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# Comparison of the Suitability of Two LCA Procedures in Selecting the Best MSW Management System

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## 1. Introduction

Nowadays, the qualitative and quantitative assessment of the environmental impacts produced by every human activity is a topical field of research. In fact, all over the world a growing amount of attention is being given to the environmental issues and influences exerted by productive and management sectors. In particular, the management of waste is a crucial sector involving important aspects of our life, with it producing several environmental impacts that have to be adequately monitored and managed in a sustainable development perspective.

This cgapter focuses on the study of different municipal solid waste management systems in a district of the Campania region, in Southern Italy, which is sadly known due to it is suffering from a serious solid waste emergency that has lasted over 15 years. It has been the culmination of a process of insufficient implementation of European waste legislation for which Italy has repeatedly been condemned by the European Court of Justice. In particular, the images of heaps of rubbish in the streets of Naples and other nearby cities as well as the revolt of people against the realization of landfills and incinerators have been impressively documented by the international press (De Feo and Malvano, 2009; De Feo and De Gisi, 2010).

In order to manage these questionable situations, giving clear as well as affordable information to the people about the environmental impacts of waste management plants is fundamental. In this perspective, the study focused on the evaluation of the positive (induced) and negative (avoided) impacts caused on different environmental components by several municipal solid waste management systems defined on a provincial scale. This assessment was carried out by means of two different Life Cycle Assessment (LCA) procedures called WISARD and SimaPro, respectively.

LCA is a general methodological framework introduced to assess all the environmental impacts relating to a product, process or activity by identifying, quantifying and evaluating the overall resources consumed as well as all the emissions and wastes released into the environment (De Feo and Malvano, 2009).

In 1990, the society for environmental toxicology and chemistry (SETAC) defined the concept of LCA and developed a general methodology for the carrying out of LCA studies (Azapagic, 1999; De Feo and Malvano, 2009). The term ''LCA'' is used most frequently to

describe all the cradle-to-grave approaches (Curran, 1996). A lot of these tools have been separately developed by different groups of specialists in order to support the decision maker within environmental management processes (SETAC, 1996; De Feo and Malvano, 2009). LCA methodology, as defined by SETAC or by ISO (International Organization for Standardization), consists of four steps (Curran, 1996; SETAC, 1996; De Feo and Malvano, 2009): (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) improvement assessment.

LCA can be useful and conveniently applied only to the life cycle related to the collection, treatment and landfill disposal of solid waste. In this particular case, the reference flux is given by the amount of waste produced by a community, while the output is represented by the emission of pollutants due to the several parts of the MSW management system. Therefore, the LCA procedure applied to the MSW management can be seen as a useful analysis instrument aimed at the evaluation of possible actions. In fact, the European Commission's Thematic Strategy on the prevention and recycling of waste outlines how adopting a life cycle perspective is essential for the sustainable management of wastes (Koneckny and Pennington, 2007; De Feo and Malvano, 2009).

The LCA procedures were able to calculate the consequences produced by the whole system as well as by each phase; in this case the goal is also to compare the two procedures. In particular, WISARD has been specifically designed for MSW applications, while SimaPro is a more general tool.

The aim of this study was to apply the two LCA procedures to MSW management on a provincial scale in order to choose the "best" management system in environmental terms (impacts minimization) as well as compare the results obtained with a specific tool (WISARD), on one hand (the sociological and environmental goal), and with a more general tool (SimaPro), on the other (the technical goal).

## 2. Material and methods

### 2.1 Study area and reference data

The study area was the Province of Avellino in the Campania region, in Southern Italy, with a surface area of 2,792 km² and a population of 422,292 inhabitants (National Institute of Statistics, 1st January 2007). The total MSW production was 140,177,372 kg, the specific daily MSW production was around 0,9 kg/inhabitant/d, while the MSW composition was based on the presence of 42% of putrescibles, 30% of paper and cardboard, 14% of plastics, 8% of glass and 3% of metals and 1% of textiles (Table 1).

| Fraction | Percentage (%) | Production (t/year) |
|---|---|---|
| Putrescibles (ex. Garden) | 30% | 42053.2116 |
| Putrescibles (garden) | 12% | 16,821.2843 |
| Paper and Cardboard | 30% | 42053.2116 |
| Plastics | 14% | 19,624.8320 |
| Glass | 8% | 11,214.1897 |
| Metals | 3% | 4205.3211 |
| Textiles | 2% | 2803.5474 |
| Undersieve | 1% | 1401.7737 |
| Total | 100% | 140,177.372 |

Table 1. MSW composition of the study area (De Feo and Malvano, 2009)

## 2.2 MSW management scenarios

The LCA study was developed considering twenty-one different MSW management scenarios. They were obtained considering different separated collection percentages, as well as various types of treatment for the dry residue deriving from the MSW without the materials being separated, collected and recycled or composted.

The MSW management scenarios considered can be conveniently divided into three categories: the first includes the scenarios from 1 to 10 (Fig. 1) and is based on the incineration of the dry residue ("Incineration scenarios"), the second includes the scenarios from 11 to 20 (Fig. 2) and is based on the sorting of the dry residue ("Sorting scenarios"), while the third relates only to scenario 21 (Fig. 3) and does not consider the treatment of dry residue, directly disposed of in landfill.

Scenarios 1-10 were based on a separated kerbside collection of paper and cardboard, putrescibles and dry residue, on a combined kerbside collection of plastics and metals and, finally, on a bring collection of glass with banks. The collected materials of paper and cardboard, glass, plastics and metals are then transported to recycling plants. Putrescibles, after collection, are transported to a composting plant. The dry residue is firstly transformed into RDF pressed bales and subsequently transported to an incineration plant. Discards deriving from all the treatment processes are collected and transported to a landfill. The ten scenarios (1–10) differ only in the percentage of separated collection. In fact, scenario 1 was based on a 35% separated collection, which was the lowest level allowed by Italian legislation, while scenario 10 was based on an 80% separated collection, a threshold which is difficult to achieve and only relates to a few and/or well organized territories. Scenarios 2–9 were progressively obtained by adding a 5% value to the separated collection of the previous scenario (Fig. 1).
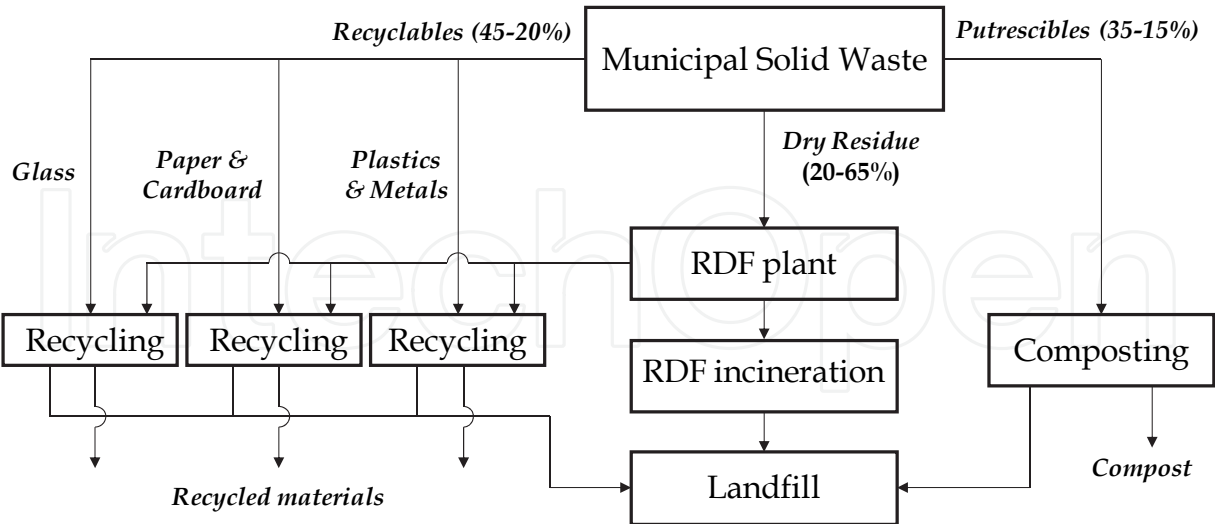


Fig. 1. Flow chart of MSW management scenarios 1–10 (De Feo and Malvano, 2009)

Scenarios 11-20 differ from scenarios 1-10 in only the treatment of the dry residue, which is transported to a sorting plant for a supplementary recovery of materials.

Management scenario 21 differs from scenario 20 (based on an 80% separated collection) with the dry residue being directly transported to a landfill (Fig. 3).
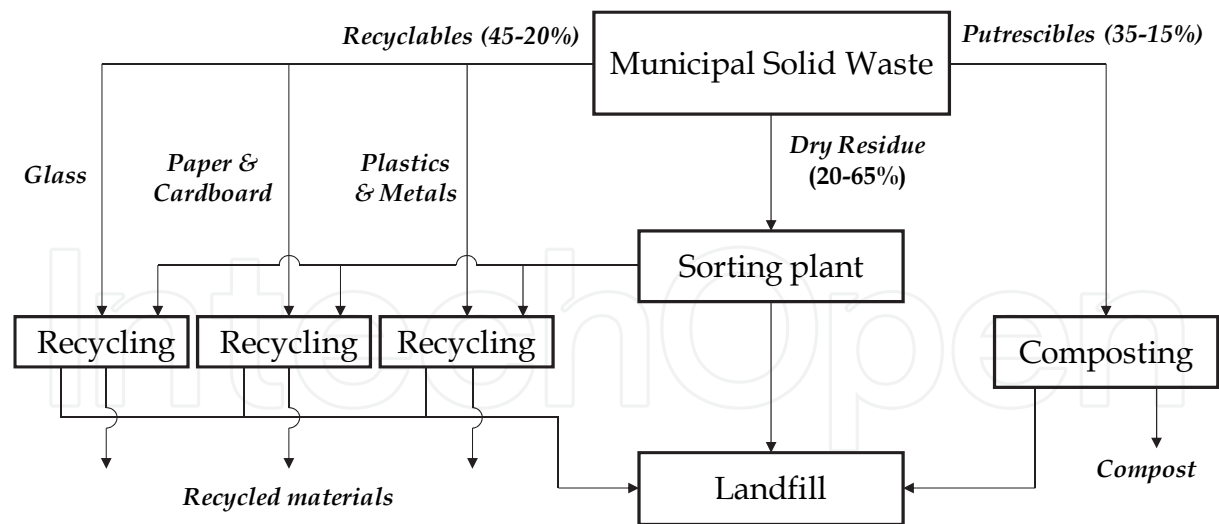
Fig. 2. Flow chart of MSW management scenarios 11-20 (modified by De Feo and Malvano, 2009)
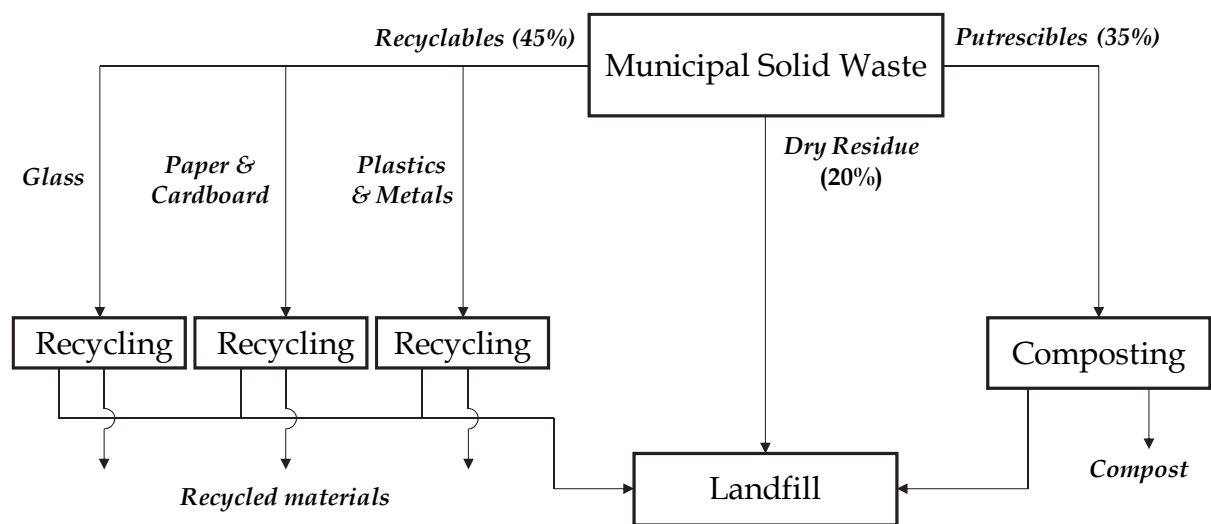


Fig. 3. Flow chart of MSW management scenario 21 (De Feo and Malvano, 2009)

## 2.3 The LCA procedures: SimaPro and WISARD

The Goal and Scope of the study was the use of LCA for the analysis of different MSW management systems in order to characterize the environmental impact as well as provide information to decision makers in choosing the best management solution to be adopted on a provincial level. The Function of the study was the activities of treatment and disposal of MSW, while the Functional Unit (quantified performance of a product system for use as a reference unit) was a tonne of waste of specific composition and, finally, the Reference Flow (measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit) was quantified as the production of MSW in a year.

