



An Eco-Balanced and Integrated Approach for a More-Sustainable MSW Management

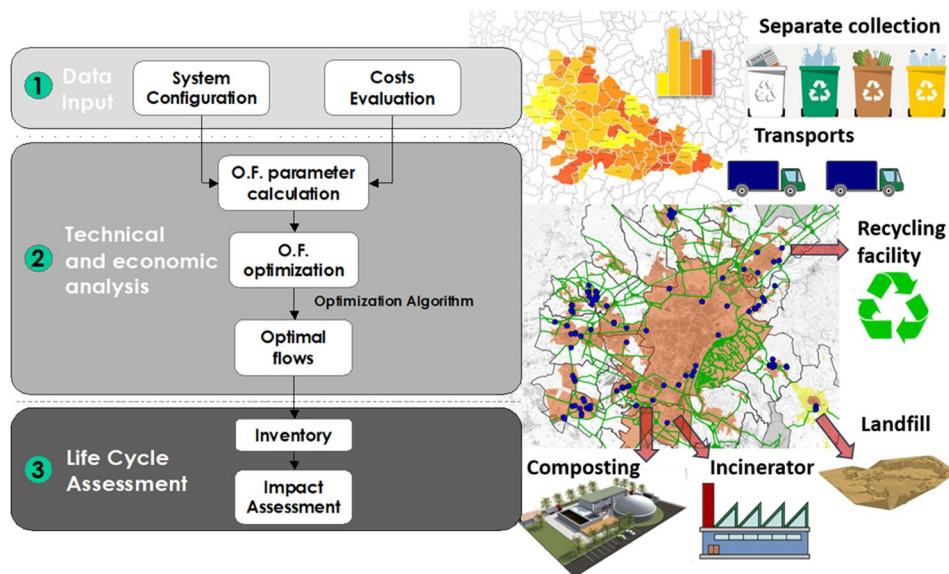
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Abstract

Strategies for Municipal Solid Waste (MSW) management can be sustainable only because of site-specific analyses and choices that take into account not only financial but also environmental costs. Generally, a correct approach should use different scenarios based on the environmental, social, economic and technological conditions of the specific area and on its expected potential. The aim of this paper is to presents an innovative model for the implementation of integrated MSW management approach which can result extremely useful where the MSW systems have to be refined or even designed such in the case of low-income countries. The proposed approach provides the best solid waste (SW) allocation/distribution among the available treatments and disposal options minimizing at the same time the total cost by means of an optimization procedure. The environmental impacts of potential scenarios are simultaneously estimated by means of a tailored Life Cycle Assessment procedure. The LCA tool in the model focus on the specific impacts from a SW management scenario that makes the model more explicit with respect to traditional LCA application. Additional tools allow, through site-specific numerical models, to provide also a preliminary evaluation of local impacts when required (e.g. atmospheric emissions). Such a model can be useful as a supporting tool in decision making for both governmental and non-governmental institutions involved in the planning of more sustainable eco-friendly strategies for MSW management.

Graphic Abstract



Keywords Municipal solid waste management · Waste flow · Allocation · Life cycle assessment (LCA) · Minimum cost · Technical and economic analysis · Numerical models

Statement of Novelty

The paper presents an innovative holistic model that, based on optimization function, can allocate, in the framework of several scenarios, the optimal fluxes of solid waste to the different treatment/disposal (in operation or in programming) allowing to achieve, at the same time, environmental impact minimization and the optimum reduction of the overall costs. Waste fluxes are optimized on the basis of the minimum cost of the whole system management and a LCA procedure is applied to verify the environmental impact/costs either at local scale (if required) and at the global one. In this way the most sustainable solution can be implemented for a correct management of waste

Introduction

MSW management system design, involves social, environmental and economic aspects. Protect human health and environment and conserve natural resources should represent a primary goal for a really a sustainable waste management [1]. However the most diffused design approach, especially in developing countries, is mainly based on achieving an affordable waste management cost.

Introducing circular economy in waste management system design requires adequate valorization and treatment plants and related management schemes for solid waste management (SWM) that need sophisticated approaches for their correct planning. It is then necessary to develop comprehensive computational tools, which should be based on advanced mathematical methods [2] and on a more strict involvement of the environmental aspects which naturally occur when a designed strategy is applied at the local/regional scale.

MSW management involves a number of strategic and operational decisions, such as the selection of SW treatment technologies, the location of treatment sites, waste flow allocation, service territory partitioning, fleet composition determination, and routing and scheduling of collection vehicles [2].

Most of the currently applied mathematical models are only addressed to specific aspects of the management i.e. facility location, vehicle routing [3] waste collection schemes and routes [4, 5], allocation, network modelling, or center location [6, 7].

The facility location is one of the aspect of major concern due to the fact that collection of municipal wastes

is performed on large geographical areas, where various aspects should be considered like the best position of intermediate collection areas, transfer stations (TSs) as well as the treatment sites for recycling, composting, incinerating [8, 9] and final disposal. Optimization problem related to facilities location has been widely studied [10], also because they represents one of the most prevalent approaches to make MSW management system financially sustainable [11–14]. Several authors [15, 16] have already developed management schemes based on optimization algorithms and multicriteria decision making; such procedures, in fact, can help planning the capital cost allocation which can result in the greatest cost saving.

Environmental and energetic aspects could be considered separately using Life Cycle Assessment [17] and different application to waste management are available in literature being most of them related to specific technology or waste fractions (e.g. paper, plastic, WEE) [18–21]. Some studies reports LCA application for evaluating performance of adopted waste management at local scale [22–25] even if LCA is still not used by public administration as an effective decision-supporting tool. This is because commercial software for LCA application are not specifically addressed to waste management design and there are not integrated software available to perform technical–Economic analysis together with Life Cycle Assessment.

