SUWAMAS,
A Decision Support Model
For Sustainable Waste Management Systems

Zur Erlangung des akademischen Grades eines

Dr.-Ing.

von Fachbereich Bio- Chemieingenieurwesen der Universität Dortmund

genehmigte Dissertation

vorgelegt von

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aus

Mexico City, Mexiko

Tag der mündlichen Prüfung: 23.06.06

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Dortmund 2006

VORWORT

Die vorliegende Arbeit entstand im Rahmen meiner Tätigkeit als wissenschaftlicher Gast im Geschäftsfeld Kreislaufwirtschaft des Fraunhofer Instituts UMSICHT und als Doktorand am Lehrstuhl für Umwelttechnik der Universität Dortmund. Finanziell gefördert wurde das Projekt durch CONACYT (Consejo Nacional de Ciencia y Tecnología, Mexiko) und den DAAD (Deutscher Akademischer Austausch Dienst, Deutschland). Ohne deren großzügige Unterstützung wäre diese Arbeit nicht möchlicht gewesen. Dafür sei an dieser Stelle gedankt.

Mein besonderer Dank gilt Herrn Prof. Dr.-Ing. Hans Fahlenkamp für die stetes wohlwollende Förderung und Betreuung dieser Arbeit. Herrn Prof. Dr.-Ing. Klaus Görner danke ich für die Übernahme des zweiten Gutachtens, Prof. Dr.-Ing. Gerhard Schembecker und Prof. Dr.-Ing. Rolf Wichmann für ihre Mitwirkung in der Prüfungskommission.

Allen Angehörigen der Abteilung Kreislaufwirtschaft des FhI-UMSICHT, die zum Gelingen dieser Arbeit beigetragen haben, möchte ich an dieser Stelle meinen Dank aussprechen. Dieser gilt besonders Dr. Kai Keldenich für die konstruktive Begleitung meiner Arbeit.

Schließlich danke ich von ganzem Herzen meiner Frau, die mich in jeder Hinsicht unterstützt und begleitet hat. Ohne sie wäre ich nicht in der Lage gewesen, mein Ziel erfolgreich zu beenden.

Düsseldorf, im August 2006.

ZUSAMMENFASSUNG

Im Rahmen der vorliegenden Arbeit wurde unter dem Akronym *SUWAMAS* ein EDV-gestütztes Planungsinstrument entwickelt, das es volkswirtschaftlichen Entscheidungsträgern ermöglichen soll, die Vielschichtigkeit einer auf Nachhaltigkeit ausgerichteten Steuerung zu quantifizieren und somit Entscheidungen vorbereiten zu helfen. Dieses methodisch neue Konzept bewertet Abfallwirtschaftsstrategien so, dass die Wirkung auf das Wirtschaftswachstum, den sozialen Zusammenhalt und die Umweltqualität quantifizierend erkennbar wird; darauf aufbauend ermöglicht *SUWAMAS* die Eingrenzung derjenigen Abfallwirtschaftsstrategie, welche das höchste Potenzial an Nachhaltigkeit bietet und gleichzeitig die Ziele des produktintegrierten Umweltschutzes und die der europäischen Abfallwirtschaft beinhaltet. *SUWAMAS* wurde entworfen, um wenig zukunftsfähige Produktionsweisen und Verbrauchsmuster für Produkte innerhalb ihrer Produktzykluszeit, also für das Produktsystem zu minimieren. Das Produktsystem beinhaltet nicht nur die Abfallbeseitigung, sondern auch die mechanischen, biologischen, mechanisch-biologischen und thermischen Abfallentsorgungsanlagen. Jede Technologie wird entsprechend ihrer spezifischen Gestaltung, den Betriebsbedingungen und den technischen Anforderungen modelliert.

Mathematisch betrachtet ist *SUWAMAS* ein ganzzahlig, nichtlinear arbeitender Optimierungs-Algorithmus. Dieses Programm wurde auf Basis einer Lingo-Plattform als maßgebendem Code geschrieben. *SUWAMAS* ermittelt das Optimum der nachhaltigen Abfallwirtschaftsstrategie, indem das Minimum einer gewichteten Produkt-Zielfunktion berechnet wird, die auf definierte Systemsachzwänge beschränkt wird. Sowohl die Zielfunktion als auch die Systemsachzwänge simulieren die Wechselbeziehungen der Umwelt-, Ökonomie-, Sozial- und Logistik-Aspekte innerhalb des Systems. Die verschiedenen Kriterien der Nachhaltigkeit werden in *SUWAMAS* mit einschlägigen Bewertungshilfsmitteln, wie der Ökobilanz-Methode (LCA), der Nutzen-Kosten-Analyse (CBA), der Multi-Kriterien-Analyse (MCDA) und den Warenstrom-Verteilungsstrukturen (MCFD) bewertet. Infolgedessen ermöglicht *SUWAMAS*, dass die vorgeschlagene nachhaltige Abfallwirtschafts-strategie nicht nur auf die Umwelt bezogen wirkungsvoll, sozial annehmbar und ökonomisch erschwinglich ist, sondern auch logistisch optimiert ist; die Umwelteffektivität dieser Vorgehensweise wird sicher gestellt, indem die direkten und indirekten Umweltbelastungen des Produktsystems durch eine umfassende Ökobilanzierung herabsetzt werden. Das Ökobilanz-Verfahren folgt dabei den produkt- und prozessspezifischen Modellen. Analog wird die ökonomische Erschwinglichkeit der Strategie erzielt, indem man die Nettosozialkosten des Systems so herabsetzt, wie es durch die Zielfunktion definiert wird. Die Nettosozialkostenfunktion schließt die Bruttoverkaufspreise, die Umweltkosten und die sozialen Einsparungen ein, die aus der Rückgewinnung an Energie und Betriebsmitteln aus dem Produktsystem, also für Produkte innerhalb ihrer Produktzykluszeit, abgeleitet werden. Die soziale Akzeptanz wird mit der Einbeziehung der allgemeinen Präferenzen erreicht, was über eine wirkungsvolle allgemeine Teilnahme am Entscheidungsprozess gelingt. Das System wird logistisch mittels der Bestimmung der Stoffstromverteilung für die Primär- und Sekundärabfallmengen optimiert. Zur Aufteilung der Abfallströme werden die Zahl und die Lage der Abfallwirtschaftsbetriebe bzw. der Abfallbehandlungsschritte bewertet. Infolgedessen liefert der Algorithmus die kürzesten Wege zwischen Erzeuger und Entsorger. Schließlich ist *SUWAMAS* ein zuverlässiges und robustes Hilfsmittel zur Untersuchung der für die Analyse und die Entwicklung der für den Abfallwirtschaftssektor erforderlichen nachhaltigen Konzepte oder Strategien.

ABSTRACT

Over the last years, economic growth has resulted in an unsustainable consumption of scarce natural resources and consequently the generation of greater volumes of waste. Consequently, decision makers must develop effective strategies that ensure the integration of environmental protection, economic growth and social cohesion during every stage of the waste life cycle in the context of sustainable development. Unfortunately, they do not count with an assessment tool that is able to recognise the multidimensionality of sustainability.

SUWAMAS was developed to provide decision makers with a decision-aiding tool that recognises the multidimensionality of sustainability. This new approach seeks the development of waste management strategies that promote economic growth and social cohesion without impairing environmental quality. *SUWAMAS* recommends the most effective sustainable waste management strategy taking in consideration the integrated product policy approach and European waste management strategic drivers. *SUWAMAS* is designed to minimise unsustainable production and consumption patterns through the life cycle of the product system. The product system consists of recovery and disposal waste management operations such as mechanical, biological, mechanical-biological, incineration and landfill. Every waste management operation is modelled according to its installed choice of technology, operational conditions and technical requirements.

Technically, *SUWAMAS* is an integer non-linear mathematical programming model. This model is written in a Lingo environment as a key solving methodology. *SUWAMAS* finds the most effective sustainable waste management strategy by means of minimising a weighted product objective function, which is restricted to defined system constraints. Both the objective function and the system constraints simulate the inter-relation of environmental, economical, social and logistical issues within the system. Every sustainable issue is integrated in *SUWAMAS* with a specific assessment tools such as life cycle assessment, cost benefit analysis, multicriteria decision analysis and multi-commodity flow distribution. As a result, *SUWAMAS* ensures that the proposed sustainable waste management strategy is not only environmentally effective, economically affordable and socially acceptable, but also logistically optimised. Firstly, the environmental effectiveness of the strategy is ensured by minimising the generation of direct and indirect environmental impacts through the entire life cycle of the product system. The life cycle inventory of the product system follows both waste-specific and process-specific models. Similarly, the economically affordability of the strategy is achieved by minimising the net social cost of the system as defined by the objective function. The net social cost function integrates the gross private costs, the environmental costs and the social savings costs derived from the recovery of energy and resources through the complete life cycle of the product system. Social acceptability is reached with the integration of public preferences through effective public participation in the decision making process. The system is logistically optimised by means of determining the optimal flow distribution of primary and secondary waste. This waste flow distribution considers the number and location of the waste management operations. As a result, it provides the shortest disposal routes between generation and treatment sources. Finally, *SUWAMAS* is a reliable and robust assessment tool, which is ideal for the development of sustainable concepts or strategies required by the waste management sector.

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LIST OF ABBREVIATIONS

AbfAbIV	Ordinance on environmentally compatible storage of waste from human settlements (Abfallablagerungsverordnung)
AIDA	Abfall-Informations-Daten-Drehscheibe
AltholzV	Waste Wood Ordinance (Altholzverordnung)
AOX	Adsorbable Organically Bound Halogen
AP-42	Compilation of Air Pollutant Emission Factors
APC	Air Pollution Control Units
ASA	Arbeitsgemeinschaft Stoffspezifische Abfallbehandlung
BayLU	Bavarian Environmental Protection Agency (Bayerisches Landesamt für Umweltschutz)
BDE	Federation of the German Waste Management Industry (Bundesverband de Deutschen Entsorgunswirtschaft)
BGK	Bundesgütegemeinschaft Kompost EV
BImSchV	Federal Immission Control Ordinance
BioAbfV	Biowaste Ordinance (Bioabfallverordnung)
BOD5	Biochemical Oxygen Demand
BTC	Biological treatment composting: aerobic biological treatment
BTD	Biological treatment digestion: anaerobic biological treatment
CAFE	Clean Air for Europe Programme
CBA	Cost Benefit Analysis
CEN	European Committee for Standardization
CENTREL	Central European power association
CEWEP	Confederation of European Waste-to-Energy Plants
CFCs	Chlorofluorocarbons
CHP	Combined Heat and Power
CIWMB	California Integrated Waste Management Board
cMRF	“clean” mechanical recycling facility
COD	Chemical Oxygen Demand
CPA	Critical Path Analysis
DALY	Disability Adjusted Life Years
DC	Disposal cost: private cost
DEC	Displaced environmental cost: displaced externality
DepV	Deponieverordnung (Landfill Site Ordinance)
dMRF	“dirty” mechanical recycling facility
DOC	Degradable Organic Carbon
DOCF	Dissimilable organic carbon fraction
DSM	Decision Support Model
EC	Environmental cost: externality
ECOINVENT	Swiss Centre for Life Cycle Inventories Database
EEA	European Environment Agency
EIIP	Emission Inventory Improvement Program
ELU	Environmental Load Unit
EPA	US Environmental Protection Agency
EPS	Environmental Priority Strategies
ETC	European Topic Centre on Waste and Material Flows
EU	European Union
EURITS	European Union For Responsible Incineration And Treatment Of Special Waste
FD	Final Disposal
FWS	Fuzzy weighted sum
GewAbfV	Commercial waste Ordinance (Gewerbeabfallverordnung)
GHG	Greenhouse Gases
GWP	Global Warming Potential
AP	Acidification Potential
EP	Euthrophication Potential
TOFP	Tropospheric Ozone Formation Potential
PFP	Particle formation potential
CRP	Carcinogenic Risk Potential
HTP	Human Toxicity Potential
POCP	Photochemical Ozone Creation Potential

