An approach to islands' self-contained waste management system with the goal of maximizing the recovery while limiting transportation costs

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Abstract

Purpose. The research focus on defining typology, capacity and location of facilities for waste treatment and disposal for both present and future management scenarios in Sicily.

Methods. After estimating the amount of waste produced in Sicily and proposed a pathway for the rapid achievement of the 50% recovery target established by the European Union, five scenarios for the residual waste management in Sicily are proposed and analyzed through a GIS software platform (TransCad) in terms of "*facility location*" and "*minimum-cost flow*" problems. The cost of transportation was calculated as the sum of different cost components related to the distance traveled, the personnel, and the vehicle utilized to collect waste including fuel costs, tires costs, property tax and truck maintenance costs.

Results. The five scenarios were critically compared in terms of transportation costs also evaluating the impact on traffic due to the increase of "trucks per day" in three critical sections of the road network in Sicily. Overall transportation costs were found to be of the order of 10% of the treatment/disposal costs.

Conclusions. The best scenario provided that 50% of non-recyclable waste is treated in five mechanical and biological treatment plants and the refuse derived fuel here produced is disposed to the existing furnaces for the production of clinker (cement) in Sicily. The analysis of traffic flows was helpful to obtain the general framework of the increased traffic due to the proposed scenarios. However it results that the transportation cost for all the scenario is definitively lesser important when compared to the treatment and disposal cost and should be not be emphasized and used to condition public acceptance and the choice of the size and typology of the facilities.

Keywords: Waste management, GIS, environmental impact, facility location, minimum-cost flow.

1 Introduction

Planning and design of a regional waste management system involves the location of treatment and disposal facilities, the allocation of wastes and waste residues from the treatment to disposal sites and the choice of the best transportation routes within the road network. While facilities such as electrical substations or dumping grounds provide necessary services, waste treatment and disposal facilities may cause unpleasant odors, health concerns and reduce property values and is often hard to newly construct or extend these facilities due to the extreme opposition. Although such facilities are actually beneficial to the general public, and fulfill essential life demands, they are usually referred as undesirable facilities.

The non acceptance of undesirable facilities by communities has been popularized by “not in my backyard” (NIMBY) and “not in anyone’s backyard” (NIABY) campaigns, which have become an enormous challenge to decision makers and planners with regards the demarcation of landfill sites.

Legislation and regulations have been introduced at local and national levels to address waste management policies, but the complexity of all the interacting issues involved in the system, suggests that decision makers can largely benefit by analytical or simulation supporting tools to address their choices.

A number of authors has argued that undesirable facilities selection process should utilize relevant available data and planners should arrive at results accepted by all key players in the selection process [1]. The processing of such disaggregated data by traditional means requires considerable time and sometimes may not yield the desired result. To overcome delays and inaccuracies, geographic information systems (GIS) a handy decision making tool is used in contemporary studies. GIS, being a digital database management systems, has the advantage of storing, retrieving, and analyzing a considerable amount of data from various sources and displaying results with ease [2].

Song et al. [3] proposed two alternative mathematical models for locating undesirable facilities to minimize the total degree of NIMBY phenomena. A genetic algorithm and assignment methods were developed to seek optimal or near optimal solutions.

Eiset and Marianov [4] proposed a model for the locations of landfills and transfer stations in a region in Chile and to simultaneously determine the sizes of the landfills that had to be established. The model was formulated as a bi-objective mixed integer optimization problem, in which one objective was the usual cost-minimization, while the other minimizes pollution.

Farahani et al. [5] presented a very comprehensive review on hierarchical facility location models classified on the basis of multiple characteristics including the type of flow pattern, service availability, spatial configuration, objective function, coverage, network levels, time element, parameters, facilities, capacity, and real world application. Solid waste management (disposal) system was identified as a typical application of hierarchical facility location problem (HFLP) modeling, including facilities such as transfer stations, disposal centers, and landfill stations.