Within this context the aim of this paper is to presents an innovative model for the implementation of integrated MSW management utilizing a more sustainable and holistic approach. The model is designed to individuate the best waste management option by evaluating the cost and environmental burden of different integrated MSW strategies. The proposed approach can be useful in case of general planning or improvement of existing MSW systems but could be extremely useful in low income countries where the overall system has to be completely implemented, or integrated by introducing some additional components (transfer stations, districts treatments, disposal etc.) in order to obtain a more sustainable management system.

Materials and Methods

Model Description

Model operates combining in a sequence the following procedures:

1. First stage – *Technical and Economic Analysis*

2. Second stage – Life Cycle and Impact Analysis

The program structure is displayed in the flowsheet reported in Fig. 1 and described in deeper details in the following paragraphs.

Different scenarios can be assumed first, based on the environmental, economic and technological conditions of the specific area and on its developing potential.

A program, edited in C language, is linked to the main software to solve the optimization algorithm and further VB applications are introduced in order to provide the users with guided and friendly data input procedures. The most interesting aspect is that there is a preliminary evaluation of the best fluxes distribution of SW depending on the available technological solution for both treatment and disposal. The optimization algorithm application results in the determination of the minimum cost for MSW management system; such a system is defined by the best waste flow allocation, based on the specified set of input parameters (distance of the treatments plants or of the final disposal ones, distance of the recovery areas, characteristics of the transportation system, savings due to recovery and reuse of materials, saving from the energy production, etc.). In the model is possible to choose the system boundaries considering different treatment plants in term of typology, location and treatment capacity. It is also worth to notice that usually a best allocation can represent also a first step towards the minimization of the environmental impacts. The results (in terms of involved plants and in term of used potentiality of each plant) are then analysed by means of an LCA-based procedure in

order to evaluate the potential impact of the selected scenario on the environment. As a result, a simulation, referred to certain specific management decisions, returns a complete overview of the technical and economic features of the system as well as its environmental implications. By changing the “structured system” different viable scenarios can be analyzed and compared in order to define the one which results in the best optimization taking into account both costs and environmental impacts. The proposed methodology has already been applied to a specific part of the MSW management, where the impact assessment was considered in case of reuse of incinerator ash for the production of ceramic tiles [26].

Economic Analysis

The economic analysis is based on an Objective Function (OF) to be minimized by means of an Optimization Algorithm. The OF is obtained by summing up all the costs associated to the whole system (costs of transportation, costs of treatments and costs of final disposal). Eventual environmental taxes, returns from the recycled materials sale are also considered. The optimization process results in the calculation of the variables set (in terms of fluxes of SW to the different elements that constitute the “system of SW management”) in order to reach a minimum in the total cost. The system can be configured by defining three groups of input parameters:

1. Main parameters
2. System parameters
3. LCA parameters

Main parameters refer to: (a) site information (such as the number and type of waste generation sources, etc.); (b) waste production and characterization (sorting by categories); (c) collection and treatment unit cost specification; and d) capital cost assumption according to the presumed developing trend.

System parameters include: (a) treatment capacity and efficiency of each facility; (b) distances between transfer stations, treatment and disposal sites. Transfer stations, as well as further treatment facilities or disposal sites, can be defined considering them as existing or as future implementation both in number and in typology. As a results different clusters of waste generation sites (areas) can be obtained and the effects of each specific aggregation scheme can be investigated. In addition, different strategies for separate waste collection can be defined for each area.

The above mentioned OF is defined by the following expression:

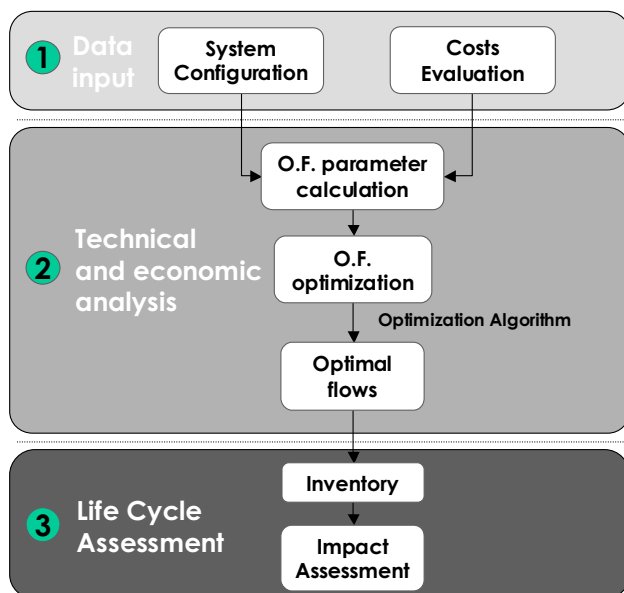


Fig. 1 Program structure

$$O.F. = \sum_{i=1}^n \sum_{j=1}^m x_{ij} * A_{ij} \tag{1}$$

$$\sum_{i=1}^n x_{ij} \leq C_j \quad \forall j \tag{3}$$

Were: $x_{i,j}$ Represent the system variables (amount of waste to be moved from i -th transfer station to j -th facility). n total number of transfer stations. m total number of treatment or disposal facilities. $A_{i,j}$ multiplier, which accounts for transport, treatment and disposal costs. The following constraints must be met:

$$\sum_{j=1}^m x_{ij} = Q_i \quad \forall i \tag{2}$$

where Q_i is the amount of waste stocked in the i -th transfer station.

where C_j is the maximum treatment capacity of j -th treatment or disposal facility. The algorithm returns the set of values for each $x_{i,j}$ which correspond to a minimum in the total cost of the MSW management system. $A_{i,j}$ multipliers computation is strictly dependent on the specific system configuration. Parameters that contribute to the definition of multipliers are reported in Table 1. Some examples are reported in the following to better explain their meaning.