ADP	Abiotic Depletion Potential
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
HHV	Higher heating value
IPCC	Intergovernmental Panel on Climate Change
IPPC	Integrated Pollution Prevention and Control
ISO	International Organization Standardization
ITAD	Interessengemeinschaft der Thermischen Abfallbehandlungsanlagen in Deutschland e.V
LAGA	Länderarbeitsgemeinschaft Abfall
LC 0	Landfill class 0: Inert Waste Landfill
LC I	Landfill class I: Non-Hazardous Waste Landfill
LC II	Landfill class II: Non-Hazardous Waste Landfill and Co-Disposal of Waste
LC III	Landfill class III: Hazardous Waste Landfill
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life cycle impact assessment
LDS-NRW	Landesamt für Datenverarbeitung und Statistik, Nordrhein-Westfalen.
LFS	Landfill site
LHV	Lower Hearing Value
LUA-NRW	North Rhine-Westphalia State Environment Agency (Landesumweltamt - NRW)
MBT	Mechanical biological treatment
MCDA	Multicriteria decision analysis
MS	Member States
MSWI	Municipal solid waste incinerator
MUNLV	Ministry For Environment And Nature Protection, Agriculture And Consumer Protection (Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz)
NEX	Normalised Extinction of Species
NIST	National Institute of Standards and Technology
NMVOC	Non Methane Volatile Organic Compounds
NORDEL	Nordic countries power association
NPi	National Pollutant Inventory
NRW	Nordrhein-Westfalen
ODP	Ozone Depletion Potential
OECD	Organisation for Economic Co-operation and Development
OF	Objective function
PCP	Paper, cardboard and pasteboard
POCP	Photo Oxidant Creation Potential
RDF	Refuse Derived Fuel
REV	Revenues: social saving costs
SETAC	Society of Ecotoxicology and Chemistry
SOM	Stabilised Organic Material
SUWAMAS	Sustainable Waste Management System
TA-Abfall	TA Abfall. (Technical Instruction on Waste)
TASi	TA Siedlungsabfall. (Technical Instruction on Waste from Human Settlement)
TC	Transportation cost: private cost
THT	Thermal treatment
TOC	Total Organic Carbon
UBA	Umweltbundesamt
UCTE	Union for the Co-ordination of Transmission of Electricity
WMO	Waste management operation
WTA	Willingness to Accept
WTP	Willingness to Pay

1 INTRODUCTION

1.1 EVOLUTION OF WASTE MANAGEMENT MODELLING

As expected, the development of was management models is not a new research field. The first models were developed in the 1970s. They were designed to optimise vehicle routing problems and transfer station sittings. Unfortunately, they were restricted to some type of treatment processes, waste material fractions and unsuitable for long-term planning. Subsequently, during the 1980s models that are more sophisticated were developed. In comparison with the first ones, these new models considered the complete waste management infrastructure, they followed the hierarchy of waste approach and they were restricted to technical and economical parameters. In other words, they were cost-minimisation orientated.

Followed by the environmental awareness of the scientific community, in the 1990s appeared the earliest integrated waste management models. They took for first time into consideration not only a wider range of waste material fractions and the available waste management infrastructure, but also the exiting relation between economical and environmental factors. These models were able to analyse the material flow within the system and provided the optimum combination of appropriate waste treatment technologies and energy with the minimum environmental and economical costs. Currently, integrated waste management models are based on different assessment tools, such as cost-benefit analysis (CBA), simulation models, life cycle assessment (LCA), environmental impact assessment (EIA), environmental risk assessment (ERA), multicriteria decision analysis (MCDA) and geographic information systems (GIS). However, the main research lines are CBA, simulation, LCA and MCDA approach (EEA 2003).

CBA models for municipal solid waste aim to minimise the overall cost of the system (objective function) subjected to a set of constraints. This assessment tool is restricted only to economical parameters. However, the management of environmental impacts can be internalised as environmental costs or externalities and integrate them as constraints. Internalising environmental cost is based on the willingness to pay and willingness to accept principles. Several approaches have been taken in order to model an integrated waste management system. These include fuzzy interval multiobjective mixed integer programming model (Chang 1997), constrained non-linear model (Chang 1998), interval-parameter fuzzy stochastic programming model (Huang 2001), and integer non-linear programming models (Fiorucci 2003, Costi 2004, and Najm 2004). The Chang and Chang's models attempt to minimise the overall cost of the system, which include transportation, treatment, maintenance and recycling costs. This model is restricted only to material flows, plant capacities and recovery of energy constraints. Similarly, Huang's considers the minimisation of collection and transportation costs, capital cost for waste management operations and residual market values, which are subject to capacity limitations, mass balance and site location constraints. However, in both models none environmental or technical factors are considered. Fiorucci and Costi went one-step further. They used the same economical parameters but they incorporated environmental and technical constraints in their models. Moreover, international organisations such as the World Bank, OECD and the European Union-DG Environment have published a considerable amount of reports, which consider economic valuations of environmental externalities from different types of waste and waste management operations (COWI 2000, Hogg 2001, Hogg 20022, Smith 2001, and IPPC 2005b).

Simulation models address issues related to the environmental management and technology based on mathematical programming (Fatta 2003). Most of them represent the intrinsic

relation between environmental, technical and economical factors. They can assess the performance of current and future situations and are suitable for the evaluation and recommendation of alternative scenarios. The most representative commercial simulation tools for the waste management area are the GEM-E3 model (National Technical University of Athens), the STOAT model (WRc plc), the EIA-Markal (Brookhaven Laboratory and Kernforschunganlage), and the WastePlan (Tellus Institute). The GEM-E3 model is a general equilibrium model, which assess the effect of environmental policy on the EU economy and on the state of the environment. The EIA-Markal is a holistic target orientated energy analysis and planning model, which considers the material and energy flow within the system and the interaction of technical, economical and environmental factors for the selection of the optimal combination of waste treatment operations. WastePlan is a modelling tool that assesses the material flow within the waste management operations and accounts the full cost of the system. On the other hand, the STOAT model considers the management of wastewater treatment operations and sewage sludge production, and it is technically-economically orientated.

The life cycle assessment tool is one of the preferred methods used by the decision makers and researches. This tool assesses elemental and elementary mass flows within the boarders of the product system. This methodology allows decision makers to improve the current system performance and to compare future integrated waste management operations based on strategic planning. However, it is restricted only to technical and environmental parameters and does not consider neither economical nor social factors. This methodology is well documented and subject to the Environmental Management—Life Cycle Assessment: ISO 14040 series. Based on this standard, (Bjarnadóttir 2002) and (Grant 2003) developed guides for the use of LCA in the waste management sector. (Barton 1996, Finnveden 1999, Arena 2003) have developed as well life cycle inventories for different waste management operations by help of the LCA methodology. Additionally, there are available representative commercial models such as the WISARD model (*W*aste *I*ntegrated *S*ystem *A*ssessment for *R*ecovery and *D*isposal: UK), the IWM2 model (Integrate waste management: McDougall 2003), the EPIC-CSR model (Environment and Plastic Industry Council – Corporations Supporting Recycling: EPIC 2000) and the WARM model (Waste Reduction Model: USEPA). A common factor between all these models and previous studies is that all of them perform only a life cycle inventory analysis of a waste management system. These inventories are carried out with process-specific emission modelling equation instead of waste-specific one, which are site specific. Additionally, they don not continue with a life cycle impact assessment and interpretation of the results. Thus, the environmental impact due to fugitive emissions is not estimated (McDougall 2003, EPIC 2000, Haight 2004, EPA 2002b)

Multicriteria decision analysis models are used to find the most effective compromise between several conflicting objectives or the achievement of satisfying levels in the objectives subjected to uncertain parameters (Herrera 2004). This assessment tool is divided in 4 methodologies, which are the elementary, the single synthesising criterion, the outranking and the mixed method (Martel 1998). These methodologies are better represented by the simple weighted addition (SWA), weighted product (WP), analytical hierarchy process (AHP), technique for order by similarity to ideal solution (TOPSIS), fuzzy weighted sum (FWS), the ELECTRE family and the PROMETHEE methods, among others. Examples of the application of this methodology are given by (Alidi 1996), who developed a multiobjective optimisation goal programming model combined with AHP for the management of hazardous waste from the petrochemical sector. Other authors have used as well AHP for the selection of optimal waste management operations (McDonald 1996, Haastrup 1998, Takeda 2001). On the other hand, the ELECTRE III methodology was use for the economical, environmental

and social assessment of landfill, incineration and composting units as waste management operations (Hokkanen 1997). Similarly, (Karagiannidis 1997) used ELECTRE III for the assessment of integrated waste management systems, while (Courcelle 1998) for the assessment of the economical and environmental performance of municipal solid waste collection and sorting programmes. Other authors have compared different MCDA methodologies such as simple weighted additive (SWA), weighted product (WP), co-operative game theory and ELECTRE, finding that the most optimal or satisfactory solution varies according to the selected method (Salminen 1997, Cheng 2000, Cheng 2003). However, a common factor in all these waste management models is that they deal more with the improvement of the assessment tool rather than the improvement of the management model and the public involvement (Morrissey 2004).

During the last decade, policy makers and the scientific community are trying to go further with the development of better waste management models. They are moving from the integrated approach to the sustainable one. Some attempts have been done to develop a sustainable model. Unfortunately, they have failed because they do not consider the overall context of sustainable development. Currently two models consider the multidimensionality of sustainable development. These models are the SEEbalance® model and the LCA-IWM model (LCA-IWM 2005). The SEEbalance® provides individual sustainable assessments for existing waste management operations based on process-specific equations. This model does not consider the evaluation from the waste management infrastructure from and integrated point of view. Contrary, the LCA-IWM model integrates all the waste management operations during its assessment and it is based on both process-specific and waste-specific equations. The big disadvantage from both models is that the practitioner needs to propose several scenarios in order to determinate the best material flow distribution that could provide the most optimal solution for the system. Additionally, they assess exclusively the impact of generated primary waste and do not consider the impact of generated secondary waste, which is a considerable gap for the development of an effective and optimal sustainable strategy.

1.2 SUSTAINABLE DEVELOPMENT AND WASTE MANAGEMENT SYSTEMS

1.2.1 Sustainable Development

In 1987, the World Commission on the Environment and Development introduced the term sustainable development in the report *Our Common Future*; better know as the Brundtland Report. Sustainable development is based on the intra- and intergenerational equity principles and defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*. Subsequently, this term was world wide ratified at the United Nations Conference on Environment and Development in Rio de Janeiro (The Earth Summit), in 1992. In this summit was adopted *inter alia* the Rio Declaration on environment and development and the Agenda 21 Action Programme. However, it is Agenda 21 the mayor achievement of this summit, which promotes for first time global actions in all the areas of sustainable development.