The Definition of Goal and Scope, Function, Functional Unit and Reference Flow allowed for the construction of the main MSW management system to be analyzed. The boundaries of the system were subsequently expanded to take into account the production processes

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avoided by energy recovery as well as recycling of matter. The operation of boundaries expansion is necessary in any LCA procedure in order to eliminate the potential environmental impacts that would be induced by the avoided processes of primary production (due to secondary production) from the results of the system analyzed.

The next step of the LCA procedure is the Inventory Analysis (compilation and quantification of inputs and outputs), which is the most important phase of the activity because it allows for the acquisition of all the information which is useful in compiling and quantifying the flows of matter and energy in input and output from each phase for the quantification of emissions.

Data about the Inventory Analysis of the WISARD procedure are reported in De Feo and Malvano (2009), which contains all the information pertaining to the mass and energy balances of the treatment plants of any MSW components. While, the full details of the Inventory Analysis of the SimaPro procedure are presented here.

The following modules, described in greater detail later, were implemented: Packaging Glass Green at Plant, Aluminium Secondary, from old scrap at Plant, Recycling Paper, with deinking at Plant, Recycling Plastics, Compost, at Plant, Glass Virgin, Aluminium Primary, at Plant, Thermomechanical Pulp, at Plan, PET, HDPE, LDPE, Ammonium Nitrate, Single Superphosphate, Potassium Sulphate, Landfill, Municipal Waste Incineration Plant, Wastewater Treatment Plant (PRé Consultants, 2007a, b).

The utilized data were deduced from average European plants as well as Italian specific plants that best approximate the systems to be adopted on a provincial level as well as best meet the requirements during the Goal and Scope definition of the study. The analysis was carried out on three levels. In fact, the Inventory was drawn up simultaneously taking into account:

- raw materials and energy used;
- transport of products, waste treatment and construction, dismantling and disposal of production sites;
- characterization of the machinery necessary for production and processing.

In particular, data were deduced from two principal sources: the Ecoinvent database and real data relating to MSW treatment and disposal plants operating in Italy and, particularly, in the Campania region. The MSW management model was constructed on the basis of several hypothesis, further verified with specific evaluation tests. In particular, assumptions were made in relation to the type of goods produced by "primary production" and "secondary production". Moreover, selection, recovery and recycling efficiencies for all types of materials were adopted. The basic assumption is that 1 kg of material produced by recycling replaces 1 kg of material produced from raw materials (Rigamonti et al., 2009).

Table 2 and 3 respectively show the type of packaging products and selection, recovery and recycling efficiencies adopted in the study.

| Material | Primary Production | Secondary Production |
|---|---|---|
| Aluminium | Ingot | Ingot |
| Glass | Container | Container |
| Paper | Thermomechanical Paper | Pulp |
| Plastic | Grains of PET, HDPE, LDPE, LLDPE, PP | Grains of PET, HDPE, Mix (LDPE, LLDPE, PP) |

Table 2. Type of packaging products (Rigamonti et al., 2009)

| Material | Efficiency of Selection (%weight) | Efficiency of Recovery (%weight) | Efficiency of Recycling (%weight) |
|---|---|---|---|
| Aluminium | 95 | 93 | 88.3 |
| Glass | 94 | 100 | 94 |
| Paper | 95 | 90 | 85.5 |
| Plastic | 80 | 73.5 | 58.7 |
| Garden Waste | 80 | 37.5 | 30 |

Table 3. Selection, recovery and recycling efficiencies (Rigamonti et al., 2009)

### 2.3.1 Composting plant

Putrescibles are treated by means of an aerobic composting process for the production of high quality compost to be used for farming in substitution of traditional chemical fertilizers. The basic assumption is that 1 kg of compost replaces a certain amount of artificial fertilizer so that the intake of nutrients N, P and K remains unchanged. A ton of compost contains: 6.2 kg N, 2.0 kg P and 4.5 kg K. Table 4 shows the general characteristics as well as consumption data of the composting plan t, useful for the Inventory Analysis. Energy required, type and quantity of polluting emissions as well as waste production relating to a treatment capacity of 10,000 tonnes of putrescibles per year. Moreover, they relate to a specific production of 1 kg of compost with a final water content of 50% by weight (Ecoinvent Data).

| Composting Plant – Compost, at plant | | |
|---|---|---|
| General Characteristics | | |
| Life Time (year) | Treated Tonnes (t/m) | Type |
| 10 – Stationarity Machinery<br>5 – Mobile Machinery<br>25 – Structural elements | 10,000 | Mechanized |
| Consumption | | |
| Diesel (kg) | Electricity (kWh) | Water (l) |
| 2.65E-3 | 1.18E-2 | 0 |

Table 4. Characteristics of the composting plant (modified by Nemecek et al., 2004)

### 2.3.2 Glass recycling plant

The recovery of glass was analyzed both in terms of preparation and selection of glass waste from separate collection as well as in terms of recycling activity (fusion, secondary packaging production, cooling, packaging and transporting to end users). The treated materials are crushed and selected by means of both manual and automatic processes with the removal of 100% of the impurities originally present. Table 5 shows the general characteristics as well as consumption data of the glass recycling plant, useful for the Inventory Analysis.

| Glass Recycling Plant – Packaging Glass Green at plant | | |
|---|---|---|
| General Characteristics | | |
| Life Time (year) | Treated Tonnes (t/m) | Type |
| 20 – Stationarity Machinery 5 – Mobile Machinery 50 – Structural Elements | 100,000 | Mechanized |
| Consumption | | |
| Diesel (kg) | Electricity (kWh) | Water (l) |
| 4.19E-2 | 2.44E-1 | 1.98E-3 |
| Oil (MJ) | Natural Gas (MJ) | - |
| 4.33E-2 | 3.57 | - |

Table 5. Characteristics of the glass recycling plant (modified by Hischier, 2007)

### 2.3.3 Paper recycling plant

The management of paper and cardboard waste involves the following phases: collecting, selecting and transporting to the recovery facilities. The recovery process considered was recycling without deinking with consumption of electricity and subsidiary materials, emission of pollutants into the air and wastewater treatment. Only natural gas was used as fuel for the heat production. While, a fuel mix of 16.1% coal, 70.3% methane and 13.6% fuel oil was used for electricity production. The recycling treatment was compared with the classical process of paper production from raw materials. The technology used is the thermal-mechanical treatment for the removal of fibres from wood chips. Table 6 shows the general characteristics as well as consumption data of the paper recycling plant, useful for the Inventory Analysis.

| Paper Recycling Plant – Recycling Paper without deinking at plant | | |
|---|---|---|
| General Characteristics | | |
| Life Time (year) | Treated Tonnes (t/m) | Type |
| 20 – Stationarity Machinery 5 – Mobile Machinery 50 – Structural Elements | 33,000 | Mechanized |
| Consumption | | |
| Diesel (kg) | Diesel (kg) | Diesel (kg) |
| 0.6555 | 7.9E-1 | 1.07E-2 |
| Oil (MJ) | Natural Gas (MJ) | Coal (MJ) |
| 0.6555 | 6.7769 | 1.552 |

Table 6. Characteristics of the paper recycling plant (modified by Hischier, 2007)

### 2.3.4 Aluminium recycling plant

Aluminium deriving from MSW separate collection is sent to facilities for the selection and subsequent recycling for the production of secondary aluminium products. The process is based on the use of "old" scrap deriving from separate collection and prepared by means of the selection and removal of organic matter in order to be suitable for the subsequent fusion process. The efficiency of recycling was assumed equal to 93%. The Life Cycle Analysis considers emissions from aluminium production from raw materials, as well. In particular,

data from the Ecoinvent database and references concerning the best technologies used in industry for the production of non-ferrous metals are shown in Table 7.

| Aluminium Recycling Plant – Aluminium Secondary, from old scrap at plant | | |
|---|---|---|
| General Characteristics | | |
| Life Time (year) | Life Time (year) | Life Time (year) |
| 50 | 10,000 | Mechanized |
| Consumption | | |
| Oil (MJ) | Electricity (kWh) | Water (l) |
| 5.13 | 2.88E-1 | 0 |
| Natural Gas (MJ) | - | - |
| 8.27 | - | - |

Table 7. Characteristics of an aluminium recycling plant (modified by Althaus et al., 2004)

### 2.3.5 Plastic recycling plant and mechanical–biological plant

In the Inventory Analysis developed for the waste treatment and disposal plants, the available data have allowed for a precise and detailed characterization of all the process units with the exception of those relating to the plants of plastics recycling plants and plants of mechanical and biological treatment (MBT) of dry residue as designed in the Campania region. For plastic recycling and MBT plants, in particular, the analysis only took into account the information relating to the consumption of matter and energy of the process, without considering the consumption of a second or third level related to the construction of the production site as well as production of machineries contained in the plants.

Tables 7, 8 and 9 show the summary data of the energy balance relating to plastic recycling and MBT plants, respectively.

| Plastic Recycling Plant | |
|---|---|
| Plastics Selection | |
| Fuel (kWh/t) | Diesel (MJ/t) |
| 26.6 | 84 |
| PET Recovery | |
| Fuel (kWh/$t_{R-PET}$) | Methane (MJ/$t_{R-PET}$) |
| 258 | 2500 |
| HDPE Recovery | |
| Fuel (kWh/$t_{R-HDPE}$) | Methane (MJ/$t_{R-HDPE}$) |
| 379 | 650 |

Table 8. Data of the energy balance relating to plastic recycling plants (Rigamonti et al, 2009)

## 3. Results and discussions

### 3.1 Summary of results obtained with WISARD

With the WISARD procedure, only scenarios 1-10, 20 and 21 were studied. The outputs from each option modelled were analysed under eleven environmental effect categories as suggested by the WISARD procedure with the aim of carrying out a synthetic study of the data available (Pricewaterhouse Coopers, 2006). The impact assessment categories

| Mechanical –Biological Plant | |
|---|---|
| General Characteristics | |
| Polyethylene Film (kg) | Water (l) |
| 1.6E-4 | 0.088 |
| Wire (kg) | Electricity (MJ) |
| 3.00E-4 | 0.051 |
| Diesel (MJ) | |
| 0.01 | |

Table 9. Data of the energy balance relating to MBT plants (Arena, 2003)

suggested are as follows: renewable energy use, non-renewable energy use, total energy use, water, suspended solids and oxydable matters index, mineral and quarried matters, greenhouse gases, acidification, eutrophication, hazardous waste, non-hazardous waste (De Feo and Malvano, 2009).

Attention was given to both measuring the overall impact due to the application of the entire MSW management system adopted, as well as the evaluation of the specific contribution produced by each phase of the MSW management system. In fact, each system was subdivided into the following sixteen phases: glass collection logistics (GCL), glass collection recycling (GCR), glass collection disposal (GCD), paper collection logistics (PaCL), paper collection recycling (PaCR), paper collection disposal (PaCD), plastics and metals collection logistics (Pl&MCL), plastics and metals collection recycling (Pl&MCR), plastics and metals collection disposal (Pl&MCD), putrescibles collection logistics (PCL), putrescibles collection composting (PCC), putrescibles collection disposal (PCD), dry residue collection logistics (DRCL), dry residue collection recycling (DRCR), dry residue collection RDF incineration (DRCI), and dry residue collection disposal (DRCD) (De Feo and Malvano, 2009).

Therefore, 192 management phases were considered (corresponding to the product of 16 phases for 12 scenarios), while 2112 single impact values were analysed and compared (corresponding to the product of 11 impact categories for 192 management phases). Moreover, 132 total impact values were analysed and compared (corresponding to the product of 11 impact categories and 12 management scenarios) (De Feo and Malvano, 2009).

The goal of the study was to evaluate the results obtained (values of avoided or produced impact) in order to highlight the most environmentally sound scenarios for each environmental impact category, as well as the trend associated with the percentage of separate collection (for the first ten MSW management scenarios), thus evaluating the positive and negative effects of recycling and/or composting (Table 10). The LCA software tool calculates impact values, performing mass and energy balances on the basis of the amount of waste to be treated. For scenarios 1–10, these quantities vary linearly with the percentage of separate collection and therefore the impact values for each management phase also vary in the same manner. Since the sum of the linear function is a linear function, the total impact values for each category also have to vary linearly. Moreover, for each impact category and MSW management scenario developed, the management phase with the greatest avoided impact (Table 11) and the management phase with the greatest produced impact (Table 12) were highlighted. Finally, scenarios 10, 20 and 21 were compared in order to highlight for which impact categories for high percentages of separate

collection a management system based on recovery and recycling but without incineration would be preferable (De Feo and Malvano, 2009).