By investigating the literature on modeling municipal solid waste logistics in Europe Bing at al. [6] concluded that waste recycling is a multi-disciplinary problem that needs to be considered at different decision levels simultaneously through a holistic view and taking into account the characteristics of different waste types is necessary when modeling a reverse supply chain for MSW recycling.

Khan et al. [7] developed a model (FUNNEL-Cost-MSW) and compared nine different waste management scenarios with respect to calculated gate fees and calculated internal rate of return (IRR) recommending the best option based on waste availability and some cost specifications and cost parameters. A case study was conducted on waste management in Parkland County in Alberta, Canada.

Many other researchers have attempted to determine the type, location, size of treatment and disposal facilities and the transportation routes from waste production sites to the treatment and disposal facilities using mathematical models. Chang and Lin [8] conducted a study on the reorganization of the waste management plan for the metropolitan area of Taipei. The purpose of the study was to develop an analytical tool that could help decision makers to take appropriate choices in the management of waste on a large scale. Kagawa et al. [9] highlighted the relationship between the waste production and the capability of treatment within the same generation area in a large region of Japan. The shortage of land for landfills, a problem frequently highlighted in the literature [10] requires planners to find ways of reducing the volume of waste to be landfilled. Leao et al. [11] presented a model able to assess the demand for landfills and their allocation over time under a range of different scenarios, including different waste disposal solutions, urban growth patterns and land evaluation criteria.

Alçada-Almeida et al. [12] proposed an interactive decision support system (IDSS) based on geographical information system (GIS) to help planners to determine the most appropriate locations and capacities of incineration facilities for hazardous materials.

GIS-based approach was also adopted in selecting municipal solid waste landfill sites by combining spatial information techniques and AHP for Isparta Basin, Turkey; Beijing, China; and Lemons Island, Greece respectively [2].

Transportation is always considered a critical component of an effective solid waste management system and its optimization is supposed to widely contribute to social, economic and environmental sustainability.

This research deals with the development of a procedure aimed at the optimization of waste management through the best combination of typology and location of waste facilities (landfills, incineration plants, recycling and/or composting plants, cement plant, gasifiers) and the optimal assignment of waste flows, in order to simultaneously reduce the operation costs and the environmental impacts of transportation. The procedure is based on a mathematical model running within a GIS software platform, able to include all relevant socio-economic and territorial data.

The procedure is applied to the case study of regional waste management in Sicily, a region of Southern Italy and the largest island in the Mediterranean Sea. It has an area of 25,711 km^2 and a current population of about 5 million of inhabitants. The yearly production of municipal solid waste is about 2,6 million t/year. The average production per capita (520 kg/capita/year) is comparable to the national average value (540 kg/capita/year). The disposal of the wastes in landfills is still the dominant solution in the region (about 90%). However the European Community policy allows the use of landfills only for the disposal of waste that cannot be further treated and recycled.

The main objective for a proper management of municipal waste in the region is therefore to dramatically reduce the percentage of waste disposal into landfill. In Sicily, landfills are mainly concentrated in four geographic areas: Palermo, Catania, Messina and Agrigento. Prior to a serious implementation of separate collection (currently lower than 7%), the development of facilities for pre-treating and refining the collected materials (composting plant and selection plants) are strongly required. Therefore the flows of non-recyclable materials have to be carefully evaluated to ensure the

appropriate energy recovery options and the consequent volume reduction in order to achieve the lowest dependence on landfills.

The long delay on the implementation of waste treatment plants, as expected by the waste management regional plan, together with the economic interests of landfill private owners, has indeed seriously set back the system of separate collection. It appears therefore compulsory starting to build up these facilities, applying appropriate technologies, with the right capacity and a proper location on the territory of competence, based on the analysis of waste flows from origin to destination.

2 Methodology

2.1 Model formulation

The study focused on the analysis of the transportation of solid wastes in the region. To reduce the complexity of the system, the Sicilian territory was divided into twenty-six macrozones (zoning), each associated to a representative node to which, specific zonal information (population density, waste production, etc.), were associated.