Agenda 21 provides the same definition of sustainable development as the one given in the Brundtland Report. According to Agenda 21, sustainable development can be achieved *inter alia* with the integration of the environment and development in decision-making (Chapter 8) and with the environmentally sound management of solid waste (Chapter 21). As a result, this Agenda stresses the progressive integration of environmental, economical and social issues in the decision making process in the pursuit of development that is *economically efficient,*

socially equitable and responsible and environmentally sound. These are the three pillars of sustainable development, as shown in Figure 1-1, and they are the key drivers in development policy making. The integration of the environment and development should adopt an integrated approach and consider all possible interactions and synergisms (Holistic Approach). Moreover, it should incorporate environmental and social costs in the decision making process and in the accounting framework based on economic approaches such as the polluter-pays principle and the natural-resource-user-pays principle (Externalities). This last action internalises the relatively scarcity and total value of resources in current market-orientated economies. Similarly, it defines that the development of environmentally sound management of solid wastes is a condition to achieve sustainability. Environmentally sound management must attempt to modify unsustainable consumption and production patterns by reducing the life cycle environmental impacts of product systems.

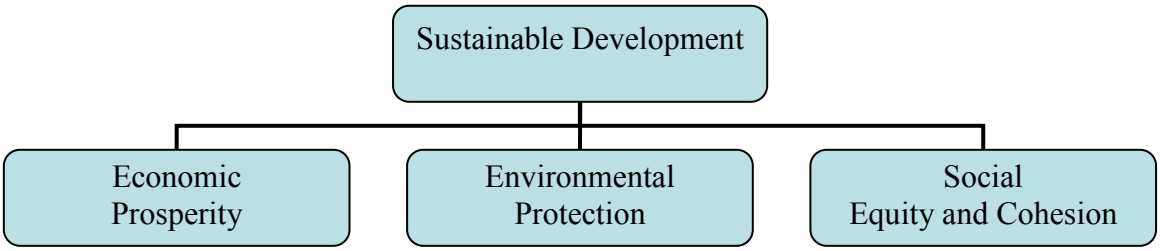


Figure 1-1 Pillars of sustainable development

Subsequently, in 2002 was agreed the plan of implementation of Agenda 21, the programme for further implementation of Agenda 21 and the commitments to the Rio Principles at the World Summit on Sustainable Development (The Johannesburg Summit). As a result, the Johannesburg Plan of Implementation promotes as well the integration of the three components of sustainable development, named *economic development, social development and environmental protection*[1]. In order to achieve sustainability it demands *inter alia* the change of unsustainable patters of consumption and production (Chapter II) and the protection and management of natural resources based on economic and social development (Chapter III). Specifically, it promotes *inter alia* the implementation of an integrated approach (Paragraph 21), the prevention and minimisation of waste and the maximisation of reuse, recycling and use of environmentally friendly alternative materials, with the participation of government authorities and all public (Paragraph 22).

After the Earth Summit in Rio, the European Union introduced the term sustainable development in the Amsterdam Treaty, signed in 1997, as a core objective for all European Community policies as set out in Articles 2, 6 and 174 of the Treaty. However, it was until 2001 when sustainable development was fully introduced to the Community with the Sustainable Development Strategy. This strategy is based on a Commission Communication[2] produced by the Gothenburg European Council. Subsequently, in 2002, the external dimension of the Strategy was added by the European Council in Barcelona[3]. Similar to the provisions of Agenda 21, this strategy mention that sustainable development is achievable only if there is a balance between economic grow, social inclusion and environmental protection. Additionally, it gives a new approach to policy making by means of placing sustainable development at the core of policymaking processes. Finally, it defines main

[1] Johannesburg Plan of Implementation, Paragraph 2
[2] COM(2001) 264 final, 15.05.2001. A Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development (Commission's proposal to the Gothenburg European Council).
[3] COM(2002) 82, 12.02.2002. Towards a global partnership for sustainable development.

unsustainable trends that pose a threat to sustainable development such as climate change and energy consumption.

The environmental components of the Community's Sustainable Development Strategy are given by the Sixth Community Environment Action Programme[4] (6EAP). This Programme agrees *inter alia* that "*a prudent use of natural resources and the protection of the global eco—system together with economic prosperity and a balanced social development are a condition for sustainable development"*. This program says that sustainability can be achieved *inter alia* through effective waste management. Effective waste management is then achieved by means of "*better resource efficiency and resource and waste management to bring about more sustainable production and consumption patterns, thereby decoupling the use of resources and the generation of waste from the rate of economic growth and aiming to ensure that the consumption of renewable and non-renewable resources does not exceed the carrying capacity of the environment*". The aims of the 6EAP are pursued with the identification of four priority areas, where the sustainable use and management of natural resources and waste is one of them. Similarly to Agenda 21: Chapter 21 and to the Paragraph 22 of the Johannesburg Implementation Programme, this priority area aims to achieve *inter alia* more sustainable production and consumption patterns via waste prevention and the minimisation of environmental impacts of waste management via waste reuse and following the hierarchy of waste, as key issues to achieve sustainable development. These objectives are pursued taking in consideration the Integrated Product Policy[5] (IPP) approach and the Community's strategy for waste management[6]. The IPP approach is based on the principles[7] of life cycle thinking, market involvement, public involvement, continues improvement and policy integration. On the other hand, the community's strategy for waste management is based *inter alia* on the thematic strategy on the sustainable use and management of resources[8] (Resources Strategy) and the thematic strategy on the prevention and recycling of waste[9] (Waste Strategy). The integration of the IPP and the community's strategy for waste management provide provisions to reduce effectively the cumulative life cycle environmental impacts of product systems combined with the benefit of public participation in policy-making to identify eco-efficient solutions.

The IPP approach requires *inter alia* public involvement in decision-making as key principle to achieve sustainability. This principle is reinforced with the provisions offered by the Aarhus Convention[10]. This convention was adopted by the UN Economic Commission for Europe at the fourth Ministerial Conference, which was named "Environment for Europe" process. The Aarhus Convention lays down a set of provisions to promote public involvement in environmental matters and improve enforcement of environmental law. Therefore, it aims to contribute to the protection of the rights of present and future generations to live in an environment adequate to their health and well-being. This aim is achieved through the guarantee of the right of the public with regard the access to environmental information, public participation in the decision-making process and the access to justice in environmental matters.

[4] Decision No. 1600/2002/EC of the European Parliament and of the Council laying down the Sixth Community Environment Action Programme, OJ L 242,10.09.2002.
[5] COM(2001) 68 final, 07.02.2001. Green Paper on Integrated Product Policy.
[6] Council Resolution of 24 February 1997 on a Community strategy for waste management (O) C 76,11.3.1997
[7] COM(2003) 302 final, 18.06.2003. Integrated Product Policy: Building on Environmental Life-Cycle Thinking. Sec.3.
[8] COM(2003) 572 final, 1.10.2003. Towards a Thematic Strategy on the Sustainable Use of Natural Resources.
[9] COM(2003) 301 final, 27.05.2003. Towards a thematic strategy on the prevention and recycling of waste.
[10] The UN Economic Commission for Europe (UNECE) Convention on Access to Information, Public Participation in Decision Making and Access to Justice in Environmental Matters adopted on 25 June 1998.

The right to have *access to environmental information* (Art 4) provides public access to environmental information held by or for public authorities without an interest having to be stated. The right to *participate in the decision-making* process (Art 6, 7 and 8) provides public participation in the decisions on the specific activities listed in Annex I. Waste management operations such as incineration and landfill are included in this list. This right provides as well not only public participation concerning plans, programmes and policies relating to the environment but also public participation during the preparation of executive regulations and/or generally applicable legally binding normative instruments. Finally, the provision to have *access to justice* in environmental matters (Art 9(2) and 4) provides the public with the right to a review procedure when they have been denied to have access environmental information. As well, this right faculty the public concerned to challenge the substantive and procedural legality of any decision subject to Art 6 of this Convention.

The European Union ratified the Aarhus Convention on 17 February 2005. The legal provisions of the Aarhus Convention are transposed into European law through the Directive 2003/4/EC on Public Access to Environmental Information[11], Directive 2003/35/EC on Public Participation[12] and the Commission Proposal for a Directive on Access to Justice[13]. This legal framework provides the same rights as defined in the Aarhus Convention. In practice, this legal framework provides to the European citizens the right to get involved more effectively in environmental decision-making. This contributes not only to increase the environmental awareness among the public but also to improve the quality and transparency in environmental policymaking. Additionally, when public involvement is ensured in the decision-making, the decisions are likely to be better implemented and respected. In the opposite case, when it is not ensured public involvement in the decision-making the effectiveness of the system cannot be ensured or it is doomed to fail (Joos 1999). Therefore, public involvement is an excellent way to ensure social equity and cohesion within the sustainable development context. These provisions are compulsory and need to be included in the decision-making related to the specific activities listed in Annex I of the Convention.

Finally, in December 2004 was proposed the Constitution[14] of the European Union. Once again, with this document the Community confirmed its commitment to sustainable development and integrated it as a core element in the development of policymaking. The sustainable principle based on Articles 2, 6 and 174 of the EC Treaty has been now been replaced by Articles I-3(3), III-119 and III-233 of the Constitution, where Art I-3(3) aims that "*The Union shall work for the sustainable development of Europe based on balanced economic growth and price stability, a highly competitive social market economy, aiming at full employment and social progress, and a high level of protection and improvement of the quality of the environment…*"

Today we see that the unsustainable trends are getting worse, not better. As a result, the European Commission is reviewing the Sustainable Development Strategy to improve its objectives and to set new methods or principles to follow. In 2005, the European Commission

[11] Directive 2003/4/EC of the European Parliament and the Council of 28 January 2003 on public access to environmental information and repealing Council Directive 90/313/EEC. (OJ L 41 of 14.02.2003, p.26)
[12] Directive 2003/35/EC of the European Parliament and of the Council of 26 May 2003 providing of public participation in respect of the drawing up of certain plans and programmes relating to the environment and amending with regard to public participation and access to justice Council Directives 85/337/EEC and 96/61/EC. (OJ L 156 of 25.06.2003, p.17)
[13] COM(2003) 624. Commission Proposal for a Directive on access to justice.
[14] C 310, 16.12.2004. Treaty establishing a Constitution for Europe.

circulated a draft Declaration on Guiding Principles for Sustainable Development[15] as a renewal of its Sustainable Development Strategy. Similar to the current Sustainable Development Strategy, this Declaration seeks to promote economic prosperity, to ensure high levels of environmental protection, to promote social equity and cohesion, and to meet international responsibilities. Thus, it proposes policy guiding principles such as the enhance participation of citizens in the decision making, the integration of economic, social and environmental issues in policy making, the use of the best available knowledge, and the implementation of the precautionary and polluters pay principle.

1.2.2 European Waste Management Strategic Drivers

European waste management strategic drivers are based on international agreements and on its own waste legislation. International agreements such as Agenda 21, the Johannesburg Plan of Implementation and the Aarhus Convention move towards sustainable development principles that led to a change how waste is viewed. These agreements have in common that they promote sustainable production and consumption patterns by the prevention and minimisation of waste and the maximisation of the reuse of resources.

Additionally, the European Union waste legislation is driving this change in Europe. The Community's waste legislation is a well define set of policy instruments, which can be divided in three main categories:

- Horizontal legislation
- Legislation on waste treatment operations
- Legislation on specific waste streams

Horizontal Legislation

Horizontal legislation establishes the overall framework for management of waste. It is represented by the Council Directive 75/442/EEC on waste[16] (the "waste framework directive"), the Council Directive 91/689/EEC on hazardous waste[17] and the Council Regulation (EEC) No. 259/93 on the supervision and control shipments of waste within, into and out of the European Community[18].