In summary, the following outcomes were obtained with the WISARD procedure (De Feo and Malvano, 2009):

- Scenario number 21 (80% separate collection, no RDF incineration, dry residue sorting) was the most environmentally sound option for the following six impact categories: renewable energy use, total energy use, water, suspended solids and oxydable matters index, eutrophication, and hazardous waste;
- Scenario number 10 (80% separate collection, RDF production and incineration) was the most environmentally sound option for the following three impact categories: non-renewable energy use, greenhouse gases, and acidification;
- Scenario number 1 (35% separate collection, RDF production and incineration) was the most environmentally sound option for the following two impact categories: mineral and quarried matters, and non-hazardous waste;
- For the following eight impact categories (of the eleven considered), all the MSW management scenarios considered produced negative impacts, and the highest percentage of separate collection corresponded to the highest avoided impact: Renewable Energy Use, Non-Renewable Energy Use, Total Energy Use, Water, Suspended Solids and Oxydable Matters Index, Acidification, Eutrophication, and Hazardous Waste;
- For "Mineral and Quarried Matters" the MSW management scenarios considered produced positive and negative impacts, and the highest percentage of separate collection corresponded to the highest produced impact;
- For "Greenhouse Gases", the MSW management scenarios considered produced positive and negative impacts, and the highest percentage of separate collection corresponded to the highest avoided impact;
- For "Non-Hazardous Waste" all the MSW management scenarios considered produced positive impacts, and the highest percentage of separate collection corresponded to the highest produced impact;
- For the following six impact categories (of the eleven considered), for high percentages of separate collection (80%), a management system based on recovery and recycling but without incineration would be preferable: Renewable Energy Use, Total Energy Use, Water, Suspended Solids and Oxydable Matters Index, Eutrophication and Hazardous Waste;
- "Paper Collection Recycling" was the system component with the greatest avoided impact for 45.5% of the cases considered;
- "Dry Residue Collection Logistic" was the system component with the greatest produced for 54.5% of the cases considered.

## 3.1 Results obtained with SimaPro

The results obtained with the SimaPro procedure were evaluated by means of three keys.

The first key evaluates the results of the Inventory Analysis consisting of the data on the emissions of pollutants into the environment due to the different phases of the MSW management system, focusing on the treatment activities of the several MSW components. Thus, it was possible to compare in quantitative environmental terms, the impacts generated

| Impact Category | MSW Management Scenario | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 35% (1) | 40% (2) | 45% (3) | 50% (4) | 55% (5) | 60% (6) | 65% (7) | 70% (8) | 75% (9) | 80% (10) | 80%S (20) | 80%L (21) |
| Renewable Energy Use (equivalent inhabitant) | -428,695 | -489,507 | -543,589 | -597,599 | -650,858 | -704,852 | -725,547 | -792,498 | -860,128 | -927,731 | -952,854 | -916,814 |
| | Impact (equivalent inhabitant)= -10,628 × (percentage of separate collection) – 60,995 | | | | | | | | | | -2.7% | +1.2% |
| Non-Renewable Energy Use (equivalent inhabitant) | -14,934 | -15,927 | -17,227 | -18,149 | -18,912 | -20,158 | -21,379 | -22,249 | -23,494 | -24,284 | -23,655 | -20,679 |
| | Impact (equivalent inhabitant)= -209.89 × (percentage of separate collection) – 7,602 | | | | | | | | | | +2.6% | +14.8% |
| Total Energy Use (equivalent inhabitant) | -30,725 | -33,002 | -37,316 | -40,264 | -43,030 | 46,288 | -48,253 | -51,646 | -55,425 | -58,764 | -59,117 | -54,880 |
| | Impact (equivalent inhabitant)= -607.49 × (percentage of separate collection) – 9,640 | | | | | | | | | | -0.6% | +6.6% |
| Water (equivalent inhabitant) | -2,991 | -3,589 | -4,191 | -4,785 | -5,568 | -6,168 | -6,784 | -7,388 | -8,174 | -8,756 | -9,117 | -8,876 |
| | Impact (equivalent inhabitant)= -129.18 × (percentage of separate collection) – 1,588 | | | | | | | | | | -4.1% | -1.4% |
| Suspended Solids and oxydable matters index (equivalent inhabitant) | -6,905 | -7,905 | -8,945 | -10,075 | -11,075 | -12,031 | -13,039 | -14,044 | -15,045 | -15,894 | -16,393 | -15,874 |
| | Impact (equivalent inhabitant)= -201.53 × (percentage of separate collection) – 96,36 | | | | | | | | | | -3.1% | 0.1 |
| Minerals and Quarried Matters (t) | -1,279 | -767 | 51 | 257 | 1,077 | 1,920 | 2,712 | 3,481 | 3,504 | 4,375 | 21,396 | 27,404 |
| | Impact (t)= 129.28 × (percentage of separate collection) – 5,910 | | | | | | | | | | +389.1% | +526.4% |
| Greenhouse gases (equivalent inhabitant) | 58 | -677 | -108 | -788 | -969 | -1,466 | -1,444 | -1,899 | -2,077 | -2,337 | 4,370 | 10,425 |
| | Impact (equivalent inhabitant)= -51.85 × (percentage of separate collection) + 1,810 | | | | | | | | | | +287% | +546.1% |
| Acidification (equivalent inhabitant) | -8,968 | -9,247 | -9,600 | -9,871 | -9,986 | -10,337 | -10,603 | -10,710 | -11,148 | -11,321 | -10,296 | -4,237 |
| | Impact (equivalent inhabitant)= -51.61 × (percentage of separate collection) + ,211= 0.9931 | | | | | | | | | | +9.1% | +62.6% |
| Eutrophication (equivalent inhabitant) | -1,120 | -1,291 | -1,460 | -1,634 | -1,806 | -1,979 | -2,152 | -2,314 | -2,486 | -2,593 | -2,619 | -2,517 |
| | Impact (equivalent inhabitant)= -33.470 × (percentage of separate collection) + 40,8 | | | | | | | | | | -1.0% | +2.9% |
| Hazardous waste (t) | -1,375 | -1,427 | -1,480 | -1,543 | -1,565 | -1,617 | -1,659 | -1,702 | -1,755 | -1,807 | -2,204 | -1,642 |
| | Impact (t)= -9.32 × (percentage of separate collection) + 1,056 | | | | | | | | | | -22.0% | +9.1% |
| Non Hazardous Waste (t) | 21,023 | 21,477 | 22,038 | 22,511 | 23,065 | 23,676 | 24,263 | 24,732 | 25,387 | 25,824 | 42,317 | 43,470 |
| | Impact (t)= 108.89 × (percentage of separate collection) + 17,139 | | | | | | | | | | +63.9% | +68.3% |

Table 10. Summary of the numerical results obtained with WISARD for MSW management scenarios 1-10 developed in terms of avoided or produced impact (De Feo and Malvano, 2009)

| Impact Category | MSW Management Scenario | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 35% (1) | 40% (2) | 45% (3) | 50% (4) | 55% (5) | 60% (6) | 65% (7) | 70% (8) | 75% (9) | 80% (10) | 80% s (20) | 80% l (21) |
| Renewable Energy Use (equivalent inhabitant) | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR |
| | -380,753 | -441,945 | -496,339 | -550,732 | -605,125 | -659,518 | -679,913 | -747,908 | -815,899 | -883,891 | -883,891 | -883,891 |
| Non-Renewable Energy Use (equivalent inhabitant) | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR |
| | -10,791 | -12,140 | -13,759 | -15,378 | -16,727 | -18,345 | -19,694 | -21,313 | -22,932 | -24,281 | -24,281 | -24,281 |
| Total Energy Use (equivalent inhabitant) | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR |
| | -14,973 | -17,360 | -19,514 | -21,641 | -23,795 | -25,923 | -26,779 | -29,426 | -32,073 | -34,746 | -34,746 | -34,746 |
| Water (equivalent inhabitant) | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR |
| | -4,201 | -4,749 | -5,297 | -5,845 | -6,575 | -7,123 | -7,671 | -8,219 | -8,950 | -9,498 | -9,498 | -9,498 |
| Suspended Solids and oxydable matters index (equivalent inhabitant) | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR |
| | -6,825 | -7,807 | -8,821 | -9,929 | -10,863 | -11,845 | -12,827 | -13,809 | -14,791 | -15,614 | -15,614 | -15,614 |
| Minerals and Quarried Matters (t) | DRCR | DRCR | DRCR | DRCR | GCR | GCR | GCR | GCR | GCR | GCR | GCR | GCR |
| | -7,200 | -6,622 | -6,043 | -5,575 | -5,490 | -5,948 | -6,446 | -6,954 | -7,452 | -7,951 | -7,951 | -7,951 |
| Greenhouse gases (equivalent inhabitant) | DRCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR |
| | -11,152 | -12,280 | -13,518 | -15,346 | -16,583 | -18,416 | -19,667 | -21,499 | -22,736 | -24,569 | -24,569 | -24,569 |
| Acidification (equivalent inhabitant) | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR |
| | -16,488 | -18,641 | -20,795 | -22,948 | -25,101 | -27,255 | -29,408 | -31,561 | -33,715 | -35,868 | -35,868 | -35,868 |
| Eutrophication (equivalent inhabitant) | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR | PaCR |
| | -1,154 | -1,328 | -1,499 | -1,675 | -1,851 | -2,029 | -2,205 | -2,369 | -2,544 | -2,655 | -2,655 | -2,655 |
| Hazardous waste (t) | DRCR | DRCR | DRCR | DRCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR | PI&MCR |
| | -1,938 | -1,791 | -1,613 | -1,496 | -1,544 | -1,686 | -1,829 | -1,971 | -2,114 | -2,256 | -2,256 | -2,256 |
| Non Hazardous Waste (t) | PCC | PCC | PCC | PCC | PCC | PCC | PCC | PCC | PCC | PCC | PCC | PCC |
| | -1,332 | -1,437 | -1,642 | -1,846 | -2,050 | -2,155 | -2,359 | -2,564 | -2,769 | -2,974 | -2,974 | -2,974 |

Table 11. Management phase with the greatest avoided impact for each impact category and for MSW management scenarios 1-10 developed in the study performed with WISARD. DRCL = dry residue collection logistics; DRCD = dry residue collection disposal; DRCR = dry residue collection recycling; PaCR = paper collection recycling; Pl&MCR = plastics and metals collection recycling; GCR = glass collection recycling; PCC = putrescibles collection composting; PCD = putrescibles collection disposal (De Feo and Malvano, 2009)

|  | 35% (1) | 40% (2) | 45% (3) | 50% (4) | 55% (5) | 60% (6) | 65% (7) | 70% (8) | 75% (9) | 80% (10) | 80%S (20) | 80%L (21) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Renewable Energy Use (equivalent inhabitant) | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | GCL | GCL | GCL |
|  | 1,020 | 952 | 816 | 748 | 680 | 626 | 558 | 483 | 394 | 347 | 347 | 347 |
| Non-Renewable Energy Use (equivalent inhabitant) | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL |
|  | 5,935 | 5,666 | 5,126 | 4,586 | 4,317 | 3,777 | 3,237 | 2,968 | 2,374 | 2,023 | 2,023 | 2,023 |
| Total Energy Use (equivalent inhabitant) | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL |
|  | 5,748 | 5,486 | 4,961 | 4,440 | 4,178 | 3,657 | 3,135 | 2,873 | 2,299 | 1,959 | 1,959 | 1,959 |
| Water (equivalent inhabitant) | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL |
|  | 676 | 639 | 584 | 530 | 493 | 438 | 384 | 329 | 274 | 237 | 237 | 237 |
| Suspended Solids and oxydable matters index (equivalent inhabitant) | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | PCD | DRCD | DRCD |
|  | 41 | 38 | 35 | 32 | 29 | 26 | 23 | 20 | 16 | 17 | 21 | 24 |
| Minerals and Quarried Matters (t) | DRCD | DRCD | PCD | PCD | PCD | PCD | PCD | PCD | PCD | PCD | DRCD | DRCD |
|  | 9,412 | 8,711 | 8,510 | 9,412 | 10,413 | 11,414 | 12,615 | 13,716 | 13,818 | 15,019 | 18,424 | 21,727 |
| Greenhouse gases (equivalent inhabitant) | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | PCD | PCD | PCD | DRCD | DRCD |
|  | 10,003 | 9,269 | 8,535 | 7,828 | 6,929 | 6,222 | 5,502 | 5,415 | 5,832 | 6,249 | 8,053 | 10,527 |
| Acidification (equivalent inhabitant) | DRCL | DRCL | DRCL | PCC | PCC | PCC | PCC | PCC | PCC | PCC | PCC | PCC |
|  | 17,001 | 15,428 | 14,587 | 14,702 | 16,046 | 17,596 | 18,950 | 21,294 | 21,248 | 23,198 | 23,198 | 23,198 |
| Eutrophication (equivalent inhabitant) | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | DRCL | PCD | PCD | DRCD | DRCD |
|  | 69 | 65 | 58 | 53 | 49 | 44 | 39 | 34 | 37 | 39 | 49 | 55 |
| Hazardous waste (t) | DRCI | DRCI | DRCI | DRCI | DRCI | DRCI | DRCI | DRCI | PaCR | PaCR | PaCR | PaCR |
|  | 1,262 | 1,165 | 1,068 | 970 | 903 | 806 | 719 | 631 | 580 | 610 | 610 | 610 |
| Non Hazardous Waste (t) | DRCD | DRCD | PCD | PCD | PCD | PCD | PCD | PCD | PCD | PCD | DRCD | DRCD |
|  | 11,020 | 10,019 | 9,219 | 10,021 | 11,023 | 12,024 | 13,026 | 14,028 | 15,030 | 16,032 | 20,040 | 21,046 |

Table 12. Management phase with the greatest produced impact for each impact category and for MSW management scenarios 1-10 developed in the study performed with WISARD. DRCD = dry residue collection disposal; DRCL = dry residue collection logistics; DRCI = dry residue collection RDF incineration; DRCR = dry residue collection recycling; GCL = glass collection logistics; PaCR = paper collection recycling; Pl&MCR = plastics and metals collection recycling; PCC = putrescibles collection composting; PCD = putrescibles collection disposal (De Feo and Malvano, 2009)

by the production units of materials from raw materials and impacts resulting from treatment processes that lead to the production of secondary materials deriving from the separate collection.