A software tool integrating transportation and logistics modeling within a GIS platform (TRANSCAD) was applied and, through a procedure of "*facility location*" the most appropriate areas for the allocation of facilities were defined. By solving a "*minimum-cost flow*" problem, it was possible to represent the Refuse Derived Fuel (RDF) and Residual Municipal Waste (RMW) optimized flows for the different scenarios.

The Minimum Cost Flow Problem was implemented as a specific formulation of the general "Transportation Problem". The minimum cost flow problem is solved finding the optimal set of flows of waste x_{ij}, from the generation zone 'i' to the destination treatment plant 'j', associated to a relevant route of cost c_{ij}, that minimize the total transportation cost Z:

$$Z = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij}$$

The problem is subjected to different constraints (waste production for each zone and capacity of the treatment plants) so that the shortest transportation path is not always the most convenient to be utilized.

To identify and choose the best locations of the new facilities, a Facility Location Problem was solved through the relevant algorithm available within TRANSCAD.

Defining the unit cost of transportation is not easy because there are many involved variables that are not always easily quantifiable in monetary terms. In the study, the cost of transportation was calculated as the sum of different cost components related to the distance traveled, the personnel, and the vehicle utilized to collect waste including fuel costs, tires costs, property tax and truck maintenance costs [13]. Using the above specific costs and assuming and average speeds of 30 km/hin the urban road network and 55 km/hin the extra-urban road network, a unit transportation cost of 0.11 €/ton-km was considered in this work.

2.2 Hypothesis of integrated waste management in Sicily

According to the proposed procedure, the entire regional waste was separated into wastes from the major cities (Palermo, Catania, Messina, Siracusa, for a total of 1,315,000 inhabitants, about 710,000 tons/y of waste) and waste from the small towns (a total of about 3,736,000 inhabitants, about 2,017,000 tons/y of waste). Different recovery goals were consequently hypothesized for the two waste origins according to the regional data on the few positive separate waste collection experiences. These optimistic hypothesis were however confirmed by the national data on separate waste collection [14] indicating rate up to 50% for small town and rate lower than 30% for large town in the South of Italy.

Five scenarios for waste management in the region were then proposed in order to investigate the related environmental and economic transportation costs. A recovery rate equal to 50% of the total waste produced (50% MSW) in Sicily (about 1,300,000 tons/y) was considered for all the scenarios, in an optimistic management prospective characterized by potential high rates of waste collection in the small towns.

The *first scenario* represents the “worst” case (the closest to the current situation), where the remaining 50% of MSW is disposed to the existing 14 landfills, afterMechanical Biological Treatment (MBT) plants (currently available only in five of the 14 landfills).

The *second scenario* considered the remaining 50% of MSW disposed at four large incinerators. This scenario almost corresponds to the prevision of the previous and out to date waste plan in Sicily.

The *third scenario* assumed the remaining 50% of MSW to be treated in the five existing MBT plants in order to separate the dry fraction to produce Refuse Derived Fuel (RDF). The RDF is then totally used to supplies the existing furnaces for the production of clinker (cement) in Sicily. This hypothesis implies to replace the fuel currently used with the RDF up to the feeding limits of each cement plant (according to EU BAT on cement industry [15]. The *fourth scenario* is similar to the previous one but a reduced rateof RDF is addressed to the existing cement plants while the remaining amount is sent to three small gasifiers, located in Palermo, Catania and Milazzo respectively.

The *fifth scenario* considered the remaining 50% of MSW addressed to only three large incinerators, located in Palermo, Catania and Milazzo, the three macro area of waste production in the region.The incinerators capacities were obtained by the procedure of "*Facility Location*" implemented with the software TransCad.

3 Results and discussion

The percentage of separate collection assumed for large and small cities are shown in Tab. 1.

According to these hypothesis, about 510,000 tons/y of organic waste are supposed to be turned into quality compost, about 680,000 tons/y recycled as Secondary Raw Materials (SRM) and about 560,000 tons/y transformed into RDF and sent to thermal treatment. In this way only about 1 million tons/y of waste needs to be disposed to landfill.