The waste framework directive provides definitions and principles concerning waste management. It provides the basis on which other policy framework rest such as the hierarchy of waste, the precautionary principle and the polluter pays principle. These objectives are as well the objectives the 6EAP priority area on the sustainable use and management of natural resources and wastes. On the other hand, this directive provides a list of disposal and recovery operations listed in annexes IIA and II B. However, these lists are subjective and subject to critic. For example, the deposit of waste into or onto land is considered as a disposal operation, but according to the European Court of Justice, filling a mine with waste is considered as a recovery operation only if the waste is used as a substitute for filling material[19]. Similarly, the Court has concluded that the use of waste as fuel in a cement kiln is considered as a recovery operation[20], while the thermal treatment in a municipal solid waste incineration is considered as a disposal operation[21], even thought that this operation is able to recover energy from waste.

[15] COM (2005) 218 final. Draft Declaration on Guiding Principles for Sustainable Development. 25.05.2005
[16] Council Directive 75/442/EEC of 15 July 1975 on waste, OJ L 194, 25.07.1975
[17] Council Directive 91/689/EEC of 12 December 1991on hazardous waste, OJ L 377,31.12.1991
[18] Council Regulation (EEC) No. 259/93 of 1 February 1993on the supervision and control of shipments of waste within, into and out of the European Community, OJ L 30, 06.02.1993.
[19] Case C-6/00
[20] Case C-228/00
[21] Case C-458/00

The Council Directive on hazardous wastes lists in Annex III the properties of waste, which render them as hazardous. As well, it provides the permitting, registration and inspection requirements for the management of hazardous waste. Together with the Waste Framework Directive, the Commission implemented the European Waste Catalogue (EWC)[22]. The EWC extends the definition and properties of waste, which render as hazardous and a harmonised list of waste subject to the provisions of the Waste Framework Directive.

Finally, the waste shipment regulation is based on the principles of proximity, priority for recovery and self-sufficiency at Community and national levels. It implements the international obligations derived from the Basel Convention[23] and the OECD Decision[24] that apply to the shipment of waste. Furthermore, it prohibits the cross-border shipment of waste for disposal within, into and out of the European Community, while the cross-border shipment of waste for recovery is restricted to specific agreements between Member States and third States.

Legislation on waste management operations

The framework on waste management operations aims *inter alia* to prevent or to limit as far as possible the environmental impacts from the treatment and disposal of waste. Broadly, this is achieved by means of stringent operational conditions, technical requirements and through emission limit values. This legal framework is represented by the landfill directive[25], the incineration directive[26] and the directive on integrated pollution prevention and control (IPPC)[27].

The landfill directive is the major strategic driver for the development of waste management policies in Member States. This directive defines *inter alia* targets concerning the reduction of biodegradable municipal waste going to landfills and bans the disposal of certain waste fractions. It defines the type of waste that are accepted in the different classes of landfills, indicating as well that only pre-treated waste is suitable for landfill. Moreover, Member States must ensure that all cost relating to the setting up, operation, closure and after care of a landfill are internalised and covered in the disposal cost. As a result, these targets promote the diversion of waste fractions towards material recycling and biological treatment.

Directive 2000/76/EC on the incineration of waste provides legal requirements for incineration and co-incineration plants. It establishes *inter alia* operational conditions for normal/abnormal conditions and the maximum limit values for fugitive emissions to air and water.

Finally, some waste management operations are ruled as well by the IPPC Directive. These management operations are listed in Annex I of this directive. Annex I include *inter alia* installations for the disposal or recovery of non-hazardous and hazardous wastes and installations for the incineration of municipal solid waste. These waste management operations are required to obtain an operational permit based on the application of Best

[22] Decision 2000/532/EC establishing a list of waste, as amended
[23] Basel Convention on the control of transboundary movements of hazardous wastes and their disposal.
[24] OECD Council Decision C(92)39/Final on the control of the transboundary movements of wastes destined to recovery operations.
[25] Council Directive 1999/31/EC of 26 April 1999on the landfill of waste, OJ L 182, 16.07.1999
[26] Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste, OJ L 332, 28.12.2000
[27] Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control, OJ L 257,10.10.1996

Available Techniques (BAT), as defined in its corresponding Best Available technique Reference (BREF)[28].

Legislation on specific waste streams

The Community has developed a certain number of directives for specific waste streams on a case-by-case basis. In general, they promote source separation and recycling of waste streams, which include *inter alia* packaging waste, electrical and electronic waste, waste oils and batteries. However, the directive on Packaging and Packaging Waste[29, 30] and the directive on Waste Electrical and Electronic Equipment (WEEE)[31] are the only ones covered by the scope of this study.

The Packaging and Packaging Waste Directive contains provisions on the prevention of packaging waste, on the reuse of packaging and on the recovery of packaging waste. Member States were required to fix minimum targets for packaging waste recovery and recycling. These targets were reviewed by the Commission on a basis of an eco-efficient analysis. As a result, a Communication[32] was presented, which establishes minimum and maximum recovery and recycling targets to be achieved by 30 June 2006. These targets are material specific targets and they provide a greater coherence of Internal Market for the collection and recycling of packaging waste.

The WEEE Directive provides as well provisions, which encourage the prevention and recovery of waste electrical and electronic equipment. It seeks to improve the performance of this waste fraction through its life cycle and it establishes recovery targets as a function of the WEEE category. It is expected that Member States ensure producers to meet these targets by 31 December 2006.

It is important to notice that the legislation on waste streams is limited due to its case-by-case basis or end-of-life products approach. Recycling is targeted exclusively these streams and exclude other waste fractions which are as well suitable for recycling. For example, the packaging and packaging waste directive has established recovery targets for paper and cardboard from packaging, but it excludes paper from other sources. Therefore, the recovery and recycling efficiency of the system may be improved if the existing legislation is complemented with a material approach rather than a product one.

1.2.3 Sustainable Waste Management Systems

A sustainable waste management system has to be considered within the overall context of sustainable development. Therefore, it must consider the integration of environmental, economical and social issues in the decision making process in the pursuit of development that is *economically efficient, socially equitable and responsible and environmentally sound.* Additionally, a sustainable waste management system must be pursued taking in consideration existing waste management strategic drivers. This holistic combination ensures the effective reduction of cumulative environmental, social and economical impacts through the entire life cycle of the product system. This is achieved by means of life cycle thinking,

[28] *inter alia* BREF for the Waste Treatment Industries and BREF for Waste Incineration

[29] Directive 94/62/EC of the European Parliament and the of the Council of 20 December 1994 on packaging and packaging waste, OJ L 365, 31.12.1994

[30] Directive 2004/12/EC of the European Parliament and the of the Council of 11 February amending Directive 94/62/EC on packaging and packaging waste, OJ L 47/26, 18.02.2004

[31] Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE), OJ L 34, 13.02.2003.

[32] COM(2001) 729 final, 07.12.2001. Proposal for a Directive of the European Parliament and of the Council amending Directive 94/62/EC on packaging and packaging waste.

market involvement and the benefit of public participation in policy-making for the identification of sustainable and eco-efficient strategies.

1.3 GOAL OF THE MODEL

The decision support model for sustainable waste management systems is a decision-aiding tool designed to provide strategic solutions to decision makers, but it leaves it up to them to take a final decision. The model aims to develop the most effective sustainable waste management strategy for a specific and known waste management infrastructure. Therefore, the model aims to integrate environmental, economical and social issues in the decision making process in the pursuit of development that is *economically efficient, socially equitable and responsible and environmentally sound*.

This objective is pursued taking in consideration the Integrated Product Policy approach and the community's waste legislation by means of the following actions:

- Developing sustainable use of and management of resources
- Preventing and minimizing waste generation
- Defining eco-efficient treatment and disposal waste flows
- Minimising the accumulative environmental impacts through the entire life cycle of the product system
- Minimising the net social cost of the system as a function of its gross private cost, environmental costs and social saving costs through the internalisation of externalities
- Incorporating the added value of public participation or public involvement
- Optimizing waste flow distribution

1.3.1 Reason for carrying the study

As mentioned in the introduction, during the last decade, policy makers and the scientific community are trying to go further with the development of better waste management models. They are moving from the integrated approach to the sustainable one. This is in response to existing waste management strategic drivers and to the necessity to secure sustainable development. For instance in Europe, strategic drivers are represented *inter alia* by the Sustainable Development Strategy, the Sixth Environment Action Programme (6EAP), the Aarhus Convention and the Community's waste legislation. However, so far there is not an available model, which can integrate efficiently sustainable criteria in decision-making. Some approaches has been done but without success. This is due to the inherent limitations of used assessment tools or simply because it was not considered the integrated and holistic relation between economical, environmental and social issues, which are key issues to achieve sustainability. Consequently, without a decision tool that can deliver sustainable solutions in the waste management sector:

- How can decision makers ensure the integration of environmental, economical and social issues in the decision making process in the pursuit of development that is *economically efficient, socially equitable and responsible and environmentally sound*?
- How can they achieve sustainable production and consumption patterns?

In order to solve these questions, a decision support model for sustainable waste management systems was developed to attend the current existing gaps and to promote the effective integration of economical, social and environmental considerations in decision making by respecting the integrated product policy approach and community's waste legislation.

1.3.2 Intended Audience and Applications

The intended audience and expected applications of the model are the following ones:

- Municipal authorities will be able to determinate the most effective sustainable distribution flow of the different municipal solid waste fractions within available waste management operations.
- Waste management companies will determinate which is the optimal amount and type of waste fraction, which can be treated in their plants. They will be able as well to establish sustainable solutions for the management of their secondary waste and to assess existing markets for recycling and reuse of their tertiary waste.
- Policy makers will be able to analyse the impact of current and future legislation on waste and on waste management operations.
- Environmental organisations will be able to assess the implementation of local, regional and/or national waste management plans and programmes.
- Concerned public will be able to exert their participation right with scientific facts during environmental decision-making procedures for the implementation of waste management plans and programmes.

2 SCOPE

2.1 FUNCTION

SUWAMAS is a decision support model for sustainable waste management systems. It is designed to integrate sustainable criteria in the pursuit of development that is *economically efficient, socially equitable and responsible and environmentally sound*. Therefore, *SUWAMAS* ensures the minimisation of cumulative economical, environmental and social impacts through the life cycle of product systems combined with the benefit of public participation in policy-making to identify eco-efficient solutions.

The model is able to optimise:

- Generation and flow distribution of primary, secondary and tertiary waste
- Generation of fugitive emissions to air and water from waste management operations
- Material production and consumption patterns
- Energy used during the treatment and disposal of waste
- Energy and emissions saved from displaced materials and energy
- Net social costs, gross private costs, environmental costs and social saving costs
- Public preferences for existing waste management operations

The model is conceived to consider all environmental impacts through the life cycle of the system product, but it excludes the ones generated due plant construction operations.

2.2 FUNCTIONAL UNIT

As a functional unit, *SUWAMAS* assesses the sustainable management of mixed municipal solid waste fractions *(i)* produced at the geographical area (*j*) in a given annual time period and further treated in the waste management operation (*k*).

