A multi-approach model to optimize Municipal Solid Waste Management. An application to an Italian metropolitan area.

Stefania TATTONI*, Marco D'AVINO*,
Angela FUMAROLA**, Massimiliano M. SCHIRALDI*

*Department of Enterprise Engineering, University of Rome "Tor Vergata", Rome, Italy
**Department of Mechanical Engineering, University of Rome "Tor Vergata", Rome, Italy
(correspondence author: stefania.tattoni@uniroma2.it)

Abstract: In the last decade, people concerns and regulations pressure have made sustainability and waste management key topics both in political and companies agendas. The European Commission (EC) with its new Directive on waste (2008/98/CE) has set as a main goal for every Member State government to radically minimize the negative environmental impacts from producing and managing waste. Thus, the aim is to facilitate and promote the differentiated waste collection starting from local municipalities, in order to strongly increase the percentage of waste that can be recovered and recycled. Although at international level some organizational models have been proposed, they are not extensively applicable because of peculiarities in each country. Moreover, most of these models are focused on manufactures or final users rather than on municipalities. Literature does not present many reference models to support these critical actors in their strategic decisions. In particular, there seem not to be any models which can deal simultaneously with operating cost, legislative targets and the way these elements vary in function of waste quality and efficiency of the reverse logistics system. Therefore, objective of this paper is to introduce a model which supports the decision making process in designing a reverse system for Municipality Solid Waste Management (MSWM). Specifically, the model aims to determine which sites (selection, processing and disposal facilities) needs to be opened and the optimal waste quantity - per each collection alternatives (i.e. diversified or undiversified) - to be sent through different sites, taking into account transportation and processing cost on top of the targets imposed by current legislation. A genetic optimization algorithm is adopted to solve the model. Then, a validation has been performed using a data set representing a real municipality operating in a large metropolitan area in Italy.

Keywords: municipal solid waste management, diversified disposal, recovery, disposal to landfill

## 1. Introduction to Municipal Solid Waste Management

High priority has been assigned to waste management in European law. However, the initiatives undertaken so far seems not to have significantly reduced the constant increase of waste production all over Europe. The rising level of prosperity in industrialized countries, on top of the increasing number of products and services provided and consumed, reflect the considerable amount of waste generated, making more difficult to achieve the ambitious goals set by the institutions. Moreover, nowadays industries use a wider range of materials and produce much more complex products than in past decades, with an intrinsic hazardous nature. Approximately 4 billion tons of agricultural, domestic and industrial waste are annually generated by EU27 (Eurostat, 2008).

At national and international level, efforts have been asked to institutionalize waste minimization and prevention through regulatory guidelines: since 1975 a Community Strategy for Waste Management was proposed by an EC Council Directive; in 1989 a hierarchical system in waste management was established giving the highest priority to waste minimization, then to recycling and disposal. Nowadays, the regulatory process is still ongoing, despite a common framework of Directives for Waste Management has been established in different areas of action (Figure 1).

In general, the environmental policy aims to reduce the excessive exploitation of (scarce) resources and to promote a pragmatic application of the "waste hierarchy". In other words, it is fundamental for every organization to manage waste applying the best environmental option, in an ordered process: prevention, preparation for re-use, recycling, recovery and disposal. With the aim of complying with recycling and recovery target quantities set by EC, each Member State is working on different organizational models, based however on the same simple principle: each player operating in the waste sector must actively participate in managing the whole waste value chain.