Tab. 1 Percentage of recovery for each waste category in large cities and small towns

		Large Cities	Small cities and village	Sicily
Inhabitants		1,315,000(26%)	3,736,000(74%)	5,051,000(100%)
Total waste produced (tons/y)		710,250(26%)	2,017,320(74%)	2,727,570(100%)
Waste components				
tons/y	Compost	24,149 (0.9%)	484,158(17.8%)	508,307(19%)
	Secondary Raw Materials	122,909(4,5%)	560,918(20.6%)	683,827(25%)
	Refuse Derived Fuel	214,284(7.9%)	344,358(12.6%)	558,642(20%)
	Total recoveredwaste	361,342(13.2%)	1,389,434(50.9%)	1,750,776(64%)
	Waste disposed tolandfill	348,908(12.8%)	627,886(23.0%)	976,794(36%)

The optimization model was then implemented obtaining the graphic processing of optimized waste daily flows (tons/day) and the respective costs from the waste generation node to disposal plants (Fig. 1).

The cost (7,951 €/day) of transportation for the disposal of waste in landfills (scenario 1) is significantly lower than the other scenarios, This result, regarding only transportation costs, was expected because the direct transportation and the high number of disposal sites decrease the mean distance of waste mass transfer. This of course does not mean that it is more convenient to dispose of in landfills, because the other solutions allows other and more important benefit such as the recovery of energy and the minimization of landfill environmental drawback (e.g. leachate and biogas production). Moreover land is becoming on the Island an important and scarce resource and the process of consumption of landfill space in urban regions is a potential problem. So the reduction of landfill volume requirement is strongly desirable to reduce environmental impact and to implement a real integrated waste management.

Scenarios 2 and 5 have a comparable costs of transportation (respectively 14,600 and 15,203 €/day), but the scenario 2 involves the building up of four incinerators instead of the three expected in the fourth scenario. This result shows that the correct location and the right plant capacity allows to optimize the waste management.

Scenario 3 has the highest cost of transportation (21,521 €/day) compared to others because it provides for two phases of transportation (Fig. 1– Scenario 3a and 3b): from waste generation nodes to MBT plants (11,992 €/day) and from these last to the existing cement plants in Sicily (9,529 €/day). To reduce the cost (15,041 €/day), this scenario was upgraded, in the scenario 4 (4a and 4b), considering to send part of the RDF in three gasifier, located close to the centres of production in Palermo, Catania and Milazzo.

To evaluate which scenario is the least impacting on the road congestion, the number of “truck a day” in three critical sections of the road network in Sicily (Fig. 2) was calculated (Tab. 2): highway A19 close to Catania, highway A19 close to Palermo and highway A18 close to Messina.

Among the different analyzed scenarios, again scenario 1, presents the lower number of "truck per day"(63 truck/day) and therefore it is the less impacting on traffic in the critical sections of the road network in Sicily. However it still does not fulfill European Union guidelines being the landfill role still predominant.