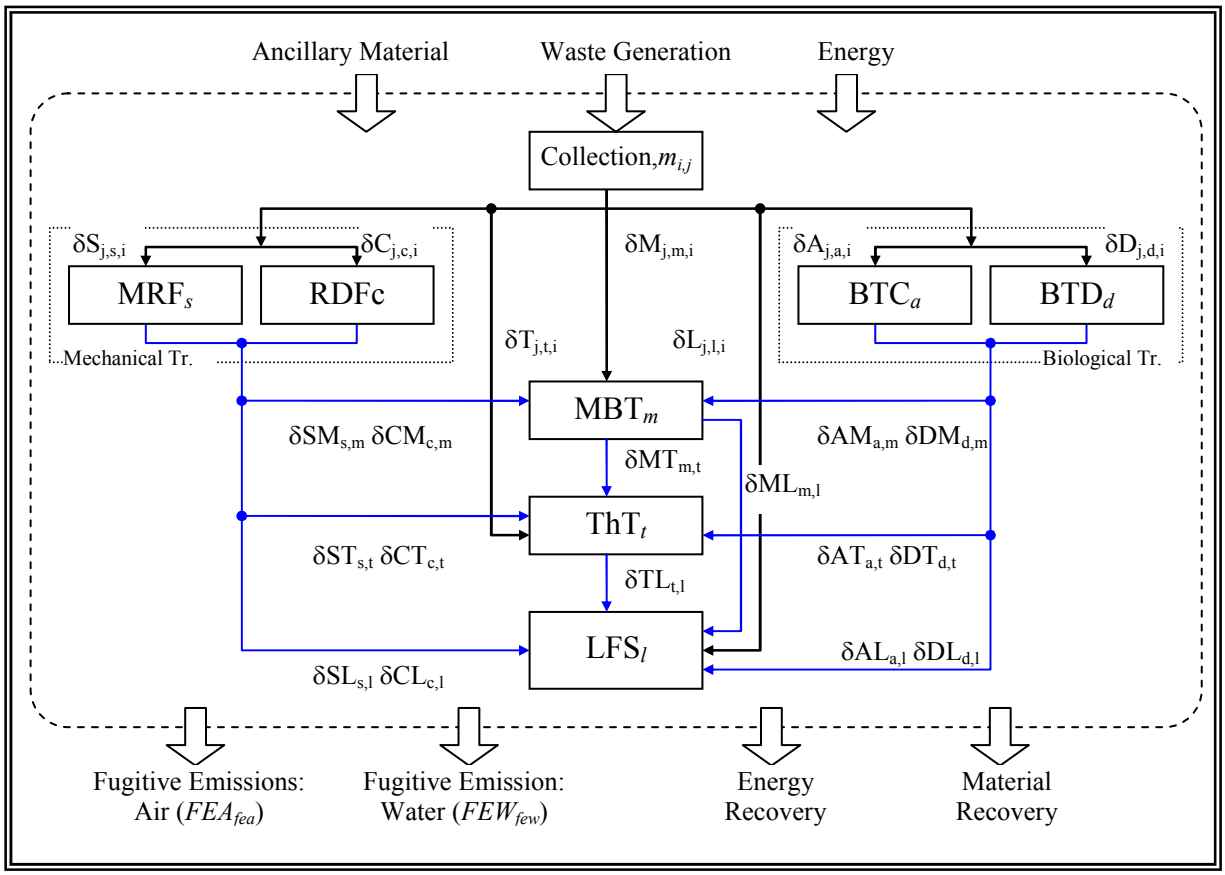
Several definitions have been given to the term municipal waste. In the EU waste legislation, municipal waste is defined in the EU Landfill Directive Article 2(b) as "*waste from households, as well as other wastes, which, because of its nature composition, is similar to waste from household"*. Similarly, the definition provided by the EU Incineration Directive Article 3.3 is better. This directive defines MSW as "*waste from households as well as commercial, industrial and institutional waste, which because of its nature and composition is similar to waste from households, but excluding fractions indicated in the Annex to Decision 94/3/EC under the heading 20 01 that are collected separately at source excluding the other wastes indicated under heading 20 02 of the Annex*". This last definition is more complete and includes the waste fractions considered in the scope of the model. Therefore, the model uses the definition provided by the EU Incineration Directive.

2.3 SYSTEM BOUNDARIES

2.3.1 Inputs and outputs

The model develops the most effective sustainable strategy for a waste management system operating within the boundaries of the product system, as shown in Figure 2-1. Following the life cycle assessment methodology, the product system starts when the municipal solid waste fraction (*i*), which will be further named as waste category, generated at the geographical area *(j)* is collected and transported to the waste management operation (*k*). Finally, the product system ends when the waste category (*i*) is either transformed into a valuable end product (recycled material or recovered energy), or when it is emitted as fugitive emission to air (FEA_{fea}) and water (FEW_{few}) as an elemental flow, or when it is finally disposed in a landfill.

The system boundary considers as inputs the generated waste categories from the specified geographical area ($m_{i,j}$), the process energy (e.g. electricity, diesel, heat) and the ancillary material used by every waste management operation. On the other hand, the ancillary input is restricted to those ones used by installed APC units. Outputs from the product system include not only direct and indirect fugitive emissions to air and water but also valuable products such as recovered material and energy.



where:
MRF: Material Recycling Facility; RDF: Mechanical Treatment Conditioning; MBT: Mechanical-biological Treatment; BTC: Biological Treatment Composting; BTD: Biological Treatment Anaerobic Digestion; THT: Thermal Treatment

Figure 2-1 Boundaries of the Sustainable Waste Management System

2.3.2 Decision Variables

As mentioned before, generated waste categories (*i*) are transported from the generation point *(j)* to the waste management operation *(k)*. The flow distribution of primary waste categories is defined with the decision variable $\delta X_{j,x,i}$. The term *X* represent the waste management operation type, while the term *x* represents the specific waste management treatment unit. Both terms are then substituted by the specific waste management operation index (*s, c, a, d, m, t ,l*) and identified by the decision variable $\delta S_{j,s,i}$ $\delta C_{j,c,i}$ $\delta A_{j,a,i}$ $\delta D_{j,d,i}$ $\delta M_{j,m,i}$ $\delta T_{j,t,i}$ *and* $\delta L_{j,l,i}$ respectively. Subsequently, every waste management operation generates secondary waste categories *(si)* or intermediate material, which is then eco-efficiently treated or disposed of. If the secondary waste fulfils quality criteria for landfilling then it can be sent directly to the disposal site (LFS_l), otherwise it will compete for scarce treatment capacity in another waste management operation *(k)*. The flow distribution of secondary waste categories between waste management operations is defined with the decision variable $\delta XY_{x,y}$. Similarly, the terms *Y* and *y* represent the waste management operation type and specific operation unit which is allowed to treat secondary waste, in this case mechanical-treatment, thermal

treatment or final disposal in a landfill. Therefore, the term *y* can be substituted with the waste management operation index (*m, t, l*) and defined by the decision variables: $\delta SM_{s,m}$ $\delta ST_{s,t}$ $\delta SL_{s,l}$ $\delta CM_{c,m}$ $\delta CT_{c,t}$ $\delta CL_{c,l}$ $\delta AM_{a,m}$ $\delta AT_{a,t}$ $\delta AL_{a,l}$ $\delta DM_{d,m}$ $\delta DT_{d,t}$ $\delta DL_{d,l}$ $\delta MT_{m,t}$ $\delta ML_{m,l}$ *and* $\delta TL_{t,l.}$

2.3.3 Waste Management Operations

The product system consists of *k* types of waste management operations, which are divided according to the installed choice of technology as shown in Table 2-1. Considered waste management operations include mechanical, biological, mechanical-biological, thermal and landfill. These waste management operations are recovery and disposal operations according to the Annex IIB of the EU waste framework directive 75/442/EC.

Table 2-1 Waste Management Operations classification

k(x)	Waste Management Operation Type	Waste Management Operation Code		Choice of Technology
1	Material Recycling Facility	MRF_s	s=1..S	▪ Sorting material ▪ Conditioning sequence
2	Mechanical Treatment: RDF production	RDF_c	c=1..C	▪ Conditioning sequence
3	Biological Treatment: Composting	BTC_a	a=1..A	▪ Non-reactor system ▪ Enclosed reactors system ▪ In-Vessel Reactor System
4	Biological Treatment: Anaerobic Digestion	BTD_d	d=1..D	▪ 1 Stage and Multiple Stages ▪ Dry and Wet process ▪ Mesophilic and Thermophilic process
5	Mechanical-Biological Treatment	MBT_m	m=1..M	▪ Conditioning sequence ▪ Composting or Anaerobic Digestion
6	Thermal Treatment	THT_t	t=1..T	▪ Mono-combustion (Moving Grate Incinerator)
7	Landfill	LFS_l	l=1..L	▪ Landfill Class I & II

a. **Mechanical Treatment:** Mechanical treatment refers to sorting, separation, size reduction and sieving technologies. The purposes of these waste management operations are to recover and recycle valuable waste materials without changing its chemical structure. Mechanical treatment units are classified as recovery operations R4 and R5 according to the Annex IIB of the EU waste framework directive 75/442/EEC. In this model, considered mechanical treatment units include both “clean” and “dirty” material recycling facilities.

b. **Biological Treatment:** Biological treatment refers to the aerobic or anaerobic biological treatment of biodegradable waste into a compost-like product and if suitable biogas. Both treatments are recovery operations R3 according to the Annex IIB of the EU waste framework directive 75/442/EEC, where R3 refers to recycling/reclamation of organic substances that are not used as solvents (including composting and other biological transformation processes). Simulated aerobic biological treatment units include non-reactor, enclosed reactor and in-vessel reactors systems. On the other hand, simulated anaerobic biological treatment units include the combination of single stage consisting of a dry or wet process under mesophilic or thermophilic temperatures, as installed.

c. **Mechanical-Biological Treatment:** Mechanical-biological treatment is a combination of both mechanical and biological treatments. In this model, the mechanical-biological treatment consists of the combination of sorting, separation, size reduction and sieving technologies with either aerobic or anaerobic biological treatment, as installed.

d. **Thermal Treatment:** Thermal treatment refers exclusively to the thermal oxidation process or mono-combustion of waste with or without energy recovery in an incineration plant as defined by Article 3.4 of the Incineration Directive (2000/76/EC). Other thermal processes such as pyrolysis, gasification plasma processes or co-incineration are not considered in this model. This waste management operation is a disposal operation D10 according to the Annex IIB of the EU waste framework directive 75/442/EEC.

e. **Landfill:** Landfill is a disposal operation D1 or D5 according to the Annex IIB of the EU waste framework directive 75/442/EEC. D1 refers to deposit into or onto land (e.g. landfill), while D5 refers to specially engineered landfill (e.g. placement into lined discrete cells which are capped and isolated from one another and the environment, etc). Article 2(d) of the Landfill Directive (1999/31/EC) provides the same definition of landfill. Simulated landfills are non-hazardous landfills class I and II, as defined by TASi[33].

2.4 DATA CATEGORIES

2.4.1 Primary and Secondary Waste

Generated municipal solid waste is classified in *i* primary waste categories, divided in *w* waste categories indicators and represented by the matrix $MWC_{i,w}$. Secondary waste categories are divided in *si* fractions as a function of their sources. Studied primary and secondary waste categories are shown in Table 2-2, while the waste category indicators are given in Table 2-3. Considered primary and secondary waste categories are named according to the European Waste Catalogue[34]. The definition of every primary waste category is given in Table 2-4.