The sustainability model addresses economic growth; social cohesion and environmental protection must go hand in hand as an inseparable whole (Adams, 2006).

anagement
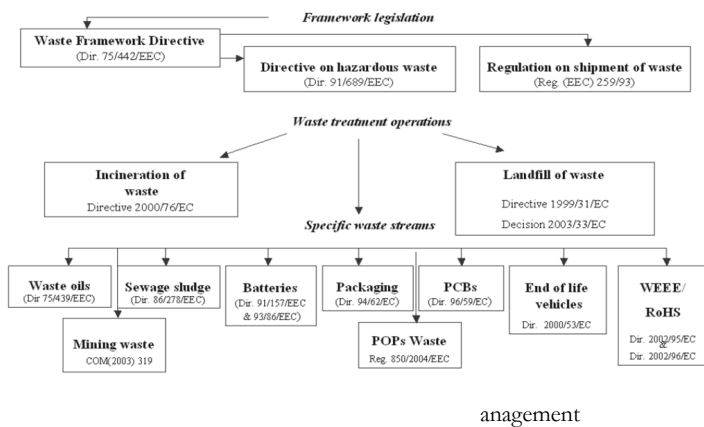
Studies on sustainability embrace a broad spectrum of fields.

Despite the wide range of literature disseminated so far, current literature suggest few models and theories concerning MSWM. MacDonald (1996a), Berger, Savard et al. (1999) and Tanskanen (2000) are some of the few cases who provided an insight on evolution of this stream of research over the last decades. They outlined that the majority of models deal with operational issues (e.g. scheduling and routing problems for waste collection and vehicles management) and are distinctively focused on economics or environmental aspects. Models such as dynamic mixed integer programming (Baetz and Neebe, 1994), a multi-period and multi-regional (Everett and Modak,1996) and a static non-linear programming (Sundberg et al., 1994), represent some examples of optimization approaches applicable to waste management. Vehicle routing planning is one of the main area of interest: Nuortio et al. (2006) analyzed the problem of using two different patterns, respectively arc and node routing problem, while McLoad (2008) adopted the capacitated vehicle routing problems (CVRP) to solve the same kind of problem.

Localization of disposal areas (Bautista and Pereira, 2006) and the consequences deriving by adopting different positioning policies (Hammond and Beullens, 2007) are other field of research but few comprehensive studies seems to have been performed so far: on the analysis of the different recovering and sorting processes in relation with their cost structures (Carrol, 1995), on the effects of recycling or special treatments (Morris, 1991, Smith and Baetz 1991) and on planning modifications based on the regulations changes (Clift et al., 2000).

To sum up, waste management literature can be grouped into three different branches (Mora et al., 2009):

- the study of environmental, social and human health impact of waste collection strategies;

- the planning of waste collect/management vehicle routing;

- localization and allocation of waste selection/disposal sites.

2. The case of MSWM in an Italian metropolitan area

Besides legislative pressures, also the financial crisis – along with the consequent need to decrease operating costs - have pushed several industries and local municipalities (i.e. the main waste producers and the main players in collecting and treating waste stream) to progress their approach to waste management. For instance, in Italy a national decree law (D.Lgs. n. 22/97) has institutionalized a system of Consortium (precisely, six Material Consortia), with the aim of guaranteeing to local administrations the necessary connections with the various players dealing with waste management. Main purpose of the Italian legislation was to rationalize and organize the activities regarding MSWM, focusing on principles of efficiency, efficacy and cost reduction.

In 2007, the amount of solid waste produced in Italy was 32,5 millions of tons, with a national production per capita of 550 kg/inh. Over years, the growing attention given to diversified waste disposal has led to good results even though the performance obtained are still far from targets set by legislation. In particular, in 2008 the percentage of diversified disposal achieved at national level was 30,6% of the total solid waste produced (Rapporto Rifiuti Urbani, 2009). Although this percentage is annually increasing (25,8% in 2006 and 27,5 in 2007), the results are well under the target established by directives, i.e. 50% in 2009 (D.Lgs 152/2006 and 296/2007). Moreover the situation appears not to be homogenous all over the Country: the North indeed, relying on more effective organizational systems, collects up to 6,74 million tons of diversified waste (45,5%, 2008 data), which is higher than the sum collected both in the Centre and in the South (respectively 22,9% and 14,7%, 2008 data).