The second interpretation key directly derives from the evaluation model adopted, which allows for the definition of the damage level induced by the MSW management system with reference to the following macro-categories: Human Health, Ecosystem Quality and Resource Consumption. Thus, it was possible to compare different scenarios and express judgments about the influence of the percentage of separate collection on the impacts produced. In particular, the damage category "Human Health" includes the following damage/impact sub-categories: Carcinogens, Respiration Organics, Respiration Inorganics, Climate Change, Radiation, Ozone Layer. While, "Ecosystem Quality" is the combination of data related to the following damage/impact sub-categories: Ecotoxicity, Acidification/Eutrophication, Land Use. Finally, "Resources consumption" comprises the sub-categories Minerals and Fossil Fuels.

The third and final key relates to the identification of the management phases having a significant impact on the overall impact as well as how these results vary with the scenarios considered.

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### 3.1.1 Results of the inventory analysis

The analysis of the emission data related to the packaging materials highlighted that, in most cases, the pollutant emissions from secondary production were lower than that for primary production for each impact category. Tables 13, 14 and 15 show the results obtained for the packaging materials of glass, aluminium and paper, respectively.

| Emissions | Primary Production | Secondary Production |
|---|---|---|
| $CO_2$ | 955 g | 880.9 g |
| CO | 1.42 g | 0.825 g |
| $NO_X$ | 1.43 g | 3.24 g |
| $SO_X$ | 5.07 g | 4.85 g |
| $BOD_5$ | 0.584 mg | 1.74 g |
| COD | 0.011.9 g | 2.18 g |
| Tot. Nitrogen | 11.5 mg | 10.1 mg |
| Sand | 562 g | 1.99 mg |

Table 13. Comparison between the emissions due to the primary production of glass and recycling of the same quantity of glass (secondary production)

| Emissions | Primary Production | Secondary Production |
|---|---|---|
| Dust (< 2.5 µm) | 4.97 g | 269 mg |
| Dust (> 10 µm) | 12.3 g | 622 mg |
| Dust (> 2.5 µm <10 µm) | 7.43 g | 232 mg |
| NOx | 19.8 g | 2.58 g |
| Cadmium | 628 µm | 243 µm |
| $BOD_5$ | 20.7 g | 1.86 g |
| COD | 33.4 g | 4.07 g |
| PAH | 424 µm | 23.4 µm |
| Chrome VI | 18.9 mg | 4.36 mg |

Table 14. Comparison between the emissions due to the primary production of aluminium and recycling of the same quantity of aluminium (secondary production)

| Emissions | Primary Production | Secondary Production |
|---|---|---|
| Water | 16.8 m$^3$ | 590 l |
| Wood | 1.2 mm$^3$ | 2.45 mm$^3$ |
| $CO_2$ | 856 g | 809.6 g |
| CO | 586.4 mg | 593.6 mg |
| Chrome VI | 11 µm | 15.9 µm |
| $BOD_5$ | 1.38 g | 647 mg |
| Chlorine | 3.96 g | 3.73 g |
| COD | 5.05 g | 1.94 g |
| Mercury | 11.5 µm | 5.04 µm |
| Suspended Solid | 1.35 g | 308 mg |

Table 15. Comparison between the emissions due to the primary production of paper and recycling of the same quantity of paper (secondary production)

The presentation of the results of the Impact Assessment in terms of Environmental Damage makes it possible to analyze the problem of potential impacts in general terms. While, it is subsequently possible to extrapolate more peculiar considerations (PRè Consultants, 2000). Figures 4, 5 and 6 show the differences between the impact of secondary and primary production of glass, aluminium, paper and compost, for the damage categories Human Health, Ecosystem Quality and Resource Consumption, respectively. A positive value of the difference indicates an induced impact. Thus, for glass and paper the recycling process induce impacts both in terms of Human Health and Resource Consumption.
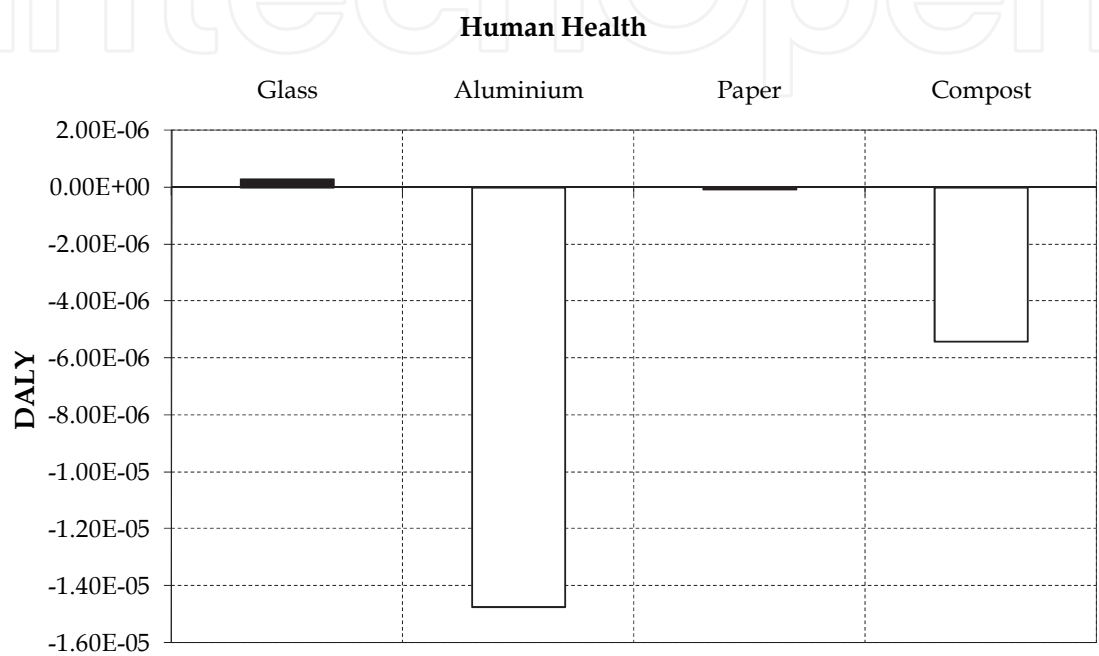
**Human Health**



Fig. 4. Difference between impact due to primary production and secondary production of packaging materials and compost in terms of "Human Health" damage category (the disability-adjusted life year, DALY, is a measure of overall disease burden, expressed as the number of years lost due to ill-health, disability or early death)

In general, identical to the results obtained with WISARD, with reference to all the management scenarios considered it was highlighted that the environmental impact linearly decreases with the percentage of separate collection for each damage category. Only the subcategory "Acidification/Eutrophication" of the damage macro-category "Ecosystem Quality" showed an induced impact increasing with the percentage of separate collection (Table 16). Moreover, the MSW management system determines avoided impacts for the damage categories "Human Health" and "Resources Consumption", while it determines induced impacts for the damage category "Ecosystem Quality".

Taking into account the contribution of the different MSW management phases, it was noted that all the considered scenarios have negative impact indicators in terms of Human Health and Resource Consumption, thus indirectly indicating that in these cases an integrated management of MSW is more environmentally sound than traditional methods of production of materials and energy. Dry residue incineration, landfill disposal, composting and glass production were the MSW management phases with the greatest influence on the final results in terms of environmental impacts.
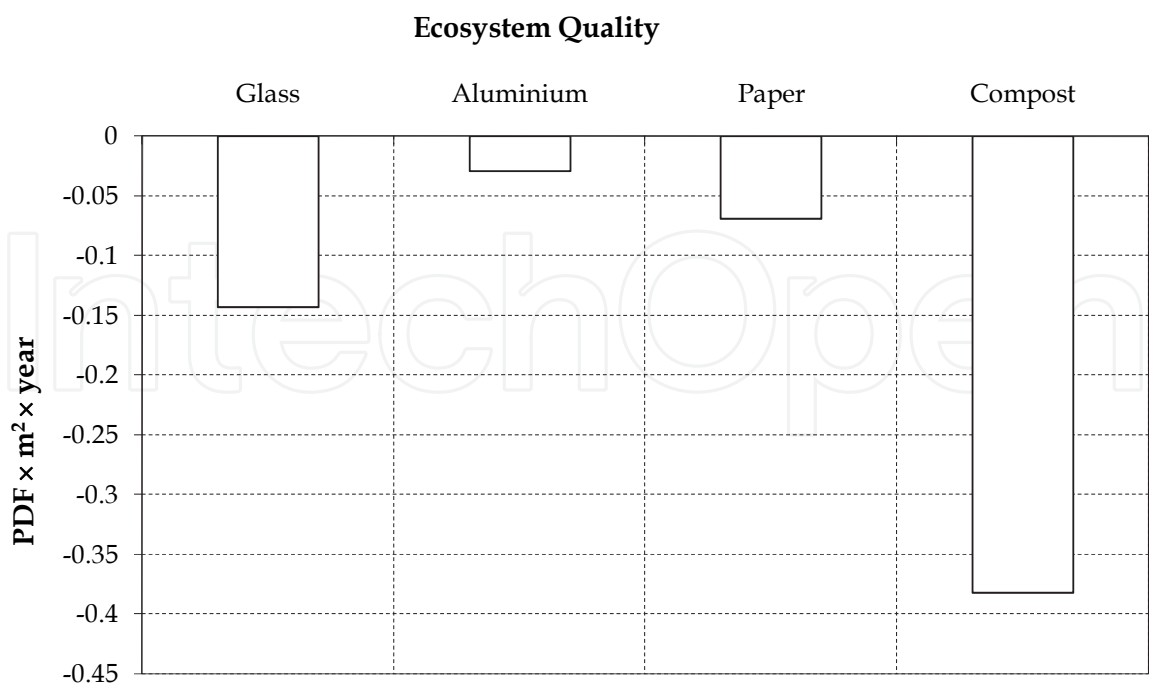
**Ecosystem Quality**



Fig. 5. Difference between impact due to primary production and secondary production of packaging materials and compost in terms of "Ecosystem Quality" (the Potentially Disappeared Fraction, PDF, is the fraction of species that has a high probability of no occurrence in a region due to unfavorable conditions)
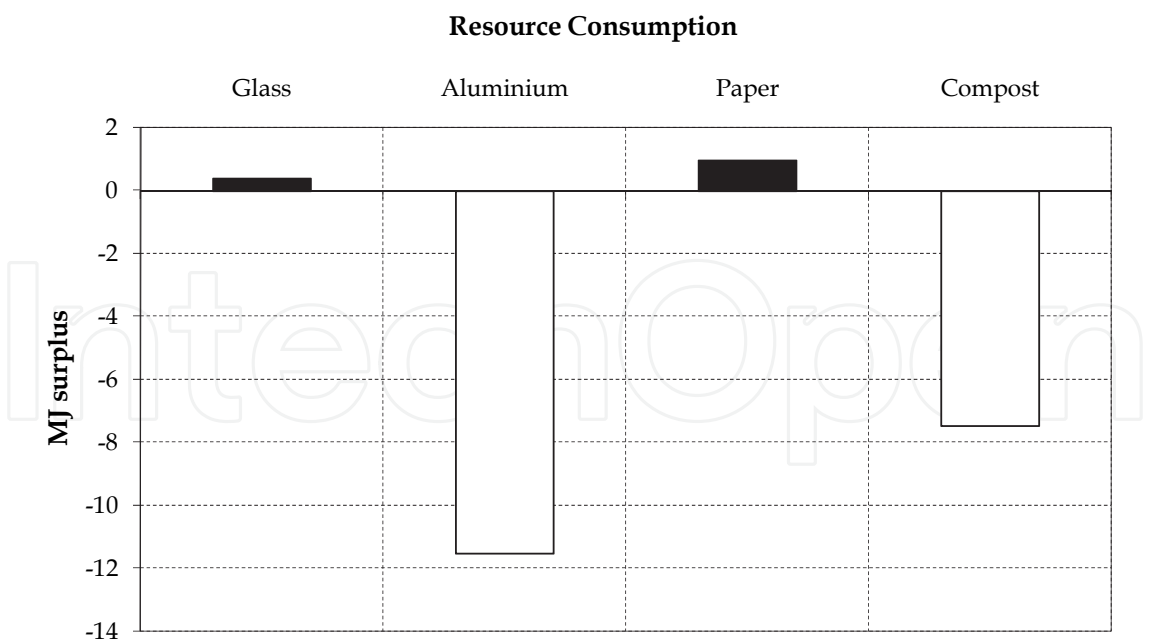
**Resource Consumption**



