitative targets set by the Municipality. In formulating scenarios 1 and 2 it is assumed that, as the programs develop to cover the entire Municipality, they are supported by a wide communication and awareness raising campaign; the participation rates will thus increase (by about 30% more) and the rejects rates will decrease.

5. CONCLUSIONS

A novel DSS, ReFlows, has been developed that aims at the detailed analysis and description of the collection subsystem and in particular the source separation and collection schemes and programs for recyclable materials. ReFlows is based on the MATLAB engine while its user interface utilises spreadsheets. It utilises mathematical equations and data for simulating the various components of the integrated solid waste management system. Application of the model at the national and local level indicates that additional effort and measures are required, should Greece is to achieve its national recycling targets. Higher levels of citizen participation and lower levels of material contamination have to be attained.

Table 3. Assumptions and scenarios developed for Athens Municipality

Programs	Performances	Current Situation	Scenario 1	Scenario 2
A	Number of bins	850	1,700	3,000
	Q collected	486.5	632.5	632.5
	Recovery rate %	56.2%	65%	70%
B	Number of bins	98	2,000	2,000
	Q collected	220.3	286.4	286.4
	Recovery rate %	87.9%	90%	90%
C	Number of bins	23	100	100
	Q collected	8,636.7	11,227.7	11,227.7
	Recovery rate %	100%	100%	100%
D	Commercial cardboard-newsprint Recovery rate %			40%

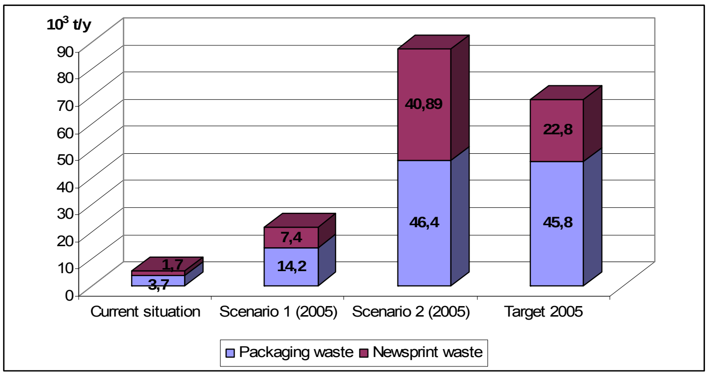

Figure 3. Recycling targets and simulation results for Athens in 2005

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APPENDIX

1. Production routine equations

$$d = \sum_i di \qquad (A1)$$

$$Q_C = P \times d \qquad (A2)$$

where, d (kg cap^{-1} y^{-1}): annual production of MSW per capita

i: waste type, i.e. glass, plastic, etc.
d_i (kg cap^{-1} y^{-1}): annual production of the i waste stream per capita
P (cap): total area population
Q_C (kg y^{-1}): total collected MSW in the area

2. Collection routine equations

$Q_C = Q_{CS} + Q_{CI}$ (A3)
$Q_{CS} = g \times Q_C$ (A4)
$Q_{CI} = (1-g) \times Q_C$ (A5)

where, Q_{CS} (kg y^{-1}): collected MSW by the recyclables system
Q_{CI} (kg y^{-1}): collected MSW by the commingled system
g: % of MSW collected by the recyclables system

3. Treatment routine equations

3.1 Recyclables recovery

$Q_{CS} = Q_R + R$ (A6)

where, Q_R (kg y^{-1}): recovered materials
R (kg y^{-1}): unwanted materials (rejects)

3.2 Toxic waste treatment Q_{Tsp} (A7)

where, Q_{Tsp} (kg y^{-1}) : toxic waste to special treatment

3.3 Incineration with energy recovery

$Q_I = w_I \times (Q_{CI} + R)$ (A8)

$PCI(Q_I) = \sum_i [Q_I \times PCI(d_i)]$ (A9)

where, w_I: % of commingled MSW entering an incineration unit
Q_I (kg y^{-1}): incinerated waste materials
$PCI(Q_I)$: lower heating value of the incinerated waste materials
$PCI(d_i)$: lower heating value of the i waste type

Incineration produces 2 sub-products:

$S_p = M + \sum_i Q_R(d_i) + F$ (A10)

where, S_p (kg y^{-1}): total incineration sub-products
M (kg y^{-1}): remaining ferrous materials. A fraction λ of it is further utilised
$Q_R(d_i)$ (kg y^{-1}): recovered material of type i
F (kg y^{-1}): remaining material that needs stabilisation prior to final lanfilling

3.4 Mechanical and biological treatment (MBT) routine

$Q_{URMC} = w_{MBT} \times Q_{CI}$ (A11)
$Q_R = \sum_i Q_R(d_i) + Q_{COMP} + Q_{RDF}$ (A12)

where, w_{MBT}: % of commingled MSW entering a MBT unit
Q_{URMC} (kg y^{-1}): quantity of commingled MSW entering a MBT unit
Q_R (kg y^{-1}): total recovered materials from the MBT unit

Q_R (d_i) (kg y^{-1}): recovered material i from the MBT unit
Q_{COMP} (kg y^{-1}): compost produced
Q_{RDF} (kg y^{-1}): RDF produced

4. Final disposal routine equations

$$Q_{CET} = Q_{CETI} + Q_{CETII} \quad \text{(A13)}$$

$$Q_{CETI} = F \quad \text{(A14)}$$

$$Q_{CETII} = Q_{CI} + R - Q_I - Q_{URMC} + (1-\lambda) \times M + R_{URMC} \quad \text{(A15)}$$

where, Q_{CET} (kg y^{-1}): total waste ending up in landfill
Q_{CETI} (kg y^{-1}): waste ending up in landfill of type I (toxic waste)
Q_{CETII} (kg y^{-1}): waste ending up in landfill of type II (municipal waste)
F (kg y^{-1}): stabilised remaining material from incineration
R_{URMC} (kg y^{-1}): rejected materials from the MBT unit
λ: fraction of the remaining materials M from incineration that is further utilised