In order to contextualize the metropolitan area which has been analyzed in this study, the following figures respectively show the trend of diversified waste disposal over the past years (Figure 2) and the recovered percentage, by material typology (Figure 3).
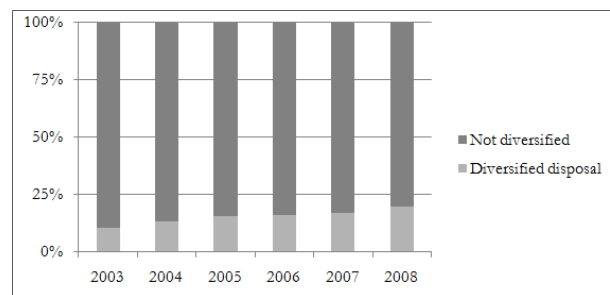

Figure 2. Diversified waste collect trend
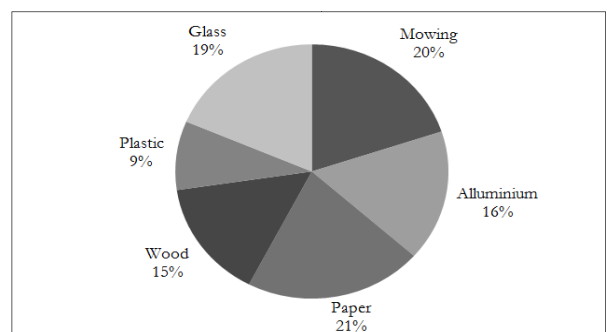in the metropolitan area analyzed

Figure 3. Percentage sent to recovery facilities
by typology of material (2008)

The metropolitan area which provided the data set for validating the model is 1300 km² extended and serves over 3 million inhabitants. We consider a basic MSWM system with undiversified and diversified waste collection. The model and can cope with mono or multi-material collection and contains four different groups of operations: collection, sorting, selection (divided into a first-level and second-level selection) and disposal. They are characterized by different inflow and outflow quantities and by the number of sites distributed across the area. Differently from other location-allocation problems present in literature, here it is introduced a further constraint, that is the target level imposed by regulations in terms of minimum percentage of recovered waste (for higher quality classes such as diversified collection).

Coordinating waste flows is a complex matter; indeed, different circuits are usually present, each with specific processes and methods, depending on the treated material, on the collection process characteristics and on the final usage alternatives. In general, the recovery processes involving the waste flow follow three steps: collection from the origination sites, sorting (only for the undiversified stream), selection depending on waste quality (measured by the valuable fraction, i.e. disposable fraction, %DF and kind of final destination (i.e. recycle, incineration, disposal to landfill). In order to give an idea about quality classes and the amount collected for each class, some examples are reported in Table 1 and Table 2.

QUALITY CLASSES (%DF)

	Paper	Plastic	Aluminum
Excellence	up to 5%	≤ 6%	up to 5%
1st class	> 5,1% up to 10%	> 6,1% up to 16%	> 5,1% up to 15%
2nd class	> 10,1% up to 15%	> 16,1% up to 24%	over 15,1%
3rd class	>15,1 up to 20%	N/A	N/A

Table 1. Examples of quality classes defined in relation to the disposable fraction, %DF (domestic flow, normal collection)

	collected %, Plastic
Excellence class	89,77%
1st class	6,36%
2nd class	0,71%

Table 2. Plastic classified by %DF at the collection center

Collection service is generally operated by municipalities, but clearly the system configuration changes in relation of the available resources (financial and logistic). Once the waste is collected, it is processed according to different treatments, among which the most valuable is to convert waste into secondary raw material (SRM). Indeed, the SRM can be sold to manufacturing plants and used as input into their production processes in order to obtain brand new products.