Example 1 The costs associated with the operation of an incinerator are:

Table 1 Costs element quantified and related to the integrated MSW management system (input parameters)

Description	Code	Unit
Cost for mass-fired incinerator INC1 (excluded slag disposal cost and profits due to energy recovery)	$C^{inc-mf-1}$	€/kg
Cost for mass-fired incinerator INC2 (excluded slag disposal cost and profits due to energy recovery)	$C^{inc-mf-2}$	€/kg
Cost for RDF-fired incinerator INC-RDF (excluded slag disposal cost and profits due to energy recovery)	$C^{inc-rdf}$	€/kg
Cost for biological treatment at Composting facilities COMP1-2-3 (excluded residue disposal cost)	$C^{comp-m.b}$	€/kg
Unit transport cost con bilico (for waste production rates under 20ton/d)	$C^{T*-bilico}$	€/km
Unit transport capacity	c-b	Kg
Unit transport cost referred to unit mass of waste	$C^T(a/r)$	€/km*kg
Unit transport cost with a dump truck (for waste production rates over 20ton/d)	$C^{T*-autocarro}$	€/km
Dump truck capacity	c-a	Kg
Unit transport cost referred to unit mass of waste (dump truck)	$C^T(a/r)$	€/km*kg
Composting residue landfilling cost (taxes excluded)	$C^{LFI-res}$	€/kg
Landfilling cost for commingled waste (taxes excluded)—LANDFILL	C^{LFI-tq}	€/kg
Taxes for commingled waste landfilling	Eco1	€/kg
Taxes for composting residue landfilling	Eco2	€/kg
Landfilling cost for slugs produced from INC2 to be disposed as hazardous materials (taxes included)	C^{LFI}	€/kg
Landfilling cost for slugs produced from INC-RDF to be disposed as hazardous materials (taxes included)	C^{LFI}	€/kg
Weight fraction of residual matter remaining after separation in Composting Facility (COMP1-2-3)	A	
Weight fraction of slags produced by waste combustion in a mass-fired incinerator INC1	$\gamma-uw\ 1$	
Weight fraction of slags produced by waste combustion in a mass-fired incinerator INC2	$\gamma-uw\ 2$	
Weight fraction of slags produced by waste combustion in a RDF-fired incinerator INC-RDF	$\gamma-fs$	
Profit due to energy recovery from INC1	b-tq1	€/kg
Profit due to energy recovery from INC2	b-tq2	€/kg
Profit due to energy recovery from INC-RDF	$\gamma-fs$	€/kg
Energy production rate (INC1)	P-E-uw-1	kWhe/kg
Energy production rate (INC2)	P-E-uw -2	kWhe/kg
Energy production rate (INC-RDF)	P-E-fs	kWhe/kg
Unit profit from energy sale	R-E	€/kWhe
Net electrical recovery fraction- INC1	Ren-uw -1	
Net electrical recovery fraction- INC2	Ren-uw -2	
Net electrical recovery fraction- INC-RDF	Ren-fs	
Unit profit from heat sale	P-E-uw -1	€/Kwht
Net heat recovery fraction- INC1	Ren-uw -1	

Transport costs
 Treatment costs
 Residue disposal costs (including taxes)

As a result $A_{i,j}$ assumes the following expression (notation refers to symbols explained in Table 1):

$$A_{i,j} = C^{inc - mf - 1} + \gamma - uw1 \times C^{LFI} - \beta - uw1 + d_{i,j} \times C^{T*} \tag{4}$$

C^{T*} accounts for transport costs which can be calculated based on the daily amount of waste to be transferred to each treatment facility.

$\gamma - uw1$ accounts for energy recovery due to waste incineration, which can be calculated as follows:

$$\beta - uw1 = P - E - \beta - uw1 \times R - E \times Ren - uw1 \tag{5}$$

$d_{i,j}$ represent the distance (in km) between i -th transfer station to j -th facility.

Example 2 In the case of operation of a composting, facility costs are calculated as follows:

$$A_{i,j} = C^{comp - m.b} + a \times C^{res} + d_{i,j} \times C^{T*} \tag{6}$$

The costs associated with residual material remaining after the separation of the organic fraction of the waste (C^{res}) depends on whether it can serve as RDF, to be burnt in an RDF-fired incinerator, or needs to be diverted to landfilling as reported:

$$C^{res} = C^{LFI - res} + Eco2 + d_{comp\# - LF} \times C^{T*} \text{ (if an RDF - fired incinerator is not present)} \tag{7}$$

$$C^{res} = C^{inc - rdf} + g - fs \times C^{LFI} - b - fs + d_{comp\# - inc - rdf} \times C^{T*} \text{ (if an RDF - fired incinerator is present)} \tag{8}$$

where $d_{comp\# - LF}$ is the distance between the composting facility and the landfilling site; $d_{comp\# - inc - rdf}$ is the distance between the composting facility and the RDF-fired incinerator; $\gamma - fs = P - E - fs \times R - E \times Ren - fs$ represents the profit due to energy recovery from INC-RDF. If the amount of waste produced exceeds the treatment capacity of the system ($\sum_{i=1}^n Q_i > \sum_{j=1}^m C_j$), exceeding material will have to be diverted to landfilling without pre-treatment. According to Italian regulations such a solution can only be attained in a transition phase. Costs associated to landfilling of untreated waste can be calculated as follows:

$$C^{untreated\ waste\ LF} = C^{LFI - uw} + Eco1 + d_{i - LF} \times C^{T*} \tag{9}$$

where $d_{i - LF}$ represents the distance between i -th transfer station and the landfilling site. Once multipliers have been calculated, based on the selected management strategy, the OF can be computed and optimized.