Table 2-2 Considered primary and secondary waste fractions

Primary waste category (*i*)	**EWC**	**Secondary waste Category (*si*)**	**EWC**
Mixed municipal waste (Household waste)	200301	***Mechanical Treatment***	
Similar to h.w. commercial waste	200301	Sorted construction and demolition waste	170904
Bulky waste	200307	Paper and board	191201
Waste from markets	200302	Ferrous metals	191202
Street-sweeping waste	200303	Non-ferrous metals	191203
Mixed construction and demolition waste	170904	Plastic and rubber	191204
Waste from sewage cleaning	200306	Glass	191205
No hazardous hospital residues	180101/04	Wood	191207
Household problematic waste	200199	Textiles	191208
Biowaste (e.g. kitchen waste)	200108	Inert material	191209
Green waste (e.g. garden, parks and grave yards)	200201	***Biological Treatment***	
Paper and cardboard	200101	No composted fraction of MSW	190501
Glass	200102	Compost out of specification	190503
Lightweight packaging	200139	Liquor	190600
Metals	200140	Digestate	190605
Waste Wood	200138	Residual waste	190606
WEEE containing CFC	200135	***Thermal Treatment***	
WEEE without CFC	200136	Solid wastes from APC	190100
Clothes and textiles	200110	Bottom ash and Slag	190107
Mixed fraction waste	200199	Boiler dust	190111

[33] TASi: TA Siedlungsabfall. Technische Anleitung zur Verwertung, Behandlung und sonstigen Entsorgung von Siedlungsabfällen.

[34] Commission Decision 2000/532/EC of 3 May 2000 replacing Decision 94/3/EC establishing a list of waste pursuant to Article 1(a) of Council Directive 75/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of Council Directive 91/689/EEC on hazardous waste. As amended.

Table 2-3 Considered waste category indicators, w

w	WCI	W	WCI	w	WCI
1	Fe-metal packages	11	Mixed plastic	21	Hazardous waste
2	NFe-metal packages	12	Composite packages	22	Leather
3	Mixed metal	13	Mixed composites	23	Rubber
4	Waste Paper	14	Biowaste	24	Diapers & Hygienic paper
5	Glass	15	Green waste	25	Fine fraction
6	Waste Textiles	16	Sewage sludge	26	Middle fraction
7	Waste Wood	17	Shoes	27	Mixed waste
8	WEEE	18	Vacuum cleaner dirt		
9	Plastic packages	19	Inert		
10	Polystyrene	20	Refurbishment waste		

Table 2-4 Definition of considered primary waste categories

Primary waste category (*i*)	**EWC**	**Definitions**
Mixed municipal waste (Household waste)	200301	Waste generated mainly by private households but also by commercial activities and other sources whose activities are similar to those of households and commercial enterprises
Similar to h.w. commercial waste	200301	Waste generated from commercial concerns such as business, services enterprises, public organisations and industry as well from waste treatment plants, whose properties are similar to the domestic refuse
Bulky waste	200307	Solid waste that is collected and transported separately from the domestic refuse due to its high bulkiness
Waste from markets	200302	Waste generated on markets, e.g. fruit and vegetable wastes and not usable packing materials
Street-sweeping waste	200303	Waste collected during the cleaning of streets, such as road and tire abrasion materials and leaves
Mixed construction and demolition waste	170904	Non-mineral materials generated from construction and demolition activities, such as the construction of buildings and civil infrastructure, total or partial demolition of buildings and civil infrastructure, road planning and maintenance
Waste from sewage cleaning	200306	Waste collected from the cleaning of the drains and sewer system
No hazardous hospital residues	180101/04	Wastes from the supply of medical services and research, which are not considered to contain hazardous materials
Household problematic waste	200199	Hazardous household waste fraction, e.g. batteries
Biodegradable waste	200108	Waste from households and commercial activities that is capable of undergoing biological decomposition
Green waste (garden, parks and grave yards)	200201	Predominantly vegetable wastes from gardening which is result of gardening from used properties, public parks, grave yards and from green waste collected from street-cleaning
Paper and board	200101	Packaging waste material as defined by the EU Packaging and Packaging Waste Directive 94/62/EC Art 3.1 and 3.2. and as amended by 2004/12/EC
Glass	200102	
Lightweight packaging	200139	
Metals	200140	
Waste Wood	200138	Waste wood fraction as defined by the Ordinance on the Disposal of Waste Wood (Verordnung über die Entsorgung von Altholz)
WEEE containing CFC	200135	As defined by the EU WEEE Directive 2000/96/EC Art 3(a) and 3(b)
WEEE without CFC	200136	
Clothes and textiles	200110	
Mixed waste fractions	200199	As defines by EU Incineration Directive Article 3.3

2.4.1.1 Physical-chemical properties

For every waste category indicator *w* are given specific *pp* physical and *cc* chemical properties in the form of matrices. The $MPP_{w,pp}$ matrix provides physical and biological information such as particle size distribution, light and heavy fraction distribution, potential degradable fraction, degradable organic carbon fraction, degradable organic carbon dissimilated, biogenic carbon fraction, feedstock energy and burnable fraction. Additionally, the calorific value is calculated based on the macro-chemical composition of the material with

the ultimate analysis equation derived by Dulong (Kathiravale 2003). Dulong's equation is shown in Equation 2-1.

Equation 2-1 Dulong ultimate analysis model, higher heating value

$$HHV = 4.184 \cdot \left[78.31C + 359.32\left(H - \frac{O}{8}\right) + 22.12S + 11.87O + 5.78N\right]$$

where:

HHV	Higher heating value, [kJ/kg]
C,H,O,N,S	Weight percentage of C,H,O,N, dry basis, [%]

The modified ultimate analysis model of Dulong is then corrected with the specific water content of the input waste. This will provide the lower heating of waste, which is the minimum amount of heat that can be recovered from it. The lower heating value is calculated with Equation 2-2.

Equation 2-2 Lower heating value

$$LHV_t = HHV_t - \lambda v_{H2O} \cdot W$$

where:

LHV	Lower heating value, [kJ/kg]
λv_{H2O}	Specific heat of vaporisation λv_{H2O} =2441J/g=43938J/mol according to DIN 51900 T2

Similarly, for every waste category indicator is given an ultimate analysis defined by the $MCC_{w,cc}$ matrix which defines the macro-chemistry of the waste composition in terms of carbon, hydrogen, oxygen, nitrogen, sulphur, chlorine, ash, moisture and heavy metals (Cd, Tl, Hg, Sb, As, Pb, Cr, Co, Cu, Mn, Ni and V).

2.4.2 Energy consumption

Energy consumption is the amount of energy required by the waste management operation *k* to operate adequately. This study considers three energy sources: electricity, diesel and heat. The demand of energy consumption depends on the waste management operation and on the amount of treated waste. Every energy category is separately assessed to determinate the indirect generation of fugitive emissions to air and water according the source of energy. Indirect fugitive emissions are subsequently integrated in the total environmental impact of the waste management operation.

2.4.3 Recovered Materials and Energy

Recovered materials consist of refuse-derived fuel (RDF), compost, stabilised organic material (SOM), metals, paper, glass cullets, wood chips and valuable plastic fractions (PET, LDPE, HDPE, PVC, PP, PS, PU and mixed plastics). This study considers as well that energy is only recovered in the form of electricity from the combustion of biogas and landfill gas through gas fired units. These gas-fired units are *inter alia* gas turbines or internal combustion engines. Similarly, feedstock energy can be recovered in thermal treatment operations such as municipal solid waste incinerators.

2.4.4 Direct Fugitive Emissions to Air and Water

Fugitive emissions to air (FEA_{fea}) and water (FEW_{few}) are generated in every waste management operation. Their magnitude depends on the waste composition input, on the waste management choice of technology and on the type of air pollution control units (APC) installed on site. For simplification reasons, the model evaluate exclusively fugitive emissions to air that are controlled by the European framework on waste and on waste management operations, as shown in Table 2-5. Similarly, considered fugitive emissions to water include

only biological oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (N-tot), total phosphorous (P-tot) and mercury.

Table 2-5 Controlled fugitive emissions to air

Chemical Compound	Symbol	Chemical Compound	Symbol	Chemical Compound	Symbol
Carbon dioxide	CO_2	NMVOC	NMVOC	Cadmium	Cd
Methane	CH_4	Dioxins and furans	PCDD/F	Thallium	Tl
Nitrous oxide	N_2O	PAH	PAH	Mercury	Hg
Hydrofluorocarbons	HFCs	Carbon monoxide	CO	Antimony	Sb
Perfluorocarbons	PFCs	Particles < 2.5 μm	$PM_{2.5}$	Arsenic	As
Sulphur hexafluoride	SF_6	Particles, 2.5 μm-10μm	PM	Lead	Pb
Sulphur dioxide	SO_2	Particles, >10μm	PM_{10}	Chromium	Cr
Nitrogen dioxide	NO_2			Cobalt	Co
Ammonia	NH_3			Copper	Cu
Hydrogen chloride	HCl			Manganese	Mn
Hydrogen sulphide	H_2S			Nickel	Ni
				Vanadium	V

a. Time Framework

Fugitive emissions are considered as instantaneous and thus they are accounted and allocated to the year in which they occur. Special consideration is given to fugitive emissions from landfills, which are not instantaneous emissions. In order to account the emissions from landfills together with the ones from other waste management operation in the year in which waste was treated or disposed of, the model assesses landfill fugitive emissions with the default method – Tier 1 recommended by the IPCC (IPCC 2000).

2.4.5 Indirect Fugitive Emissions to Air and Water (Displaced Emissions)

2.4.5.1 Recovered material

Recovered material such as glass, plastics, metals and compost are accounted through the life cycle of the product system. They displace fugitive emissions to air and water associated from the production of the same amount of recovered goods. Displaced emissions from the recovery of material will have a negative value, which represent a benefit to the system.

Equation 2-3 Displaced fugitive emissions to air and water due to recovered material

$$DFEARCM_{k,fea} = -\sum_{x}\sum_{rcm} TRCM_{k(x),rcm} \cdot MRCMEA_{fea}$$

$$DFEWRCM_{k,few} = -\sum_{x}\sum_{rcm} TRCM_{k(x),rcm} \cdot MRCMEW_{few}$$

where:

$DFEARCM_{k,fea}$ Displaced fugitive emissions to air *fea* generated in the waste management operation *k* due to the recover of the material *rcm*, [Gg]

$DFEWEU_{k,fea}$ Displaced fugitive emissions to water *few* generated in the waste management operation *k* due to the recover of the material *rcm*, [Gg]

$TRCM_{k(x),rcm}$ Total amount of recovered material *rcm* at the waste management operation *k(x)*, Gg

$MRCMEA_{fea}$ Default emissions coefficient matrix. Fugitive emissions to air *fea* vs. production of material *rcm*, kg/kg

$MRCMEW_{few}$ Default emissions coefficient matrix. Fugitive emissions to water *few* vs. production of material *rcm*, kg/kg

2.4.5.2 Energy production and consumption

Accounted consumed and recovered energy displace fugitive emissions. Energy consumption has negative displaced flows, while energy recovery has positive displaced flows. They are associated to the power plant technology and on the fuel source that is used to generate the same amount of energy (IPPC 2005b). The configuration of the power plant technology is based on the electricity generation from coal, oil, natural gas, nuclear or hydro power stations. Every country has its own distribution of electricity generation by origin. Average electricity production and supply mixes values can be obtained from UCTE, CENTREL or NORDEL.

For example, the Union for the Co-ordination of Transmission of Electricity (UCTE) provides statistical distribution values for most of the western European countries. These statistical distributions are shown in Table 2-6. Finally, the potential amount of fugitive emissions that can be displaced by the system product is calculated with Equation 2-4.