Depending on the type of material and on collection alternatives (e.g. diversified/undiversified collection or mono/multi-material collection), different treatments and methods to separate the different fractions and to remove

impurities may be required: plastic packaging coming from a separate disposal phase, for instance, is firstly sent to a specific plant (Second Selection Centre - CSS), where it is further separated from impurities and divided according to the different kinds of polymers. Then, this selected waste goes through the processing facility where a SRM is obtained. On the contrary, the undiversified collection requires a preliminary selection process in order to separate the different fractions and remove impurities; these quantities coming out after selection, separation and processing can be then directed to incineration or landfill. Obviously, the highest value is obtained by recycling waste in SRM; then by incineration with the aim of obtaining energy; thus, the lowest value comes from sending waste to landfill and the EC directives are pushing to reduce this practice.
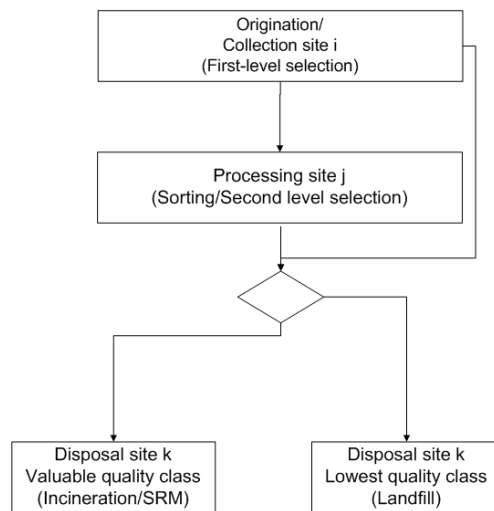

Figure 4. standard model flow

3. Model for Municipal Solid Waste Management

This paper aims to suggest a model to design a reverse system for MSWM. In particular the proposed model identifies where and how much waste shall be shipped from a set of originationcollection sites to processing facilities and disposal sites, in order to ensure the most proper treatement in accordance to waste quality, processing costs and output quality targets imposed by regulations.

The following assumptions are considered:

- all solid waste is located at the origin sites, where it is shipped after having been collected at production points. As it has been repeatedly said, there are two kinds of collection, diversified and undiversified: the first one guarantees a cheaper selection process, whereas the second one has lower collection costs;

- the collection centres are considered the initial point of selection, indeed some materials can be directly sent to disposal point, then there is a sorting operation and a second-level selection at processing sites;

- there is a fixed cost to open a processing and disposal centre. There is a limit to the number of sites that can be opened and a minimum number of open sites must be guaranteed;

- it is possible to ship directly from a collection site to a disposal site but obviously the variable cost would be different and higher (in order to prevent this possibility, an infinite cost of shipment may be simply set in the model).

The solution will indicate which sites need to be opened and how much waste they will process, per each quality class. The following notation is used:

$\{i\}$ *collection site* − Collection site where waste arrives from domestic points, where may eventually perform a first-level of selection;

$\{j\}$ *processing site* − Processing centres which receive the waste collected at i and, after sorting and selection, forward the outflow to disposal sites.

$\{k\}$ *disposal site* − Disposal sites receive material from collection as well as from processing centres. In these facilities waste can be directed to SRM production, incineration or disposal to landfill.

$\{l\}$ *quality class* − Waste quality can be divided in relation to different drivers (kind of collection, valuable fraction etc...) and in this model discrete classes of quality in which waste are classified after every selection process are considered. Waste directed to landfill belongs to the lowest quality class.

C_{ijk} Total variable unit cost of shipment from a collection site i through a processing site j and onto a disposal site k. This variable cost comprises first-level selection costs at the collection site (in relation to the typology of collection adopted: diversified or undiversified) plus inflow and outflow transportation costs for delivering from the collection site i to the disposal centres k via the processing sites j.

T_l Target imposed by legislation to increase valuable waste recovery. The target is imposed for each valuable quality class, therefore there is no target for the lowest level of quality because that waste is directed to landfill.

F_j Fixed cost of opening a processing site j

G_k Fixed cost of opening a disposal site k

a_i^l Amount of waste stored at the collection site i belonging at the quality class l.

Cp_j Maximum processing capacity of processing site j

Cp_k Maximum processing capacity of disposal site k

P_{min} Minimum number of processing sites j to open

P_{max} Maximum number of processing sites j to open

D_{min} Minimum number of disposal sites k to open

D_{max} Maximum number of disposal sites k to open

The decision variables are:

X_{ijk}^l Percentage of waste belonging to the quality class l residing at the collection site i to be shipped through processing site j onto the disposal site k. Being j zero indicates that the transportation is directed to k

without passing through j (e.g. in case of diversified collection).