Thanks to the linearity of the OF, the solution of this optimization problem can be achieved by means of a standard Linear Programming (LP) technique. In this work a Simplex Algorithm scheme has been selected. It provides a fast solution since it requires only function evaluations without derivatives calculation.

Life Cycle Assessment

Once an economically feasible system has been defined, further analyses are carried out in order to investigate its environmental implications.

In order to develop sustainable strategies for MSW management, the model has been implemented with a module for the evaluation of the environmental performance of the system in terms of greenhouse gases release, natural resources depletion, energy conservation, water and air quality preservation, etc. This target has been achieved by means of a Life Cycle Assessment (LCA) since it represents the most reliable tool for estimating global impacts of the system on the environment and interpreting the results, in order to make more informed decisions.

LCA is defined as a technique to assess the environmental aspects and potential impacts associated with a product, process, or service. There are two main steps in an LCA:

- compiling an inventory of relevant energy and material inputs and environmental releases (LCI – Life Cycle Inventory);
- evaluating the potential environmental impacts associated with identified inputs and releases (LCIA – Life Cycle Impact Assessment);

It is important to notice that while the inventory phase has reached such a high grade of standardization, the Impact Assessment phase is still far from being regulated by generally accepted procedures. This is mainly due to the difficulties associated with the definition of a globally agreed ranking of environmental priorities. Some attempts have been carried out by Kyoto Protocol intentions for quantified emission limitation or reduction commitment. Those purposes have been chosen in this work for the selection of impact categories to be considered in evaluating the environmental burdens of the system. Direct and indirect effects have been taken into consideration, as well as avoided impacts due to substitute processes (Fig. 2).

The life cycle time considered is from Gate to Grave which includes the transportation of waste to treatment facilities and later final disposal of residues at the landfill.

Life Cycle Inventory (LCI)

The inventory phase is achieved by computing all the inputs and outputs of each process which compose the MSW management system. This includes the transportation phase, each treatment process and the final disposal of residues. MSW distribution among the available options is arranged according to the results of the technical and economic analysis and represent the inputs to each treatment facility. Those amounts of waste can be transformed into outputs either as emissions in the environment or as input to subsequent treatment processes. Quantification of emissions is achieved by means of a chemical analysis of the specific process involved with respect to composting, landfilling and incineration while emission of vehicles due to waste transportation as well as energy consumption associated to plants operation are estimated according to the partition coefficient defined in the LCA input parameters (Table 2).

All that information are summarized in the general inventory table, where the entire MSW management system is presented as a process tree (Fig. 3 shows an example). Additional and more detailed information on specific emissions and energy and material consumption for each waste management operation (incineration, composting, landfilling etc.) are provided. The inventory table displays the quantities of the several substances produced during the treatment and disposal processes but does not provide an immediate quantification of their environmental impact. This has to be done by means of LCIA methods.

Life Cycle Impact Assessment (LCIA)

The main task of this phase is to convert LCI data in aggregated indexes capable of measuring the environmental impacts of the system following the ISO regulations

140,401 and 14,042 [27,28]. They are based on the following procedure:

1. selection of impact categories;
2. classification;
3. characterization.

The following impact categories are considered in the proposed model.

- *Acidification potential*—AP (kg SO₂eq.): it describes the potential of substances to acidify the water. These substances may cause acid rains which are harmful to terrestrial and aquatic species.
- *Global warming potential*—GWP (kg CO₂eq.): it describes the potential of gaseous emissions to cause global warming
- *Eutrophication potential*—EP(kg PO₄–3 eq.):it describes the possibility of nutritious substances to cause eutrophication in surface water.
- *Photochemical oxidation*—PHO (kg of formed ozone eq.): it describes the potential of gaseous emissions to form photo-oxidant substances by photochemical reactions.
- *Depletion of abiotic resources*—DAR (kg of antimony eq.): it describes the contribution of various emissions to deplete natural energy re-sources such as iron ore and crude oil.
- *Ozone layer depletion potential*—ODP (kg CFC-11 eq.): it describes the potential of substances to cause depletion of the ozone layer.
- *Terrestrial ecotoxicity potential*—TAETP (kg 1,4 DCB eq.): it describes the potential of substances to affect human, flora, and fauna. Most of these substances include heavy metals or bio-recalcitrant organics.