Fig. 6. Difference between impact due to primary production and secondary production of packaging materials and compost in terms of "Resource Consumption" damage category (MJ surplus expresses the surplus of Mega Joule needed in the extraction of resources when the demand for these will be 5 times higher than it was in 1990)

Due to the simplified basic hypothesis of the adopted model, the modality of plastics management was not considered when assessing the produced effects. Moreover, the modality of paper management did not compare with the quantitative analysis of results, with the analysis of single emissions highlighting that the balance between primary and secondary production is essentially neutral. Finally, the implemented model was not sufficiently adequate for the collecting and transporting phase, which would require the implementation of another calculation model.

| Impact Category | MSW management scenario | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 35% (1) | 40% (2) | 45% (3) | 50% (4) | 55% (5) | 60% (6) | 65% (7) | 70% (8) | 75% (9) | 80% (10) |
| Carcinogens (DALY) | -9,7E-05 | -1,0E-04 | -1,0E-04 | -1,1E-04 | -1,1E-04 | -1,1E-04 | -1,2E-04 | -1,2E-04 | -1,3E-04 | -1,3E-04 |
| (-), decreasing | Impact (Daly)= $-7 \times 10^{-7}$ × (percentage of separate collection) $- 7 \times 10^{-5}$ | | | | | | | | | |
| Resp. Organics (DALY) | -3,6E-07 | -3,9E-07 | -4,2E-07 | -4,5E-07 | -4,8E-07 | -5,2E-07 | -5,5E-07 | -5,8E-07 | -6,1E-07 | -6,4E-07 |
| (-), decreasing | Impact (Daly)= $-6 \times 10^{-9}$ × (percentage of separate collection) $- 1 \times 10^{-7}$ | | | | | | | | | |
| Resp. Inorganics (DALY) | -4,2E-04 | -4,2E-04 | -4,3E-04 | -4,3E-04 | -4,4E-04 | -4,4E-04 | -4,5E-04 | -4,5E-04 | -4,6E-04 | -4,6E-04 |
| (-), decreasing | Impact (Daly)= $-1 \times 10^{-6}$ × (percentage of separate collection) $- 0.0004$ | | | | | | | | | |
| Climate Change (DALY) | -6,3E-05 | -6,5E-05 | -6,7E-05 | -6,8E-05 | -7,0E-05 | -7,2E-05 | -7,4E-05 | -7,6E-05 | -7,8E-05 | -8,0E-05 |
| (-), decreasing | Impact (Daly)= $-4 \times 10^{-7}$ × (percentage of separate collection) $- 5 \times 10^{-5}$ | | | | | | | | | |
| Radiation (DALY) | -1,7E-06 | -1,9E-06 | -2,0E-06 | -2,2E-06 | -2,4E-06 | -2,6E-06 | -2,7E-06 | -2,9E-06 | -3,1E-06 | -3,3E-06 |
| (-), decreasing | Impact (Daly)= $-3 \times 10^{-8}$ × (percentage of separate collection) $- 5 \times 10^{-7}$ | | | | | | | | | |
| Ozone Layer (DALY) | -6,5E-08 | -7,0E-08 | -7,5E-08 | -8,0E-08 | -8,5E-08 | -9,0E-08 | -9,5E-08 | -1,0E-07 | -1,0E-07 | -1,1E-07 |
| (-), decreasing | Impact (Daly)= $-1 \times 10^{-9}$ × (percentage of separate collection) $- 3 \times 10^{-8}$ | | | | | | | | | |
| Ecotoxicity (PDF × m² × yr) | 8,3E+02 | 7,5E+02 | 6,7E+02 | 5,9E+02 | 5,1E+02 | 4,3E+02 | 3,5E+02 | 2,7E+02 | 1,9E+02 | 1,2E+02 |
| (+), decreasing | Impact (PDF × m² yr)= -15.784 × (percentage of separate collection) + 1378.1 | | | | | | | | | |
| Acidif/ Eutroph. (PDF × m² × yr) | -4,7E+00 | -4,3E+00 | -3,9E+00 | -3,4E+00 | -3,0E+00 | -2,6E+00 | -2,1E+00 | -1,7E+00 | -1,3E+00 | -8,3E-01 |
| (-), increasing | Impact (PDF × m² yr)= 0.0872 × (percentage of separate collection) - 7.8006 | | | | | | | | | |
| Land Use (PDF × m² × yr) | -5,0E-01 | -6,0E-01 | -6,9E-01 | -7,9E-01 | -8,8E-01 | -9,8E-01 | -1,1E+00 | -1,2E+00 | -1,3E+00 | -1,4E+00 |
| (-), decreasing | Impact (PDF × m² × yr)= - 0.0192 × (percentage of separate collection) + 0.1711 | | | | | | | | | |
| Minerals (MJsurplus) | -5,0E+01 | -5,5E+01 | -6,0E+01 | -6,5E+01 | -6,9E+01 | -7,4E+01 | -7,9E+01 | -8,4E+01 | -8,9E+01 | -9,4E+01 |
| (-), decreasing | Impact (MJsurplus)= - 0.9713 × (percentage of separate collection) - 15.988 | | | | | | | | | |
| Fossil Fuels (MJSurplus) | -3,3E+02 | -3,6E+02 | -3,8E+02 | -4,1E+02 | -4,3E+02 | -4,6E+02 | -4,8E+02 | -5,1E+02 | -5,3E+02 | -5,6E+02 |
| (-), decreasing | Impact (MJsurplus)= - 5.0632 × (percentage of separate collection) - 155.12 | | | | | | | | | |

Table 16. Summary of the numerical results obtained with SimaPro for MSW management scenarios 1-10 developed in terms of avoided or produced impact. (-) = avoided impact, (+) = induced impact. Decreasing = the avoided or induced impact decreases with the increasing of separate collection percentage; Increasing = the avoided or induced impact increases with the increasing of separate collection percentage.

| Impact Category | MSW management scenario | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 35% (1) | 40% (2) | 45% (3) | 50% (4) | 55% (5) | 60% (6) | 65% (7) | 70% (8) | 75% (9) | 80% (10) |
| Carcinogens | Thermal treatment | Thermal treatment | Thermal treatment | Thermal treatment | Thermal treatment | Thermal treatment | Thermal treatment | Thermal treatment | Thermal treatment | Wastewater treatment |
| Resp. Organics | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) |
| Resp. Inorganics | Glass recycling | Glass recycling | Glass recycling | Glass recycling | Glass recycling | Glass recycling | Glass recycling | Glass recycling | Glass recycling | Incineration |
| Climate Change | Incineration | Incineration | Incineration | Incineration | Incineration | Incineration | Incineration | Incineration | Incineration | Incineration |
| Radiation | Electricity consumption (nuclear) | Electricity consumption (nuclear) | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production |
| Ozone Layer | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) |
| Ecotoxicity | Incineration | Incineration | Incineration | Incineration | Incineration | Incineration | Incineration | Incineration | Incineration | Incineration |
| Acidif/ Eutroph. | Composting | Composting | Composting | Composting | Composting | Composting | Composting | Composting | Composting | Composting |
| Land Use | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers |
| Minerals | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production | Titanium dioxide production |
| Fossil Fuels | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) | Glass (green) |

Table 17. Management phase with the greatest produced impact for each impact category and for MSW management scenarios 1-10 developed in the study performed with SimaPro

| | 35% (1) | 40% (2) | 45% (3) | 50% (4) | 55% (5) | 60% (6) | 65% (7) | 70% (8) | 75% (9) | 80% (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | Electricity consumption | Electricity consumption | Electricity consumption | Electricity consumption | Leachate disposal | Leachate disposal | Leachate disposal | Leachate disposal | Leachate disposal | Leachate disposal |
| Resp. Organics | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) |
| Resp. Inorganics | Electricity consumption | Electricity consumption | Electricity consumption | Electricity consumption | Electricity consumption | Electricity consumption | Glass (white) | Glass (white) | Glass (white) | Glass (white) |
| Climate Change | Electricity consumption | Electricity consumption | Electricity consumption | Electricity consumption | Electricity consumption | Electricity consumption | Glass (white) | Glass (white) | Glass (white) | Glass (white) |
| Radiation | Radioactive emissions | Radioactive emissions | Radioactive emissions | Radioactive emissions | Radioactive emissions | Radioactive emissions | Radioactive emissions | Radioactive emissions | Radioactive emissions | Radioactive emissions |
| Ozone Layer | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) |
| Ecotoxicity | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) |
| Acid./ Eutr. | Electricity consumption | Electricity consumption | Electricity consumption | Electricity consumption | Electricity consumption | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) |
| Land Use | Softwood | Softwood | Softwood | Softwood | Softwood | Softwood | Softwood | Softwood | Softwood | Softwood |
| Minerals | Bauxite consumption | Bauxite consumption | Bauxite consumption | Bauxite consumption | Bauxite consumption | Bauxite consumption | Bauxite consumption | Bauxite consumption | Bauxite consumption | Bauxite consumption |
| Fossil Fuels | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) | Glass (white) |

Table 18. Management phase with the greatest avoided impact for each impact category and for MSW management scenarios 1-10 developed in the study performed with SimaPro

Table 17 indicates the management phase with the greatest produced impact for each impact category as well as for MSW management scenarios 1-10 developed in the study performed with SimaPro. "Glass (green)" resulted the heaviest phase 33 times out of 110 (10 scenarios x 11 impact categories), corresponding to 27.3%. While, "Incineration" and "Titanium dioxide production" were the heaviest phase 20 times (18.2%) and 18 times (16.4%), respectively.
Table 18 indicates the management phase with the greatest avoided impact for each impact category as well as for MSW management scenarios 1-10 developed in the study performed with SimaPro. "Glass (white)" resulted the lightest phase 53 times out of 110, corresponding to 48.2%. While, "Electricity consumption" was the heaviest phase 21 times (19.1%). Finally, "Radioactive emissions", "Softwood", "Bauxite consumption" were the lightest phase 10 times each one (9.1%).
More detailed results in terms of impacts due to the several phases of the MSW management system are presented in the next paragraphs in relation to the most significant impact categories.