Equation 2-4 Displaces fugitive emission to air and water due to consumption and recover of energy

$$DFEAEU_{k,fea} = \sum_{x}\left[\sum_{ES}\sum_{w}\left(MPEA_{fea,ES}\cdot m_{k(x),w}\right) - \sum_{ES}\left(RECE_{k(x),ES}\cdot MPEA_{fea,ES}\right)\right]$$

$$DFEWEU_{k,few} = \sum_{x}\left[\sum_{ES}\sum_{w}\left(MPEW_{few,ES}\cdot m_{k(x),w}\right) - \sum_{ES}\left(RECE_{k(x),ES}\cdot MPEW_{few,ES}\right)\right]$$

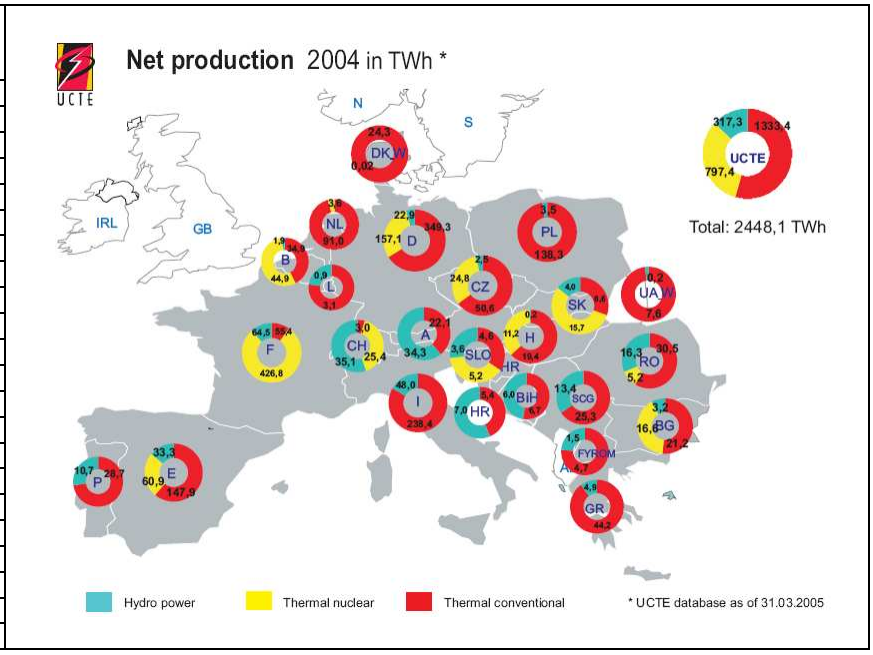
where:

$DFEAEU_{k,fea}$	Displaced fugitive emissions to air *fea* generated in the waste management operation *k* due to the use of energy, [Gg]
$DFEWEU_{k,fea}$	Displaced fugitive emissions to water *few* generated in the waste management operation *k* due to the use of energy, [Gg]
$MPEA_{fea,\ ES}$	Default emissions coefficient matrix. Fugitive emissions to air *fea* vs. process energy type *ES* , [kg/ GJ(GWh)]
$m_{k(x),w}$	Annual material flow of waste category *w* entering to the waste management operation *k(x)*, [Gg]
$RECE_{k(x),ES}$	Annual recovered energy type ES at the waste management operation *k(x)*, [GJ(GWh)]

The mixture of energy carriers and technologies differs from country to country. Thus, this equation uses country-specific supply grid distribution source and the displaced emissions generated in every type of generation plant as a function of the fuel sources.

Table 2-6 western European countries electricity generation by origin, %

Country	Hydro	Thermal nuclear	Thermal conventional
P	27,16	0,00	72,84
E	13,75	25,15	61,09
F	10,15	79,52	10,32
B	2,33	54,96	42,72
L	22,50	0,00	77,50
NL	0,00	3,81	96,19
DK_W	0,00	0,00	100,00
D	4,33	29,68	65,99
CH	55,28	40,00	4,72
A	60,82	0,00	39,18
I	16,76	0,00	83,24
CZ	3,21	31,84	64,96
SLO	26,87	38,81	34,33
HR	56,45	0,00	43,55
PL	2,47	0,00	97,53
H	0,65	36,36	62,99
BiH	47,24	0,00	52,76
SK	14,13	55,48	30,39
SCG	34,63	0,00	65,37
FYROM	24,19	0,00	75,81
GR	9,98	0,00	90,02
UA_W	2,56	0,00	97,44



Adapted from (UCTE 2005)

2.4.6 Sustainable waste management indicators

Sustainable waste management indicators (SWMI) are used as a key tool for monitoring the implementation and effectiveness of the proposed sustainable strategy for the studied waste management system. In context of the EU Sustainable Development Strategy, this model makes use of selected sustainable development indicators (SDI) proposed by the Commission[35]. These indicators are based on those of the UN Commission on Sustainable Development and OECD, the Structural Indicators (Lisbon Strategy), the Laeken indicators,

[35] Sustainable Development Indicators (SDI). Eurostat: http://epp.eurostat.cec.eu.int/pls/portal

indicators monitoring the Cardiff integration process and the core set of indicators of the European Environment Agency. As a result, the sustainable waste management indicators consider the integration of economic development, social cohesion and environmental protection. Additionally they are designed to assess the effectiveness of proposed strategies. The SWMI that are used in this model are shown in Table 2-7.

Table 2-7 Sustainable waste management indicators (SWMI)

Area	Sustainable Waste Management Indicators (SWMI)		Unit
Environmental	Eco-efficiency	Municipal waste generated	kg per capita
		Primary and secondary waste generation	Gg
		Municipal waste treatment, per waste management operation	%
		Municipal waste disposed	%
		Municipal waste recycled/recovered	%
		Emission of wastewater	Gg
		Emission of aggregated greenhouse gas emissions	Gg of CO_2-eq
		Emission of aggregated acidifying substances, AP	Gg SO_2-eq
		Emission of aggregated euthrophication precursors, EP	Gg PO_4-eq
		Emission of aggregated ozone precursors, TOFP	Gg Ethylene-eq
		Emission of aggregated abiotic depletion precursors, ADP	Gg Sb-eq
		Emission of aggregated human toxicity precursors, HTP	Gg Pb-eq
		Emission of aggregated carcinogenic risk precursors, CRP	Gg As-eq
		Emission of aggregated particle formation precursors, PFP	Gg PM-eq
	Energy	Final energy consumption	Gg of oil-eq
		Final energy generation	GWh
		Final energy generation from renewable sources	GWh
		Share of electricity from renewable energy to gross electricity generation	%
Economical	Economic Development	Total annual cost and per waste management operation	M€
		Total annual transportation cost	M€
		Total revenues from energy and material recovery	M€
	Externalities	Total environmental costs and per waste management operation	M€
		Total displaced environmental costs and per waste management operation	M€
Social	Social Acceptability	Risk perception	-
		Visual Impact	-
		Local Disamenity	-
		Social waste management operation preference	-
		Decision maker waste management operation preference	-
	Social Equity	Number of jobs	Employed people
		Quality of work	-

2.4.6.1 Environmental Indicators

Environmental indicators are designed to assess the environmental effectiveness of the system and therefore to ensure its environmental protection. This indicator is subdivided in two categories named energy and eco-efficiency. In one hand, the energy indicator considers the total amount of energy consumed and recovered within the products system. As well, it considers the share amount of electricity generated from renewable sources as a percent to the gross electricity generation. On the other hand, the eco-efficiency indicator considers the total generation of primary, secondary and tertiary waste within the product system. Additionally, fugitive emissions to air and water are classified in impact categories and they are aggregated via a weighting scheme into environmental pressure indicators. Selected environmental pressure indicators include:

- Global Warming Potential GWP: CO_2-eq
- Acidification Potential AP: SO_2-eq
- Euthrophication Potential EP: PO_4-eq
- Tropospheric Ozone Formation Potential TOFP: Ethylene-eq
- Particle formation potential PFP: PM-eq
- Carcinogenic Risk Potential CRP: As-eq

- Human Toxicity Potential HTP: Pb-eq
- Photochemical Ozone Creation Potential POCP: Ethylene-eq
- Abiotic Depletion Potential ADP: Sb-eq

These environmental pressure indicators are analogous to the impact categories referred to ISO 14042. They are calculated with Equation 2-5, which uses the default weighting factors for every fugitive emission to air and water as given in Table 2-8 and Table 2-9, respectively.

Equation 2-5 Environmental Pressure Indicators

$$EPI - eq_{EPI,k} = \sum_{x}\left[\sum_{fea} FEAX_{k(x),fea} \cdot MEPIA_{fea,EPI} + \sum_{few} FEWX_{k(x),few} \cdot MEPIW_{few,EPI}\right]$$

where:

$EPI\text{-}eq_k$	Environmental pressure indicator *EPI* emitted by the waste management operation *k*, Gg-eq
$FEAX_{k(x),fea}$	Fugitive emission to air *fea* generated at the waste management operation *k(x)*, Gg
$MEPIA_{fea,EPI}$	Weighting factor matrix of the fugitive emission to air *fea* vs. environmental pressure indicator *EPI*, -
$FEWX_{k(x),few}$	Fugitive emission to water *few* generated at the waste management operation *k(x)*, Gg
$MEPIW_{few,EPI}$	Weighting factor matrix of the fugitive emission to water *few* vs. environmental pressure indicator *EPI*, -

Table 2-8 Environmental Pressure Indicators, Fugitive Emissions to Air

$MEPIA_{fea,\ epi}$		GWP	AP	EP	TOFP	PFP	CRP	HTP	POCP	ADP
Carbon dioxide	CO_2	1	-	-	-	-	-	-	-	-
Methane	CH_4	23	-	-	0.014	-	-	-	0.006	-
Nitrous oxide	N_2O	296	-	-	-	-	-	-	-	-
Hydrofluorocarbons	HFCs	-	-	-	-	-	-	-	-	-
Perfluorocarbons	PFCs	-	-	-	-	-	-	-	-	-
Sulphur hexafluoride	SF_6	22200	-	-	-	-	-	-	-	-
Sulphur dioxide	SO_2	-	1	-	-	0.54	-	13	0.048	1.79E-04
Nitrogen dioxide	NO_2	5	0.7	0.13	1.22	0.88	-	95	1.87	-
Ammonia	NH_3	-	1.88	0.33	-	0.64	-	350	-	-
Hydrogen chloride	HCl	-	0.88	-	-	-	-	80	-	-
Hydrogen sulphide	H_2S	-	-	-	-	-	-	140	-	3.37E-04
NMVOC	NMVOC	11	-	-	1	0.012	-	-	0.416	-
Dioxins & Furans	PCDD/F	-	-	-	-	-	10.5	-	-	-
PAH	PAH	-	-	-	-	-	-	-	-	-
Carbon monoxide	CO	1-3	-	-	0.11	-	-	350	0.027	-
Particulates, < 2.5 µm	PM2.5	-	-	-	-	-	-	-	-	-
Particulates,	PM	-	-	-	-	-	-	-	-	-
Particulates, >10 µm	PM10	-	-	-	-	1	-	-	-	-
Cadmium	Cd	-	-	-	-	-	0.42	0.15	-	0.33
Thallium	Tl	-	-	-	-	-	-	-	-	5.05E-05
Mercury	Hg	-	-	-	-	-	-	0.1	-	0.495
Antimony	Sb	-	-	-	-	-	-	5	-	1
Arsenic	As	-	-	-	-	-	1	1	-	9.17E-03
Lead	Pb	-	-	-	-	-	-	1	-	0.0135
Chromium	Cr	-	-	-	-	-	0.279	0.5	-	8.58E-04
Cobalt	Co	-	-	-	-	-	-	1	-	2.62E-05
Copper	Cu	-	-	-	-	-	-	10	-	1.94E-03
Manganese	Mn	-	-	-	-	-	-	5	-	1.38E-05
Nickel	Ni	-	-	-	-	-	-	0.5	-	1.08E-04
Vanadium	V	-	-	-	-	-	-	5	-	1.16E-06

Source:

HTP: BREF ECM Annex 1
GWPs: BREF ECM. Annex 2. Information adapted from IPCC (2001). Climate Change 2001: The Scientific Basis http://www.grida.no/climate/ipcc_tar/wg1/index.htm. Specifically GWPs (http://www.grida.no/climate/ipcc_tar/wg1/248.htm) GWPs given for a 100-year time horizon
AP: BREF ECM Annex 4
EP: BREF ECM Annex 5
ODP: BREF ECM Annex 6: Information adapted from UNEP 2000. The Montreal Protocol on substances that deplete the Ozone Layer. ISBN: 92-807-1888-6 http://hq.unep.org/ozone/pdf/Montreal-Protocol2000.pdf
POCP: BREF ECM. Annex7.