Fig. 2 Considered environmental effects

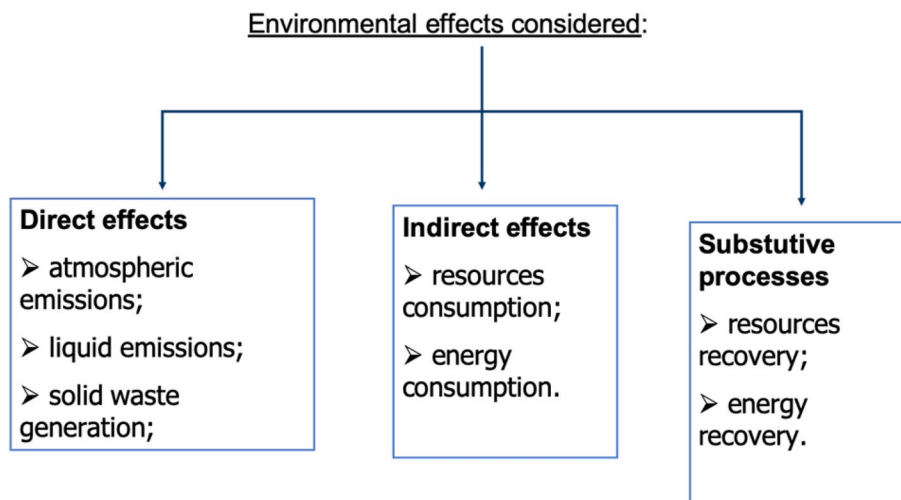


Table 2 LCI, input parameters

Description	Description
% of recycled paper used for RDF production	NOx removal via SCR
% of recycled plastic used for RDF production	Leachate produced per unit mass of waste to landfilling
% of recycled wood-textiles used for RDF production	Landfill gas produced per unit mass of MSW to landfilling
% of Organic Fraction (OF) of MSW to composting	Landfill gas produced per unit mass of MSW to landfilling
% of yard waste collected separately to composting	Landfill gas produced per unit mass of incineration residue to landfilling
Leachate produced per unit mass of OF composted	% of landfill gas recovered
Aerobic composting of the organic portion of MSW	% of landfill gas flared on the recovered one
Anaerobic composting of the organic portion of MSW	Energy recovery rate from biogas combustion
% of stabilized OF to landfilling	Energy consumption
% of processed SW RDF to incineration	Total milage (km) associated with Separate Collection management
% of processed SW RDF to landfilling	Energy consumption due to MSW sorting
Air emission rate of mass-fired incinerator	Energy consumption due to MSW composting
% of water produced by mass-fired incinerator	Energy consumption due to untreated MSW incinerator
% of bottom ashes by mass-fired incinerator	Energy consumption due to RDF incinerator
% of fly ashes produced by mass-fired incinerator	Heat recovery for RDF-fired incinerator
Air emission rate of RDF-fired incinerator	Electricity recovery for RDF-fired incinerator
% of water produced by RDF-fired incinerator	Heat recovery for mass-fired incinerator
% of bottom ashes produced by RDF-fired incinerator	Electricity recovery for mass-fired incinerator
% of fly ashes produced by RDF-fired incinerator	Paper calorific value
Acid gas removal via dry scrubbers	Plastic calorific value
Acid gas removal via wet scrubbers	Wood-textiles calorific value
NOx removal via SNCR	Landfill gas calorific value

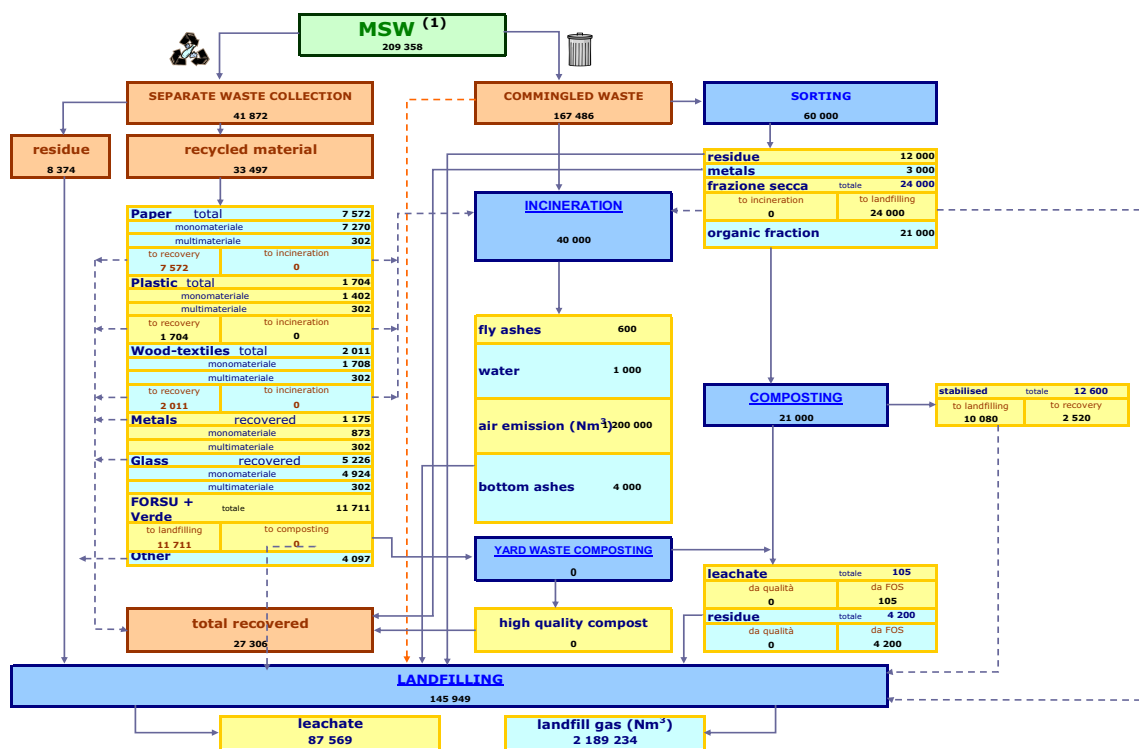


Fig. 3 General inventory table (LCI) with waste flows

- *Freshwater aquatic ecotoxicity–FETP (kg 1,4 DCB eq.)*: it refers to the impact on freshwater ecosystems (streams, rivers, and lakes that have a salinity of less than 0.05%), due to emissions of toxic substances to air, water, and soil

The above listed impact categories are those more commonly used for the assessment of the impact on the global as well as the regional scale. This is because they have been more widely studied and introduced in many international protocols for Environmental Quality Control, signed by many nations worldwide.