### 3.1.2 Climate change

The impact produced by dry residue incineration decreased linearly with the increasing of the percentage of separate collection in terms of Climatic Change. A similar result was obtained by Bruno et al. (2002), also indicating that the solution with incineration was more environmentally sound than the solution with direct landfill disposal in terms of Acidification and Global Warming. Eriksson et al. (2005) identified in the incineration the management phase with the maximum production of $CO_2$, while waste landfilling was indicated as the worst option. The composting process of putrescibles was the management phase which affected the most the production of induced impacts. The impact increases linearly with the increasing of the percentage of separate collection. Arena et al. (2003) pointed out that the worst solution was the direct landfill disposal in terms of Climate Change, due to the emission of greenhouse gases, accordingly to the findings of Ozeler et al. (2006). For the scenario with 70% of separate collection, the impact induced by the composting process recycling overcame the impact induced by the dry residue incineration, in terms of Climate Change damage category (Figure 7). A similar solution was found by Bruno et al., (2002).
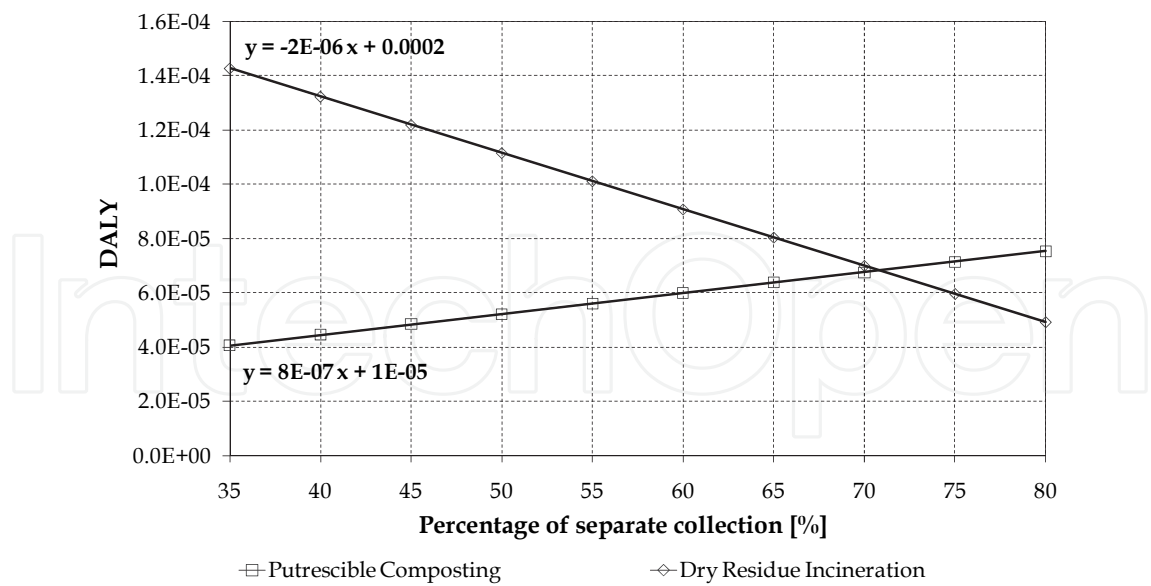
Fig. 7. Trend of the induced impacts by Putrescibles Composting and Dry Residue Incineration in terms of "Climate Change"

### 3.1.3 Acidification/Eutrophication

The MSW management phase of putrescibles composting has an induced impact on the category Acidification/Eutrophication as well as contributes to the negative results of the damage macro-category Ecosystem Quality. A similar result was obtained by Eriksson et al. (2004) considering the installation of an anaerobic digestion plant. While, different results were obtained by Salhofer et al. (2007), who found lower impact in terms of the Eutrophication of mechanical biological treatment rather than incineration. The avoided impact is due to the energy recovery with the subsequent saving of fossil fuels. This amount decreases with the increasing of the percentage of separate collection up to 60%, while for greater percentages the maximum benefit is given by the glass production. The results are shown in Figures 8 and 9.

### 3.1.4 Carcinogens

In scenarios with the incineration of dry residue (1-10), the avoided impact increases with the percentage of separate collection due to the progressive reduction of the contribution of the incineration process. The main contribution in positive terms was given by the energy saving deriving from non-renewable sources.

In relation to scenario 20 (80% separate collection, mechanical sorting of dry residue), the direct landfill disposal of dry residue (scenario 21) produced an increase of about one order of magnitude in terms of the sub-category Carcinogens, thus determining a negative result in terms of the damage category Human Health. Similarly, the landfilling of inert materials and ashes of the combustion process (scenario 20) resulted in a negligible impact than that due to the direct landfilling of dry residue in scenario 21. Similar results were obtained by Bruno et al. (2002) who showed a significant impact of landfilling due to the release of heavy metals downstream leachate treatment.

Figures 10 and 11 show the trend of induced impacts in terms of the damage category "Carcinogens" by incineration and inert waste landfilling disposal, respectively.
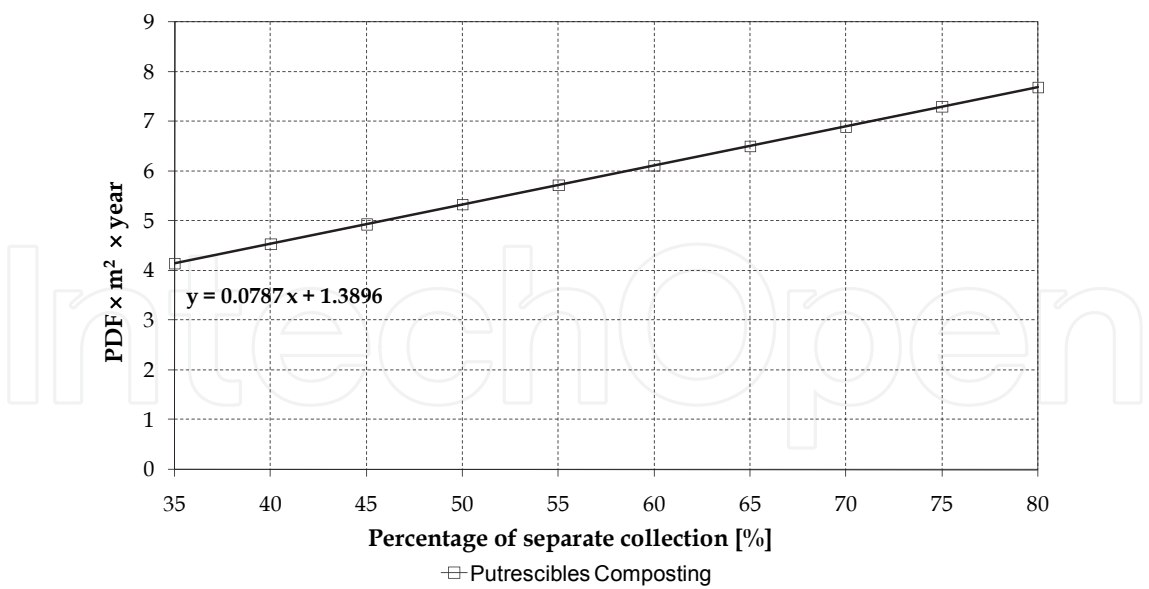
Fig. 8. Trend of induced impacts by the putrescibles composting in terms of damage category "Acidification/Eutrophication"
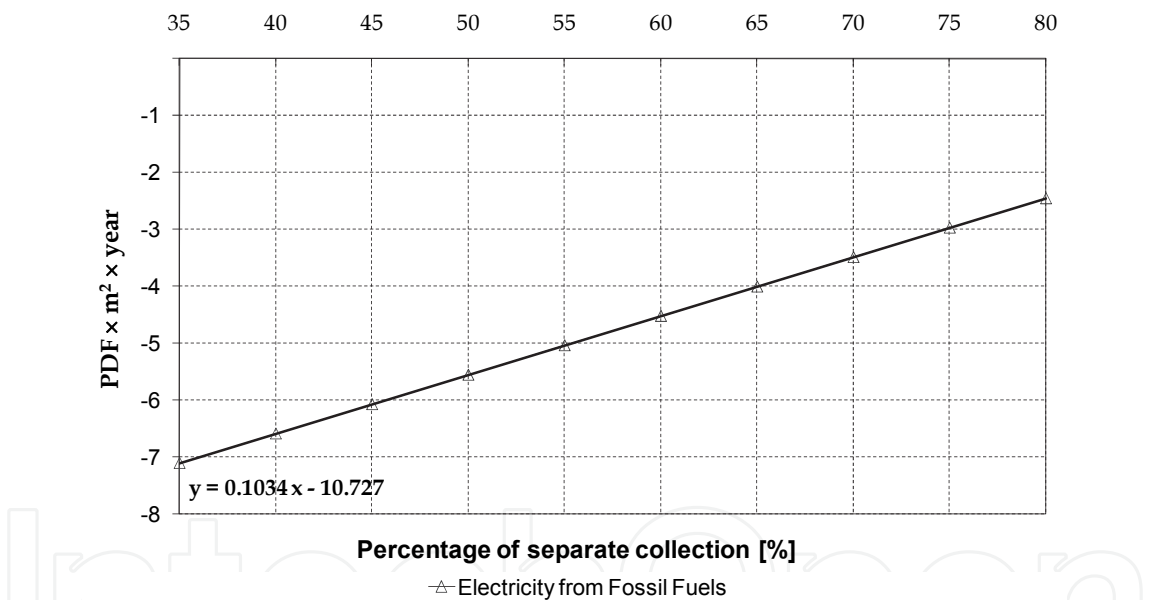


Fig. 9. Trend of induced impacts by the fossil fuels consumption in terms of damage category "Acidification/Eutrophication"

## 3.2 Comparison of the results obtained with WISARD and SimaPro

One of the aims of this study was to compare the results obtained with the application of two LCA procedures, WISARD and SimaPro, the first specific to the waste sector, while the second of a general nature. In particular, applicability and reliability of the single procedure to assess the life cycle of MSW management systems was evaluated.

It can therefore be deduced from the presentation of the results in the previous paragraphs that the comparison between the two procedures can be performed only in qualitative rather than quantitative terms because the mathematical models used for the analysis development as well as representation of the obtained data are completely different.
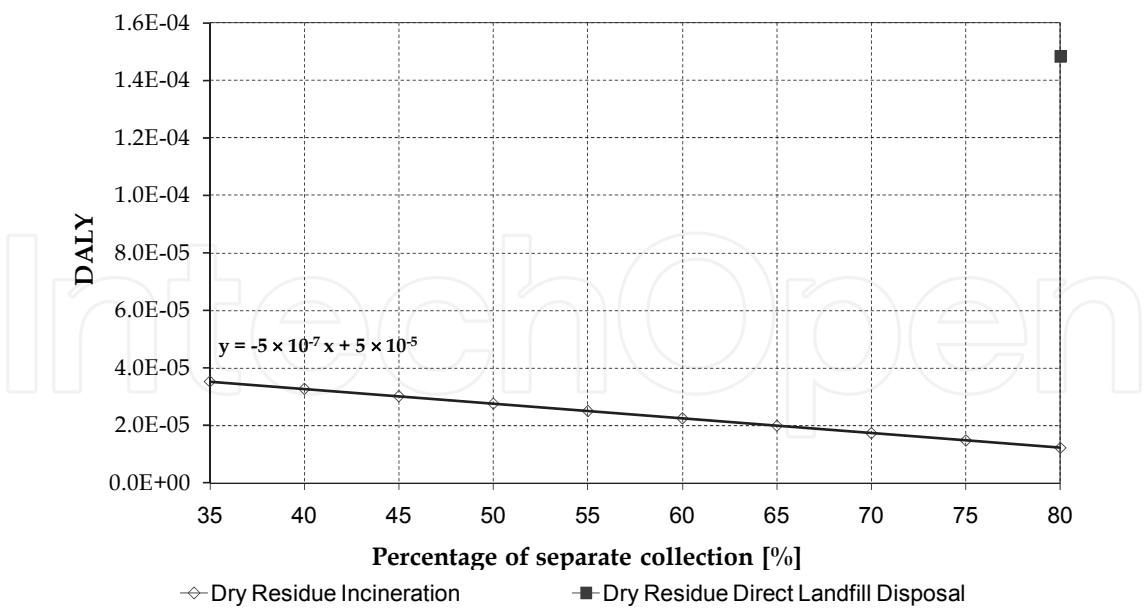
Fig. 10. Trend of induced impacts by incineration in terms of damage category "Carcinogens"
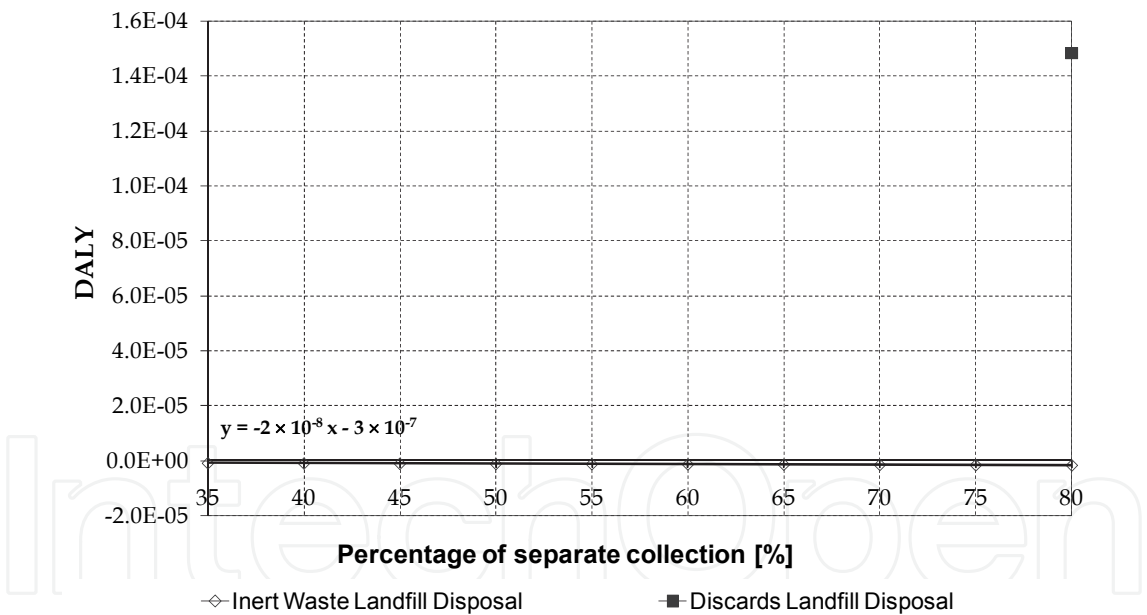


Fig. 11. Trend of induced impacts by inert waste landfill disposal in terms of damage category "Carcinogens"

Since the procedure WISARD is applied only to MSW management systems, with this procedure the results are presented only in terms of equivalent inhabitants. On the contrary, the SimaPro procedure, being of a general nature, can be adopted for the application of Life Cycle Assessment to all products, processes and activities. SimaPro, compared to WISARD, allows for a simpler and direct interpretation of the results, even by non-technical users. This is achieved with the presentation of the results in terms of the damage macro-categories Human Health, Ecosystem Quality and Resource Consumption.