P_j $\{0,1\}$ Boolean variable that assumes 1 when a processing site j is open and 0 otherwise.

D_k $\{0,1\}$ Boolean variable that assumes 1 when a disposal site k is open and 0 otherwise.

Thus, the model formulation result to be:

$$\text{Min } Z = \sum_l \sum_i \sum_j \sum_k C_{ijk} a_i^l X_{ijk}^l + \sum_j F_j P_j + \sum_k G_k D_k$$

s.t.

$$\sum_l \sum_j \sum_k X_{ijk}^l = 1 \ \forall \ i \in I \tag{1}$$

$$\sum_i \sum_j \sum_k a_i^l X_{ijk}^l \geq T_l \ \forall \ l \in L / \{lowest \ quality \ class\} \tag{2}$$

$$\sum_l \sum_i \sum_k a_i^l X_{ijk}^l \leq CP_j P_j \quad \forall \ j \in J \tag{3}$$

$$\sum_l \sum_i \sum_j a_i^l X_{ijk}^l \leq CP_k D_k \quad \forall \ k \in K \tag{4}$$

$$P_{min} \leq \sum_j P_j \leq P_{max} \forall \ j \in J / \{\text{direct shipment}\} \tag{5}$$

$$D_{min} \leq \sum_k D_k \leq D_{max} \forall \ k \in K \ / \{\text{infeasible site}\} \tag{6}$$

$$0 \leq X_{lijk} \leq 1 \tag{7}$$

$$P_j \in \{0,1\} \tag{8}$$

$$D_k \in \{0,1\} \tag{9}$$

The model minimizes the sum of variable costs to ship from a set of collection sites through processing sites to the disposal sites and the fixed costs to open those delivery points. Constraint (1) indicates that the whole amount of waste at the collection point i must be shipped to other destination facilities. In (2) the compliance of regulation target is imposed. Constraints (3) and (4) have a double effect: to limit the amount of waste transported to processing and disposal sites without exceeding their maximum capacity and meanwhile to avoid that waste are routed to closed facilities. Since municipalities must provide a homogenous service level on the territory, constraints (5) and (6) make sure that the number of open sites is not less than a minimum and not more than a maximum value. Constraint (7) ensures that X_{ijk}^l assumes values between 0 and 1 whereas constraints (8) and (9) make sure that the other two decision variables P_j and D_k are binary.

4. Validation of the model and reports of the results

The introduced model is a zero-one mixed integer-linear programming problem (MIP) and it works hierarchically, indeed it selects a percentage of waste (with a given quality) to be sent to the destination facilities. In absence of processing sites the problem would be a capacitated plant location problem i.e. a NP-complete problem. On the contrary, MIP is a NP-hard problem and its solution is not trivial even due to the high number of variables involved.

The model introduced has been implemented and solved in modeFRONTIER (mF), a design environment optimizer software. Figure 5 shows the main workflow of the optimizer (mF): the input variables, D_k, P_j and X_{ijk}^l are shown at the top of the figure while at the bottom it is

possible to see the symbolic representation of the different constraints and the objective.
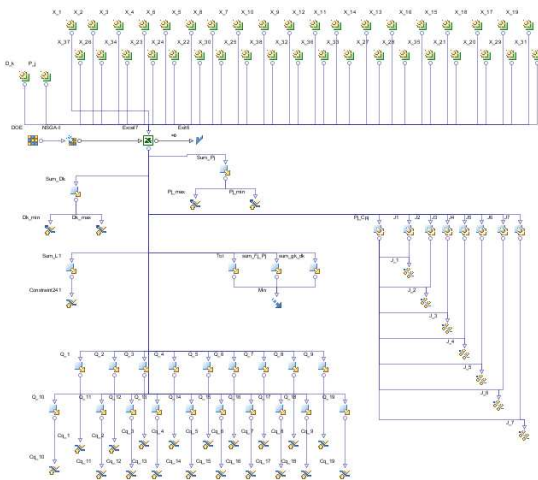

Figure 5. modeFRONTIER workflow

An important step to ensure the effectiveness of the solutions search is the choice of an appropriate algorithm, in accordance to the form of the objective function, on the available computing resources, on the complexity of the model (represented by the number of variables and by the number of constraints) and on the extension of the solution space.