In the classification step, all substances are sorted into classes according to the effect they have on the environment. For example, substances that contribute to the greenhouse effect or that contribute to acidification are divided into two classes. Certain substances can be included in more than one class. For example, CO produced by waste incineration plants, is found to be relevant for both GW and PO.

Once substances are aggregated within each class, it is necessary to produce an effect score (ES). This cannot be done by simply adding up the quantities of substances involved, as some substances may have a more intense effect than others. To overcome this problem weighting factors, generally referred to as Characterization Factors (CF), are applied in the model to the different substances, according to the mid-point perspective and the IPPC method [29] and the recent guidelines [30].

The CF of a given substance represents the potential impact of a unit mass of that substance relative to some reference substances, referred to as the common unit of the category indicator.

For example, referring to GW, the common unit is carbon dioxide (CO₂) and consequently the CF of a given greenhouse gas *i* (CF_{*i*}) is defined as:

$$CF_i^{GW} = \frac{\text{intensity of the effects on GW due to gas}_i}{\text{intensity of the effects on GW due to CO}_2} \quad (10)$$

As a consequence, the global potential effect for each impact category has been calculated as the summation of emissions multiplied by their specific CF:

$$ES_j = \sum_i ES_{ij} = \sum_i (Q_i \times CF_{ij}) \quad (11)$$

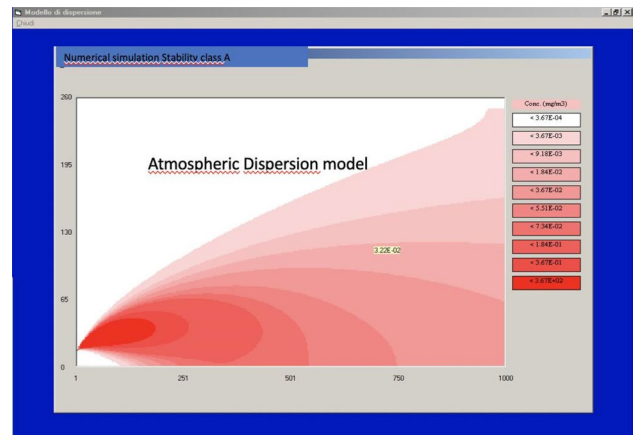


Fig. 4 Example of output concerning local impacts from atmospheric emissions

where: Q_i is the total amount of the *i*-th substance produced (ton/y).

- CF_{ij} is the Characterization Factor of the *i*-th substance referred to the *j*-th impact class. The potential impacts can then be classified as:
 - Direct impacts, which account for those effects directly related to a given impact class;
 - Indirect impacts, which account for those effects which can be associated to a given impact category as a result of a transformation after primary emission;
 - Avoided impacts, which takes into account the impacts saved due to the presence of profitable outputs such as energy generation at municipal waste incineration plants. They are equivalent to the impacts that would have occurred in actual production of the same amount of recovered energy and need to be deducted from the impacts caused by other processes.

The calculated effect scores can be plotted in a series of graphs, available on a total or process-level basis, aimed to a friendlier interpretation of the results of the environmental analysis.

To verify local effects, especially in case of atmospheric emission, a numerical model based on K-model has been developed as tool in the software in order to simulate the emissions distribution in the surrounding

area. An example of atmospheric emission and dispersion is presented in Fig. 4 where the emission concentration (dimensionless) are shown in the main (most probable) wind direction.

Results and Discussion

Case Study

The model was applied to a real MSW system in a Province of Center Italy, where data was known, with the aim to compare different solutions of the final disposal system of the solid wastes produced in the competent territory. A schematic representation of the best option in term of costs analysis is shown in Fig. 5. This option include the subdivision of the territory into four areas relating to four transfer stations from which the waste is sent to a first pre-treatment. The originated waste fractions are sent to the

different treatments (biological treatments, waste to energy, landfill).

Five scenarios have been considered and, for each one, a LCI and a LCIA was performed:

1. system with material recycling (Actual)
2. system without material recycling (No RD)
3. system with Incineration of only dry fraction (INC DF)
4. system with Incineration of the whole solid waste (INC SW)
5. system with both type of Incineration (INC DF + INC SW)

Results

The results of the combined (economic and environmental) analysis are presented in a series of worksheets, endowed with hypertextual links, which provide users with a complete overview of the full costs of the simulated MSW