The comparison between the results obtained with the two LCA procedures show the following similarities:

- all the considered scenarios showed negative overall impact indicators, indicating that the MSW management was environmentally sound compared with traditional methods of production of matter and energy. In particular, this behaviour was more evident the higher the percentage of waste collection;
- environmental emissions due to secondary production processes were lower than the corresponding emissions due to the primary production of packaging materials, with the presented exception;
- for a fixed percentage of separate collection, the solution with mechanical-biological selection of dry residue showed a reduction of the environmental benefit depending on the impact category take into account;
- for the percentages of separate collection greater than 60%, the solution with mechanical-biological selection of dry residue waste can be considered environmentally equivalent to the solution with the incineration and landfilling of ashes.

Table 19 shows the comparison between the MSW management phases with major and minor impacts for the WISARD and SimaPro procedures for the common Impact Category. Obviously, the MSW management phase with the greatest avoided impact indicates an environmental benefit, while the MSW management phase with the greatest produced impact indicates any environmental damage.

The qualitative comparison shows the perfect coincidence between the overall performances in terms of positive/negative values. While, the two LCA procedures showed a different behaviour in terms of the identification of the MSW management phase which affected the most the final result in terms of positive or negative impacts. The different behaviour is due to the different assumptions and simplifications made during the construction of the system and, particularly, in the implementation phase of the process units of the treatment and disposal plants.

As shown in table 9, focusing only on the common impact categories, Plastics and Metals Recycling and Glass Recycling was the MSW phase with the greatest avoided impacts for WISARD and SimaPro, respectively.

As shown in table 19, the collection and transporting to the treatment plants has a significant importance in the WISARD procedure, resulting as the phase with the greatest incidence on the production of induced impacts. The same results were not achieved for the SimaPro procedure because its general nature determined a major approximation in the construction of the basic calculation model.

### 3.3 Comparison with SimaPro between scenarios with dry residue incineration or sorting

The main aim of this paragraph is to compare the induced or avoided impacts due to scenarios with dry residue incineration (1-10) and scenarios with dry residue sorting (11-20), using SimaPro as an LCA tool. Firstly, it focused on the numerical results obtained with SimaPro for MSW management scenarios 11-20 developed in terms of avoided or produced impact. As shown in table 20, only for the damage category Acidification/Eutrophication do the impact values increase with the separate collection percentage, thus indicating an environmental negative effect due to the separate collection. On the contrary, for ten out of the eleven impacts considered with SimaPro, the calculated value decreased with the percentage of separate collection, thus confirming the environmental convenience to push

| Impact Category | WISARD | | | SimaPro | | |
|---|---|---|---|---|---|---|
| | Positive/ negative values – Trend | MSW phase with the greatest | | Positive/ negative values – Trend | MSW phase with the greatest | |
| | | Avoided impact | Produced impact | | Avoided impact | Produced impact |
| Non Renewable Consumption | Negative - Decreasing | Plastics and Metals Recycling | Dry Residue Collection | Negative - Decreasing | Glass Recycling | Glass Primary Production |
| Greenhouses Gas Production | Negative - Decreasing | Plastics and Metals Recycling | Dry Residue Collection | Negative - Decreasing | Glass Recycling | Glass Primary Production |
| Acidification | Negative - Decreasing | Plastics and Metals Recycling | Composting | Negative - Decreasing | Glass Recycling | Composting |

Table 19. Comparison between the MSW management phases with major and minor impacts for the WISARD and SimaPro procedures for the common Impact Category

up toward the maximization of separate collection. Moreover, for seven impact categories (see Table 20 for more details), the impact values were positive therefore indicating that they were avoided impacts (the integrated MSW management was environmentally sound in terms of these damage categories). While, the damage category "Land Use" showed both positive (for low levels of separate collection) and negative values (for high levels of separate collection). Finally, the impact values for the three damage categories Carcinogens, Ecotoxicity and Acidification/Eutrophication were only positive thus indicating that they were induced impacts (the integrated MSW management was not environmentally sound in terms of these damage categories). Table 20 gives the equation of the line giving the values of avoided or induced impacts by MSW management scenarios for each damage category. While, Tables 21 and 22 indicate the management phase with the greatest produced and induced impact for each impact category as well as for MSW management scenarios 11-20 developed in the study performed with SimaPro, respectively.

Table 21 shows the management phases with the greatest produced impact for each impact category as well as for MSW management scenarios 11-20 developed in the study performed with SimaPro. "Glass (Green)" resulted the heaviest phase 33 times out of 110, corresponding to 30%. While, "Landfill Disposal" was the heaviest phase 17 times, corresponding to 15.5%. Finally, "Wastewater treatment", "Glass Recycling", "Electricity consumption (nuclear)", "Natural fertilizers" and "Titanium dioxide production" were heaviest at the same manner: 10 times, corresponding to 9.1%.

Table 22 shows the management phases with the greatest avoided impact for each impact category as well as for MSW management scenarios 11-20 developed in the study performed with SimaPro. "Glass (White)" resulted the lightest phase 70 times out of 110 (10 scenarios x 11 impact categories), corresponding to 63.7%. While, "Leachate disposal", "Radioactive emissions", "Softwood" and "Bauxite consumption" were lightest at the same manner: 10 times, corresponding to 9.1%.

From this point forward, the aim of the paragraph is to compare scenarios 1-10 with scenarios 11-20 in order to qualitatively evaluate the environmental role of the incineration in the considered model of MSW management system. First of all, the difference between the values of Tables 20 (dry residue sorting scenarios) and 16 (dry residue incineration scenarios) were calculated in order to evaluate which scenarios are more environmentally sound in terms of the considered damage categories. The obtained results are condensed in figures 14 and 15. Essentially, for 10 out of the 11 impact categories (all excluding

| Impact category | MSW management scenario | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 35% (11) | 40% (12) | 45% (13) | 50% (14) | 55% (15) | 60% (16) | 65% (17) | 70% (18) | 75% (19) | 80% (20) |
| Carcinogens (DALY) (+), decreasing | 4.1E-04 | 3.7E-04 | 3.2E-04 | 2.8E-04 | 2.4E-04 | 2.0E-04 | 1.5E-04 | 1.1E-04 | 6.9E-05 | 2.6E-05 |
| | Impact (Daly)= $9\times10^{-6}$ × (percentage of separate collection) + $7\times10^{-4}$ | | | | | | | | | |
| Resp. Organics (DALY) (-), decreasing | -1.7E-07 | -2.2E-07 | -2.6E-07 | -3.1E-07 | -3.6E-07 | -4.0E-07 | -4.5E-07 | -4.9E-07 | -5.4E-07 | -5.8E-07 |
| | Impact (Daly)= $9\times10^{-9}$ × (percentage of separate collection) + $1\times10^{-7}$ | | | | | | | | | |
| Resp. Inorganics (DALY) (-), decreasing | -2.3E-04 | -2.5E-04 | -2.7E-04 | -2.9E-04 | -3.1E-04 | -3.3E-04 | -3.5E-04 | -3.7E-04 | -3.9E-04 | -4.1E-04 |
| | Impact (Daly)= $4\times10^{-6}$ × (percentage of separate collection) - $1\times10^{-4}$ | | | | | | | | | |
| Climatic Change (DALY) (-), decreasing | -1.2E-06 | -7.9E-06 | -1.5E-05 | -2.1E-05 | -2.8E-05 | -3.4E-05 | -4.1E-05 | -4.8E-05 | -5.4E-05 | -6.1E-05 |
| | Impact (Daly)= $-1\times10^{-6}$ × (percentage of separate collection) + $5\times10^{-5}$ | | | | | | | | | |
| Radiation (DALY) (-), decreasing | -1.7E-06 | -1.8E-06 | -2.0E-06 | -2.2E-06 | -2.4E-06 | -2.5E-06 | -2.7E-06 | -2.9E-06 | -3.1E-06 | -3.2E-06 |
| | Impact (Daly)= $-4\times10^{-8}$ × (percentage of separate collection) - $4\times10^{-7}$ | | | | | | | | | |
| Ozone Layer (DALY) (-), decreasing | -5.7E-08 | -6.2E-08 | -6.8E-08 | -7.3E-08 | -7.9E-08 | -8.5E-08 | -9.0E-08 | -9.6E-08 | -1.0E-07 | -1.1E-07 |
| | Impact (Daly)= $-1\times10^{-9}$ × (percentage of separate collection) - $2\times10^{-8}$ | | | | | | | | | |
| Ecotoxicity (PDF*m²*yr) (-), decreasing | 1.1E+03 | 1.0E+03 | 9.2E+02 | 8.1E+02 | 7.1E+02 | 6.1E+02 | 5.1E+02 | 4.1E+02 | 3.1E+02 | 2.1E+02 |
| | Impact (PDF*m²*yr)= -20.29 × (percentage of separate collection) + 1828.60 | | | | | | | | | |
| Acidif/ Eutroph. (PDF*m²*yr) (+), increasing | 4.0E-02 | 1.1E-01 | 1.8E-01 | 2.4E-01 | 3.1E-01 | 3.8E-01 | 4.4E-01 | 5.1E-01 | 5.8E-01 | 6.5E-01 |
| | Impact (PDF*m²*yr)= 0.0135 × (percentage of separate collection) − 0.4314 | | | | | | | | | |
| Land Use (PDF*m²*yr) (+, -), decreasing | 1.8E-01 | 3.4E-02 | -1.1E-01 | -2.6E-01 | -4.1E-01 | -5.6E-01 | -7.1E-01 | -8.6E-01 | -1.0E+00 | -1.2E+00 |
| | Impact (PDF*m²*yr)= -0.0297 × (percentage of separate collection) + 1.2205 | | | | | | | | | |
| Minerals (MJsurplus) (-), decreasing | -5.0E+01 | -5.5E+01 | -6.0E+01 | -6.5E+01 | -7.0E+01 | -7.4E+01 | -7.9E+01 | -8.4E+01 | -8.9E+01 | -9.4E+01 |
| | Impact (MJsurplus)= -0.9666 × (percentage of separate collection) − 16.45 | | | | | | | | | |
| Fossil Fuels (MJsurplus) (-), decreasing | -2.8E+02 | -3.0E+02 | -3.3E+02 | -3.6E+02 | -3.9E+02 | -4.2E+02 | -4.5E+02 | -4.8E+02 | -5.1E+02 | -5.4E+02 |
| | Impact (MJsurplus)= -5.9412 × (percentage of separate collection) -67.324 | | | | | | | | | |

Table 20. Summary of the numerical results obtained with SimaPro for MSW management scenarios 11-20 developed in terms of avoided or produced impact. (-) = avoided impact, (+) = induced impact. Decreasing = the avoided or induced impact decreases with the increasing of separate collection percentage; Increasing = the avoided or induced impact increases with the increasing of separate collection percentage

| Impact category | MSW management scenario | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 35% (11) | 40% (12) | 45% (13) | 50% (14) | 55% (15) | 60% (16) | 65% (17) | 70% (18) | 75% (19) | 80% (20) |
| Carcinogens | Wastew at. treatment | Wastew at. treatment | Wastew at. treatment | Wastew at. treatment | Wastew at. treatment | Wastew at. treatment | Wastew at. treatment | Wastew at. treatment | Wastew at. treatment | Wastew at. treatment |
| Resp. Organics | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) |
| Resp. Inorganics | Glass Recycling | Glass Recycling | Glass Recycling | Glass Recycling | Glass Recycling | Glass Recycling | Glass Recycling | Glass Recycling | Glass Recycling | Glass Recycling |
| Climatic Change | Landfill disposal | Landfill disposal | Landfill disposal | Landfill disposal | Landfill disposal | Landfill disposal | Landfill disposal | Glass (Green) | Glass (Green) | Glass (Green) |
| Radiation | Electricity consumpt. (nuclear) | Electricity consumpt. (nuclear) | Electricity consumpt. (nuclear) | Electricity consumpt. (nuclear) | Electricity consumpt. (nuclear) | Electricity consumpt. (nuclear) | Electricity consumpt. (nuclear) | Electricity consumpt. (nuclear) | Electricity consumpt. (nuclear) | Electricity consumpt. (nuclear) |
| Ozone Layer | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) |
| Ecotoxicity | Landfill disposal | Landfill disposal | Landfill disposal | Landfill disposal | Landfill disposal | Landfill disposal | Landfill disposal | Landfill disposal | Landfill disposal | Landfill disposal |
| Acidif/ Eutroph. | Compost. | Compost. | Compost. | Compost. | Compost. | Compost. | Compost. | Compost. | Compost. | Compost. |
| Land Use | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers | Natural fertilizers |
| Minerals | Titanium dioxide product. | Titanium dioxide product. | Titanium dioxide product. | Titanium dioxide product. | Titanium dioxide product. | Titanium dioxide product. | Titanium dioxide product. | Titanium dioxide product. | Titanium dioxide product. | Titanium dioxide product. |
| Fossil Fuels | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) | Glass (Green) |