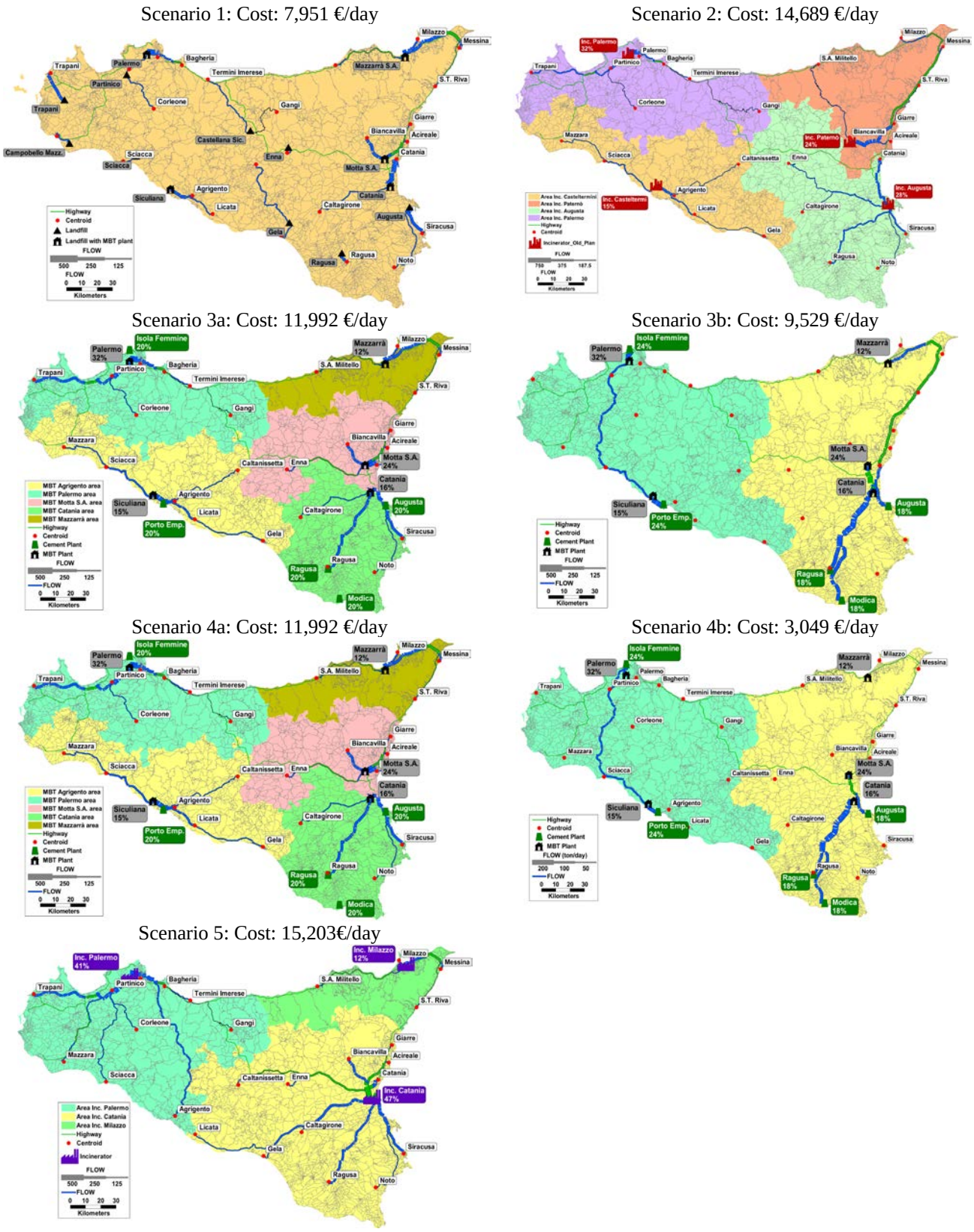

Fig. 1 Potential scenarios for waste management in Sicily and related daily transportation costs