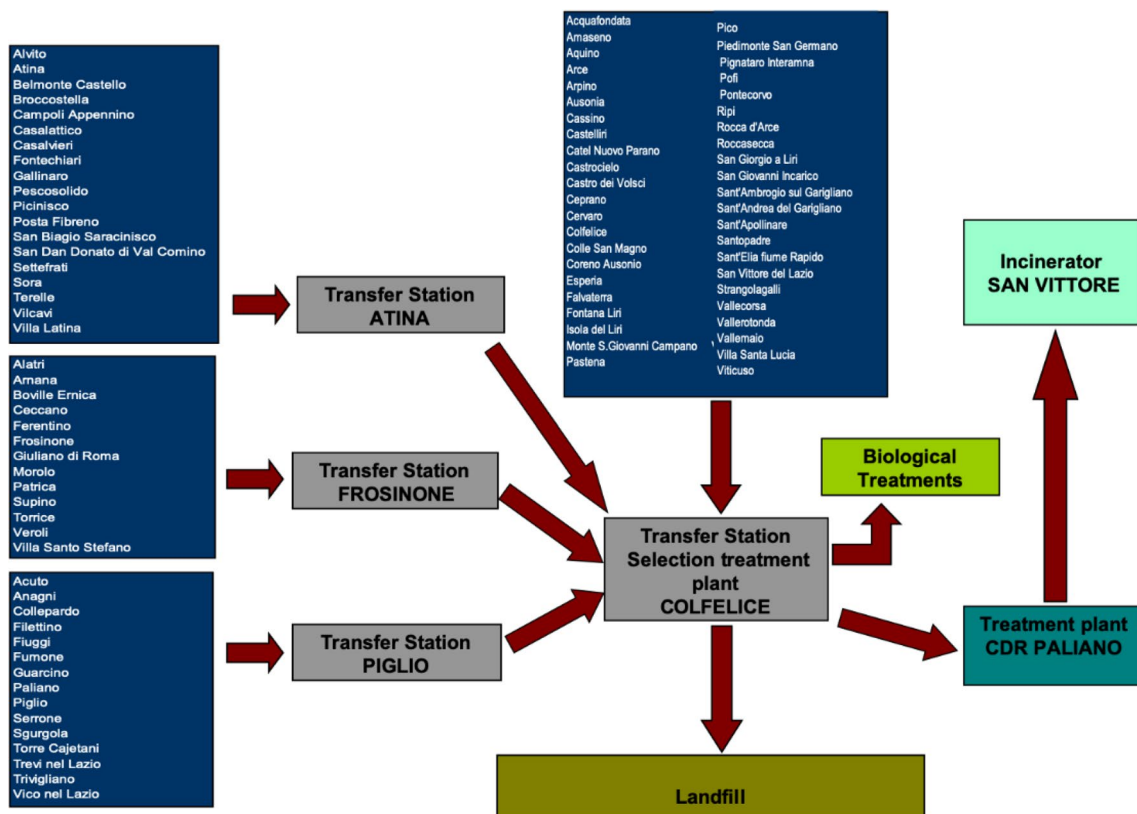


Fig. 5 The MSW scheme of the Case Study

Table 3 Results of LCA for the considered scenarios

No RD	GWP	OD	Acidification	Eutrofication	Phot. smog	toxicity	No renewable resources depletion
	ton. eq. CO ₂	ton eq CFC11	ton. eq.. SO ₂	ton. eq. NO ₃	ton. eq. C ₂ H ₄	ton. eq. C ₆ H ₄ Cl ₂	Frac. of reserves
Direct emissions	1.05E+05	5.47E-04	8.18E+00	7.91E+00	1.14E-02	6.52E+02	0.00E+00
NO direct emissions	1.74E+04	1.00E-02	1.09E+02	5.36E-01	4.36E+01	3.38E+03	2.70E-11
Avoided emissions	-6.01E+04	-3.68E-02	-3.82E+02	-2.07E+00	-1.68E+02	-1.84E+04	-9.87E-11
Total emissions	6.27E+04	-2.62E-02	-2.66E+02	6.38E+00	-1.21E+02	-1.44E+04	-7.18E-11
Actual (Recy=4.7%)	GWP	OD	Acidification	Eutrofication	Phot. smog	Toxicity	No renewable resources depletion
	ton. eq. CO ₂	ton eq CFC11	ton. eq.. SO ₂	ton. eq. NO ₃	ton. eq. C ₂ H ₄	ton. eq. C ₆ H ₄ Cl ₂	Frac. of reserves
Direct emissions	9.61E+04	4.91E-04	7.53E+00	7.39E+00	9.16E-03	5.94E+02	0.00E+00
NO direct emissions	1.55E+04	8.89E-03	9.65E+01	4.75E-01	4.10E+01	2.99E+03	2.39E-11
Avoided emissions	-5.13E+04	-3.14E-02	-3.27E+02	-1.77E+00	-1.43E+02	-1.65E+04	-6.43E-11
Total emissions	6.02E+04	-2.2E-02	-2.23E+02	-1.02E+02	-1.02E+02	-1.30E+04	-6.04E-11
INC SW	GWP	OD	Acidification	Eutrofication	Phot. smog	Toxicity	No renewable resources depletion
	ton. eq. CO ₂	ton eq CFC11	ton. eq.. SO ₂	ton. eq. NO ₃	ton. eq. C ₂ H ₄	ton. eq. C ₆ H ₄ Cl ₂	Frac. of reserves
Direct emissions	7.32E+04	3.39E-04	5.96E+00	6.61E+00	5.23E-03	5.64E+02	0.00E+00
NO direct emissions	1.27E+04	7.32E-03	7.95E+01	3.90E-01	3.38E+01	2.46E+03	1.97E+11
Avoided emissions	-3.53E+04	-2.16E-02	-2.24E+02	-1.22E+00	-9.83E+01	-1.31E+04	-5.79E-11
Total emissions	5.07E+04	-1.39E-02	-1.39E+02	5.79E+00	-6.46E+01	-1.01E+04	-3.82E-11
INC DF	GWP	OD	Acidification	Eutrofication	Phot. smog	Toxicity	No renewable resources depletion
	ton. eq. CO ₂	ton eq CFC11	ton. eq.. SO ₂	ton. eq. NO ₃	ton. eq. C ₂ H ₄	ton. eq. C ₆ H ₄ Cl ₂	Frac. Of reserves
Direct emissions	1.01E+05	5.13E-04	7.98E+00	7.92E+00	9.99E-03	6.44E+02	0.00E+00
NO direct emissions	1.62E+04	9.34E-03	1.01E+02	4.98E-01	4.31E+01	3.14E+03	2.51E-11
Avoided emissions	-5.26E+04	-3.22E-02	-3.35E+02	-1.81E+00	-1.47E+02	-1.66E+04	-8.64E-11
Total emissions	6.50E+04	-2.23E-02	-2.25E+02	6.61E+00	-1.04E+02	-1.30E+04	-6.13E-11
INC DF+INC SW	GWP	OD	Acidification	Eutrofication	Phot. smog	Toxicity	No renewable resources depletion
	ton. eq. CO ₂	ton eq CFC11	ton. eq. SO ₂	ton. eq. NO ₃	ton. eq. C ₂ H ₄	ton. eq. C ₆ H ₄ Cl ₂	Frac. Of reserves
Direct emissions	8.02E+04	3.93E-04	6.37E+00	6.61E+00	4.80E-03	5.46E+02	0.00E+00
NO direct emissions	1.30E+04	7.49E-03	8.13E+01	4.00E-01	3.46E+01	2.52E+03	2.02E-11
Avoided emissions	-3.91E+04	-2.39E-02	2.49E+02	-1.35E+00	-1.09E+02	-1.39E+04	-6.42E-11
Total emissions	5.42E+04	-1.60E-02	1.61E+02	5.66E+00	-7.44E+01	-1.09E+04	-4.41E-11