Table 21. Management phase with the greatest produced impact for each impact category and for MSW management scenarios 11-20 developed in the study performed with SimaPro

"Minerals"), the difference was positive therefore indicating that sorting scenarios were heavier than the corresponding incineration scenarios. In particular, Figure 14 shows the trend of the difference between the Sorting scenario impact and Incineration scenario impact normalized in respect to the maximum impact value of each category for the following damage categories: "Carcinogens", "Resp. Organics", "Resp. Inorganics", "Climatic

Change", "Radiation", "Ozone Layer", "Ecotoxicity", "Acidif/Eutroph.", "Land Use" and "Fossil Fuels". As clearly shown in Figure 12, in terms of one of the ten listed impact categories, an Incineration scenario is more environmentally sound than the corresponding Sorting scenario with the difference linearly decreasing with the increasing of the percentage of separate collection.

| Impact category | MSW management scenario | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 35% (11) | 40% (12) | 45% (13) | 50% (14) | 55% (15) | 60% (16) | 65% (17) | 70% (18) | 75% (19) | 80% (20) |
| Carcinogens | Leachate disposal | Leachate disposal | Leachate disposal | Leachate disposal | Leachate disposal | Leachate disposal | Leachate disposal | Leachate disposal | Leachate disposal | Leachate disposal |
| Resp. Organics | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) |
| Resp. Inorganics | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) |
| Climatic Change | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) |
| Radiation | Radioact. emissions | Radioact. emissions | Radioact. emissions | Radioact. emissions | Radioact. emissions | Radioact. emissions | Radioact. emissions | Radioact. emissions | Radioact. emissions | Radioact. emissions |
| Ozone Layer | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) |
| Ecotoxicity | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) |
| Acidif/ Eutroph. | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) |
| Land Use | Softwood | Softwood | Softwood | Softwood | Softwood | Softwood | Softwood | Softwood | Softwood | Softwood |
| Minerals | Bauxite consumpt. | Bauxite consumpt. | Bauxite consumpt. | Bauxite consumpt. | Bauxite consumpt. | Bauxite consumpt. | Bauxite consumpt. | Bauxite consumpt. | Bauxite consumpt. | Bauxite consumpt. |
| Fossil Fuels | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) | Glass (White) |

Table 22. Management phase with the greatest avoided impact for each impact category and for MSW management scenarios 11-20 developed in the study performed with SimaPro

Only for the damage category "Minerals" the difference between the Sorting scenario impact and Incineration scenario impact was negative, thus indicating that sorting scenarios were lighter than the corresponding incineration scenarios. As clearly shown in Figure 13, a Sorting scenario is more environmentally sound than the corresponding Incineration scenario with the difference linearly decreasing with the increasing of the percentage of separate collection.

Since for ten out of the eleven impact categories, the difference between the impact of a Sorting scenario and the impact of the corresponding (in terms of percentage of separate collection) Incineration scenario was positive, it can be argued that in general Incineration scenarios are more environmentally sound than the corresponding Sorting scenarios, especially for low levels of separate collection. While, on the contrary, the difference tends to diminish with the increasing of the percentage of separate collection.

## 4. Conclusion

The outputs from 12 out of 21 options modelled were initially analysed under eleven environmental effect categories as suggested by the WISARD procedure, with the aim of carrying out a synthetic study of the data available. The impact assessment categories suggested are as follows: renewable energy use, non-renewable energy use, total energy use, water, suspended solids and oxydable matters index, mineral and quarried matters, greenhouse gases, acidification, eutrophication, hazardous waste, non-hazardous waste. Attention was given to both measuring the overall impact due to the application of the

Comparison of the Suitability
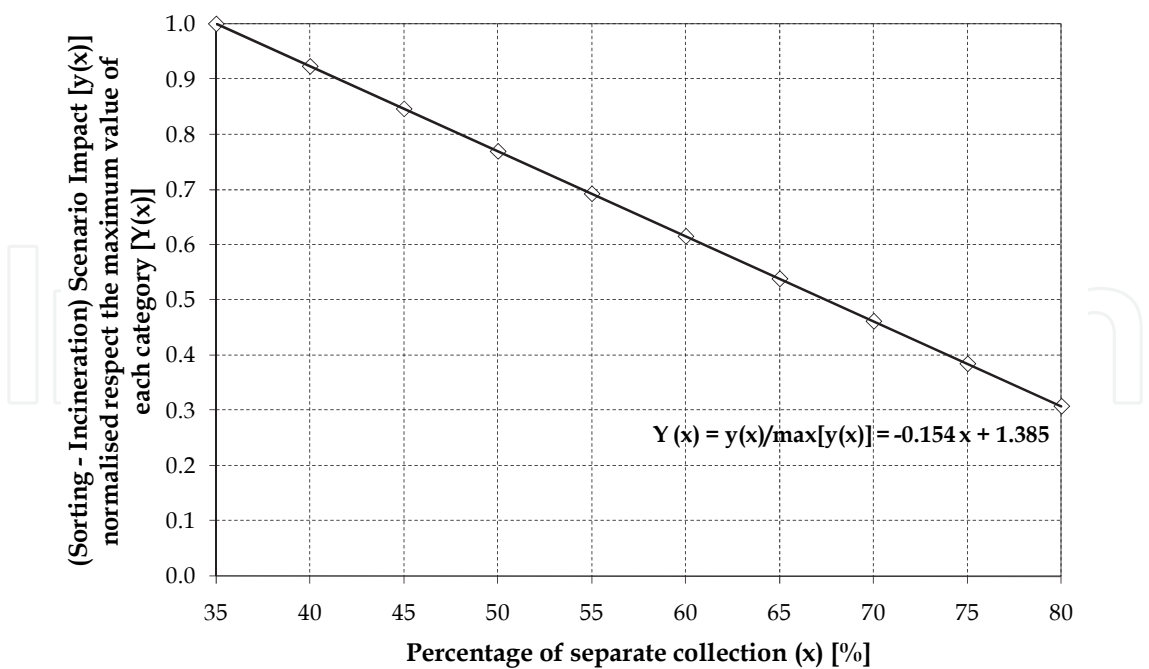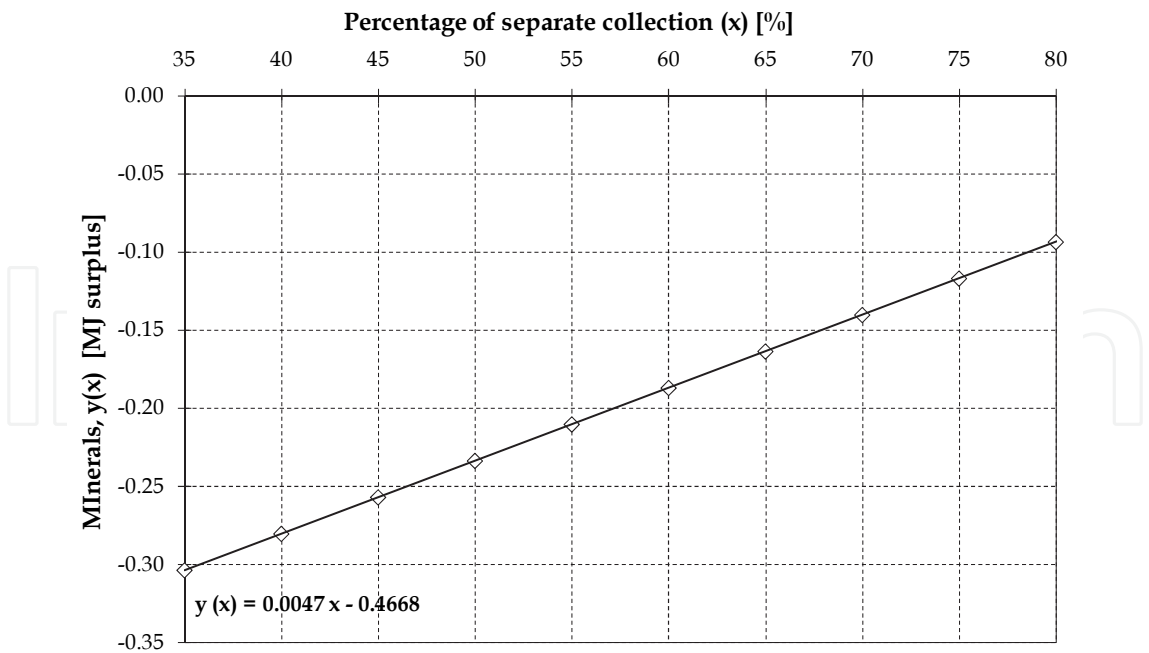of Two LCA Procedures in Selecting the Best MSW Management System
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Fig. 12. Trend of the difference between the Sorting scenario impact and Incineration scenario impact normalized in respect to the maximum impact value of each category for the following damage categories: "Carcinogens", "Resp. Organics", "Resp. Inorganics", "Climatic Change", "Radiation", "Ozone Layer", "Ecotoxicity", "Acidif/Eutroph.", "Land Use" and "Fossil Fuels" (the positive value indicates that in terms of this impact category, an Incineration scenario is more environmentally sound than the corresponding Sorting scenario)



Fig. 13. Trend of the difference between the Sorting scenario impact and Incineration scenario impact for the damage category "Minerals" (the negative value indicates that in terms of this impact category a Recycling scenario is more environmentally sound than the corresponding Incineration scenario)

entire MSW management system adopted, as well as the evaluation of the specific contribution produced by each phase of the MSW management system.

The principal conclusions were that the scenario with 80% separate collection, no RDF incineration and dry residue sorting was the most environmentally sound option for six impact categories of the eleven chosen: renewable energy use, total energy use, water, suspended solids and oxydable matter index, eutrophication and hazardous waste. The second-best scenario with three impacts of environmentally sound categories (non-renewable energy use, greenhouse gases and acidification) is 80% separate collection, RDF production and incineration. For eight impact categories (renewable, non-renewable, total energy use, water, suspended solids and oxydable matter index, acidification, eutrophication, hazardous waste), all the MSW management scenarios produced a negative impact and the highest percentage of separate collection corresponded to the highest avoided impact.

A similar analysis was made with SimaPro considering the following impact assessment categories: Carcinogens, Respiration Organics, Respiration Inorganics, Climate Change, Radiation, Ozone Layer, Ecotoxicity Acidification/Eutrophication, Land Use, Minerals, Fossil Fuels. Analysing the emission data obtained on material from packaging shows that in most cases for each item impacts emissions of pollutants in secondary productions are lower than those corresponding of primary productions.

From a more detailed analysis of results, it appeared that all the scenarios considered have impact indicators relating to human health and resources with negative values. This means that in these cases, the integrated systems waste management are environmentally advantageous compared to traditional methods of production of matter and energy. In particular, the solution with the direct landfilling of residue is not preferred over the solution with waste incineration because there is more production of carcinogens substances during incineration and landfilling of ashes. The stages of management that most affect the final results of impact are incineration of waste, disposal in landfills, composting of organic and glass production.

Comparing the two calculation methods adopted, a coincidence of the results in terms of quality and performance is evident, highlighting the feasibility of the two procedures as well as the validity of the results. However, the same results are strongly influenced by the assumptions at the base of the building model and the approximations of reality, thus not making it possible to carry out a quantitative comparison due to the different models used for the characterization and representation of the results.

The results are similar for both Life Cycle Assessment procedures in qualitative terms. The study emphasized the priority of separate collection and recycling to save energy as well as reduce the environmental impact of MSW management.

The analysis carried out only with SimaPro, showed that for ten out of the eleven impact categories, the difference between the impact of a Sorting scenario and the impact of the corresponding (in terms of percentage of separate collection) Incineration scenario was positive, thus highlighting that in general Incineration scenarios are more environmentally sound than the corresponding Sorting scenarios, especially for low levels of separate collection. While, the difference tends to diminish with the increasing of the percentage of separate collection.

## 5. Acknowledgment

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of Two LCA Procedures in Selecting the Best MSW Management System
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This book reports research on policy and legal issues, anaerobic digestion of solid waste under processing aspects, industrial waste, application of GIS and LCA in waste management, and a couple of research papers relating to leachate and odour management.

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