A Not-Sorted Genetic Algorithms (NSGA-II) was chosen to solve our model and implemented in mF. It belongs to the class of probabilistic techniques of evolutionary algorithms: genetic algorithms (Deb, 2000) are based on Darwin's evolutionary principle: only strongest races survive. Each algorithm run performs specific steps: crossover, mutation and natural selection. NSGA-II starting from a selected "population" and a pre-specified set of parameters, performs a sequence of operations: in crossover operation, pieces of initial solutions (parents) are combined together in order to obtain further solutions (children), while mutation operation makes minor changes to improve the solution. Cyclically, the selection process chooses which solutions may survive and generate new children. The routine is recursive and stops whenever any further improvement is impossible or the maximum number of generations is achieved. NSGA-II allows a global search of solution avoiding the extensive exploration the solution space, thus reducing the overall computation time.

The initialization set (DOE set, in modeFRONTIER) has been generated using uniform latin hypercube (ULH) i.e. a method able to generate random solutions uniformly distributed into the total space of solution (100, in this case). For each initial population, 50 runs of the chosen algorithm are performed (5000 iterations in total). The model considers the following parameters (Table 3)

I	19
J	7
K	3
L	2

T_l	30%
F_j	3M€
G_k	30M€
Cp_j	1,5Mton
(P_{min}, P_{max})	(1,7)
(D_{min}, D_{max})	(1,3)

Table 3 Parameters setting

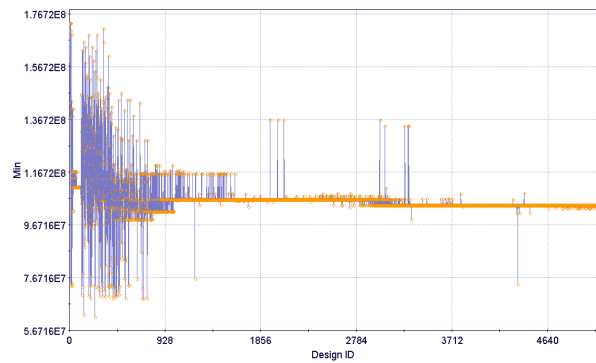The convergence graph is showed in Figure 6 below.

Figure 6. Algorithm convergence

Matrices with C_{ijk} and a_i^l have been used as the input.
As a result, the algorithm has found the following solution for the analyzed metropolitan area:

P_j : [1, 1, 1, 0, 1, 0, 0]

D_k :[1, 1, 0]

X_{ijk}^l: [0.0551, 0.029, 0.0023, 0.0301…0.0661]

For each i there are 912 jkl combinations (including the case of direct shipments to k), therefore is impossible to report the whole solution generated. However all constraints are respected, and the best value of the objective function given is 121.961.891 € that already results being a 13% decrease of the current cost for keeping opened all the facilities ensuring the same service level on the territory.

5. Conclusions

This paper aimed at introducing a model to support decision making processes in designing reverse systems for Municipality Solid Waste Management. Specifically, the model aimed at determining the percentage of waste belonging to certain quality class, residing at certain collection sites, to be shipped through certain processing sites onto some other disposal sites. Thus reverse logistic system is designed and the optimal waste quantities to be processed are determined per each collection typology (e.g. differentiated and undifferentiated), taking into account transportation and processing cost on top of the targets imposed by current legislation. The model has been validated on the case of a real municipality in a large metropolitan area in Italy (1300 km² counting more than 3 million inhabitants) and a genetic optimization algorithm has been proved to solve the problem resulting a solution which guarantees the same service level and meanwhile a 35% cost optimization.

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