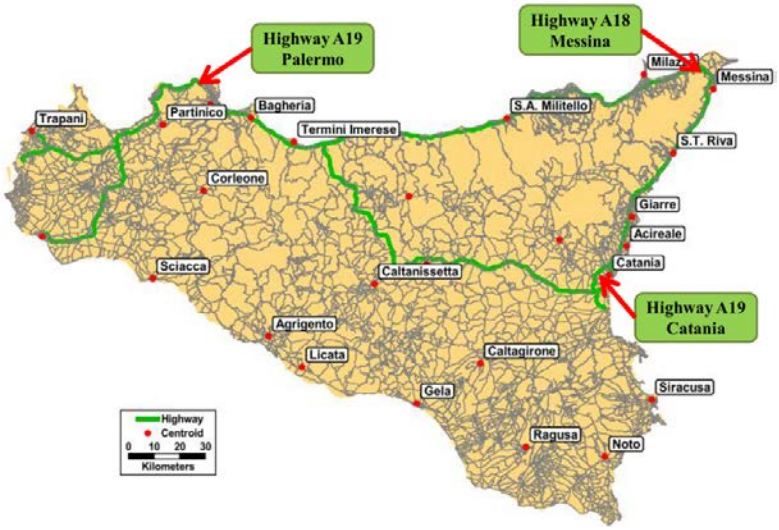

Fig. 2 Three critical sections of the road network in Sicily

Tab. 2 Comparison of the number of truck/day due to the waste transportation in three critical sections of the road network in Sicily for all the investigated scenarios

	Highway A19 – Catania (truck/day)	**Highway A19 – Palermo (truck/day)**	**Highway A18 – Messina (truck/day)**
Scenario 1	17	34	12
Scenario 2	30	39	8
Scenario 3a+3b	35	56	21
Scenario 4a+4b	28	46	12
Scenario 5	47	45	11

Scenario 2 shows a low impact on traffic flow in the three critical sections of the road network in Sicily (77 truck/day). It could thus result more acceptable by public opinion than scenario 4 (103 truck/day), thanks to a more equilibrated distribution of facilities and consequent waste flows over the territory.

Scenario 3 has the higher impact on traffic flow (112 truck/day), but it is, on the total, the more cost-effective with respect to other scenarios, since it eliminates the cost of construction of new plants exploiting the absorption capacity of RDF by cement plants. Considering to send part of the RDF in three gasifier, located in Palermo, Catania and Milazzo (scenario 4), the impact on traffic flow drops considerably up to a value of 86 truck/day.

Traffic flows of scenario 5 are moderately high (103 truck/day) and, in the case it would be not possible to implement scenario 3, it has a low impact on the area so representing a potential valid alternative for waste management in Sicily.

4 Conclusion

Municipal solid waste (MSW) is a primary concern to regional authorities and planners. Financial, political and environmental concern is a major consideration which complicates the decision making process.

The alarming increase in the generation of MSW and the manner in which wastes are being managed in Sicily is one of the greatest challenges faced by the Sicilian Government. The proposed GIS model discussed in this paper was designed to assist planners, civil engineers and developers to determining typology, capacity and location of facilities for waste treatment and disposal for both present and future management scenarios in Sicily

The present study was characterized by two steps: a) estimating the amount of waste produced in Sicily, from the large cities (low recovery rates) and from small cities and villages (high recovery rate) respectively; b) the implementation of models of "Facility location" and "Minimum cost flow" for the optimization of flow distribution of residual waste.

Some scenarios were proposed and compared, also by evaluating the impact on traffic due to the increase of "truck per day" in three critical sections of the road network in Sicily. The analyzed scenarios should not be interpreted as alternative or antagonistic solutions, but they can also be seen as complementary ones through the implementation of their partial combination in different areas of the Island. Significantly the best solution, according to transportation and disposal results is provided by the scenario 1. Landfill, although found at the bottom of waste management hierarchy (waste reduction, reuse, recycling, composting and land filling), is an integral component of the waste management chain and requires greater attention to reduce its environmental impact.

This partially justifies the strong opposition to the real introduction in the Island of the EU waste management principles that consider landfill as the last disposal solution only to be applied to non-recoverable waste. It is less expensive than other forms of waste treatment but has, nonetheless, created and continues to create environmental problems.

In order to avoid the costs of building up new incineration plants (scenarios 2 and 5), scenarios 3 and 4 are however suitable. In particular scenario 4, consisting into addressing and treating the remaining 50% of MSW in five MBT plants and the RDF, here produced, to both the existing cement plants in Sicily and to three gasifier (located in Palermo, Catania and Milazzo), is the least impacting on the road traffic.

This research has demonstrated the importance of GIS-based tool in the siting of facilities such as municipal landfill sites. It expedites the analysis of a huge spatial and a spatial data and turn out result with degree of accuracy within the shortest possible time which otherwise will be impossible with in-situ techniques

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