management strategy and of its environmental burdens. Information available with respect to the various phases of the process analysis include:

- Waste production information
- Technical and economic analysis results with respect to costs
- Environmental analysis results

An short overview of some LCIA outputs is presented in Table 3 for all the considered scenarios.

Potential impacts on the environment, measured by the aggregated effect scores for each of the seven impact category considered, can be presented separately for each of the processes involved in the system (composting, landfilling, incineration and transport) or for the whole system. Environmental impact indicators are presented on a process-level basis (Fig. 6) which allows for an easy comparison of the different impact indexes in order to depict the most affected environmental compartment.

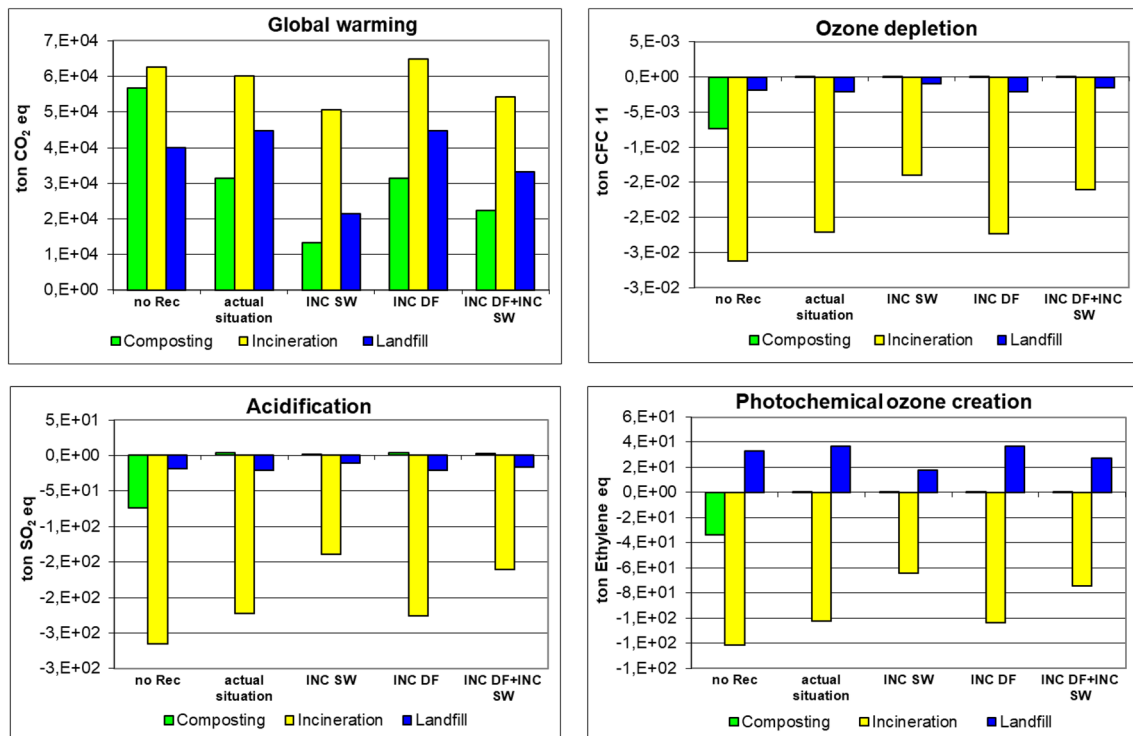


Fig. 6 Environmental impact indicators in the fifth scenarios and relative impacts for each process or component of the waste management (composting, incineration and landfill)

Conclusions

A model able to simulate integrated MSW management systems in order to evaluate the effects of specific actions involving both economic and environmental costs is presented. Operational costs, insisting generally on the community, as well as the potential impact on the environment can be used for a deeper and effective design of the best choice in the SW management. The main difference with the general approach based on traditional LCA tool is that while this last refers to large scale impacts, the proposed integrated model allow to quantify also the direct impacts on the local community that has to sustain the MSW management costs.

According to specific site configuration and constraints, different scenarios can be analyzed and compared in order to depict the one that results in the minimum cost with the lower environmental impact (identifying the most cost-effective and environmentally suitable solution).

Such a model appears to be a valid support in decision making for both governmental institutions and local administrations involved in the planning of MSW management strategies. Due to its adaptability it can easily be implemented for further development.

“The model is freely available to whom make request”

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