Table 2-9 Environmental Pressure Indicators, Fugitive Emissions to Water

$MEPIW_{few.epi}$		GWP	AP	EP	TOFP	PFP	CRP	HTP	POCP	ADP
Biological oxygen demand	BOD	-	-	-	-	-	-	-	-	-
Chemical oxygen demand	COD	-	-	0.022	-	-	-	-	-	-
Nitrogen Total	N-tot	-	-	0.42	-	-	-	-	-	-
Phosphorous Total	P-tot	-	-	3.06	-	-	-	-	-	-
Mercury	Hg	-	-	-	-	-	-	-	-	-

2.4.6.2 Economical Indicators

Economical indicators are designed to assess the economical affordability of the system and as a result to ensure its economic growth. They consider the full costs derived from the management of the generated solid waste within the existing waste management infrastructure. Therefore, this indicator is divided in economic development and externalities. In the one hand, the economic development indicator represent the social cost derived from the gross private cost (e.g. transportation, labour and capital cost for operation and maintenance of existing waste management operations) and the social costs savings associated to the revenues and displacement of recovered energy and resources. On the other hand, the externalities indicator represent the internalisation of the environmental costs derived from the generation of direct and displaced fugitive emissions to air, water and land through the entire life cycle of the product system. Therefore, generated and displaced fugitive emission pay the full costs of their impact based on shadow prices. These shadow prices are marginal social costs, which represent the willingness to pay (WTP) to avoid negative effects on the environment.

2.4.6.3 Social Indicators

Social indicators are designed to assess the social acceptability of the system and consequently to ensure social cohesion. These indicators are based on participatory policymaking. They are represented by the social acceptability indicator and the social equity indicator.

In the one hand, the social acceptability indicator guarantees the preference or disapproval for a waste management operation. It is important to stress that the efficiency of the waste management systems is close related to the behaviour of the community. If the community finds acceptable the waste management system, then the system will work. Otherwise, the community could present an important degree of resistance to the proposed waste management system, and therefore the system will not work. The social acceptability indicator subdivided in risk perception, visual impact, local disamenity and stakeholder preference.

- Risk perception: This indicator assesses the public risk perception for every waste management operation in terms of their health risk likelihoods. The practitioner can qualitatively determinate the likelihood of health risks due to physical, chemical and biological stressors (e.g. noise, temperature, fugitive emissions to air, water and land). As well, the qualitative likelihood of health risks due to changes energy use and disposal of waste could be considered. The practitioner can introduce quantitative parameters that define the health and safety risks in terms of life expectancy, mortality and morbidity.
- Visual Impact
- Local disamenity: This indicator assesses qualitatively potential disamenity derived from either the recovery or disposal of waste in existing waste management operations. This indicator could be assessed in terms of emission of odours and dust, Wind blow material, noise and traffic and lost of value in house prices.

- Stakeholder preference: This indicator assesses qualitatively the desire hierarchy of waste management operations.

On the other hand, the social equity indicator ensures equitable opportunities and distribution of goods across the community, which subsequently ensures social protection, health, safety and equality among the members of the involved community. The achievement of this indicator improves the inter-relationship between economic and social sustainability. As declared by the Lisbon strategy and the Social Policy Agenda, social equity is guaranteed *inter alia* through creating not only more but also better jobs. Therefore, the social equity indicator is subdivided in both more and better jobs indicators.

- More jobs = number of jobs. This indicator estimates the amount of jobs offered due to the recovery of disposal of waste in every waste management operation. A Commission Communicate[36] and a Commission Impact Assessment[37] give figures of 241 jobs for recycling 10 Gg, 19 to 41 jobs for incineration and 8 to 12 for landfill. These values are comparable to the ones founded in literature, as shown in Table 2-10.

Table 2-10 Social equity indicator: number of jobs per 10 Gg managed waste

Waste management operation type	Min	Max	Aver	Annual Income, €	Source
MRF-General			241		(COM(2005) 666)
MRF-paper and cardboard	189	439	245		(LCA-IWM 2005)
MRF-glass	31	725	109		(LCA-IWM 2005)
MRF-lightweight packaging	172	3846	497		(LCA-IWM 2005)
MRF-metals (aluminium)	107	3571	299		(LCA-IWM 2005)
MRF-metals (ferrous metals)	48	617	102		(LCA-IWM 2005)
MRF-waste wood					
MRF-WEEE			4,430		(LCA-IWM 2005)
MRF-C&D waste					
MRF-textiles					
MRF-refuse derived fuel					
RDF					
BTC-ERS	13	30	22	44,000	(Hogg 2001)
BTC-NRS in Italy	17	25	21	32,000	(Hogg 2001)
BTD in Finland			9	37,000	(Hogg 2001)
MBT with BTD			12		(Greenpeace 2003)
MBT with BTD	16	21	18		(LCA-IWM 2005)
MBT with BTC	8	16			(LCA-IWM 2005)
THT in Europe	19	41			(COM(2005) 666)
THT in Sweden	11	40	26		(Hogg 2001)
THT in Sweden	14	53	33		(Hogg 2001)
THT in France	28	67		25,200	(Hogg 2001)
THT in Germany			40	35,800	(Hogg 2001)
THT in Italy			27		(Hogg 2001)
THT in UK	23	35		32,000	(Hogg 2001)
LFS in Europe	8	12	10	25,200	(COM(2005) 666), (Hogg 2001)

- Better jobs = quality of work. The promotion of better jobs is a driving force for the achievement of a sustainable waste management system. Quality of work has a direct correlation between productivity, living standards and sustainable economic growth. According to a Commission Communicate[38] and to a Decision of the European Council on quality indicators[39], quality of work can be assessed within considering the

[36] COM(2005) 666 final. Taking sustainable use of resources forward: A Thematic Strategy on the prevention and recycling of waste. Brussels, 21.12.2005

[37] Commission Staff Working Document. Impact Assessment on the Thematic Strategy on the prevention and recycling of waste and the immediate implementing measures. Non-Official Document. Brussels 2005.

[38] COM(2001) 313 final. Employment and social policies: a framework for investing in quality. Brussels, 20.06.2001

[39] COM(2003) 728 final. Improving quality in the work: a review of recent progress. Brussels, 26.11.2003

characteristics of the job itself; and the work and wider labour market context. Similarly, this model assimilates these criteria for the assessment of quality of work. Quality of work criteria are shown in Table 2-11.

Table 2-11 Social equity indicator: quality of work

Criteria	Meaning	Criteria	Meaning
Job characteristics	Job Satisfaction	Work and wider labour market context	Gender equality
	Remuneration		Health and safety
	Non-pay rewards		Flexibility and security
	Working time		Access to jobs
	Skills and training		Work-life balance
	Job content		Diversity and non-discrimination
	Match between jobs characteristics and worker characteristics		Social dialogue and worker involvement

Social indicators must be obtained and considered at an early stage of the decision-making. However, when further information is required at the appraisal stage, then it is recommended that the practitioner undertake a specific survey within the community. This survey must reflect the opinion of the community concerning the use and configuration of every waste management operation.

2.4.7 Data sources

Default collected data comes from background and foreground sources. Foreground data is specific information obtained directly from governmental organisations (e.g. UBA, MUNLV, BayLfU, OECD, EC, EEA, EPA and CIWMB) and non-governmental organisations (e.g. ASA, BGK and ITAD). On the other hand, background collected data is obtained from international databases and online sources, such as Ecoinvent, Gemis, NPi, AGO, AP-42, IPCC and IPPC. Background collected data is related to generic elementary flows of material and energy from different waste management operations. In order to minimise the uncertainty derived from the quality of collected data, both foreground and background data was collected with the following criteria:

- Temporal correlation: collected data age should be less than 6 years old
- Geographical correlation: collected data should be suitable for countries, which waste management operations are similar to the ones locates in Germany, USA, Japan and West European countries.
- Technology correlation: collected data should be related to the evaluated waste management operation, considering the same process, technology and material.
- Reliability: collected data should be verified data with quantitative measurements
- Completeness: collected data should be from more than 50% of the sites
- Reproducibility: collected data should have a good reproducibility
- Sample size: the sample size of the collected data should be bigger than 20

2.5 SENSITIVITY ANALYSIS

The reliability of the model is validated through a sensitivity analysis. This analysis, as defined by ISO 14041, measures the extent to which changes, e.g. in the LCI results, characterisation models, variables values, etc, influence the indicator result (ISO 14042:2000). These changes or variations are assessed with the reduced cost of every decision variable. Reduced costs of any non-basic variable x_y are the amount by which the objective function coefficient of x_y must be improved before that variable will become a basic variable in some optimal solution. A basic variable is the one that appears with a coefficient of one in a single equation and a coefficient of cero in all the other equations, otherwise it is called non-

basic variable (Winston 1993, Lingo 2003, Lindo 2003a). For example, it is assumed that after solving the model results that one parameter of the set decision variable $\delta Al_{a,l}$ has a reduced cost of z units. Therefore, the objective coefficient of this decision variable would have to decrease z units in this minimisation problem for the variable to become an alternative optimal solution and in at least one of these optimal solutions $\delta Al_{a,l}$ will be a basic variable. Contrary, if this variable is decreased by more than z, then any optimal solution will have $\delta Al_{a,l}$ as a basic variable. Finally, the variable is considered optimal when its reduced cost is equal to zero.

3 METHODOLOGY

3.1 SUSTAINABLE WASTE MANAGEMENT SYSTEM

A sustainable waste management system has to be considered within the overall context of sustainable development. It needs to be based on the balance between environmental protection, economic prosperity and social cohesion. In order to achieve this target, the development of a sustainable waste management strategy must be pursued taking in consideration existing waste management strategy drivers and the integrated product policy approach. Additionally, it must consider the involvement of all related public groups (Public Participation) during every step of the decision making process as a key issue to ensure its successful implementation. As a result, the proposed sustainable waste management system must encourage the eco-efficient and sustainable use and management of resources through the entire life cycle of the product system from an economical, environmental and social point of view.

A sustainable waste management system should be designed making use of an assessment tool that is able to recognise the multidimensionality of sustainability. Unfortunately, so far there is not a single tool able to do so. Existing assessment tools such as life cycle assessment, cost-benefit analysis or multicriteria decision analysis provide separately excellent results in their area of specialisation but they are unable to integrate individually the complete sustainability spectrum. As a result, *SUWAMAS* was developed considering the multidimensionality of sustainability by providing a strategy that is not only environmental effective, economically affordable and socially acceptable, but also logistically optimised.

SUWAMAS puts considerable attention on the fulfilment of sustainable principles such as prevention, precautionary, polluter pays, proximity and self-sufficiency. These sustainable principles are achieved following the community's legislation on waste and on the integrated product policy approach. *SUWAMAS* ensures the multidimensionality of sustainability by integrating every sustainable parameter in a single decision support model. The model is based on a mathematical programming platform combined with the multicriteria decision analysis weighted product (WP). Additionally, the model is extended and coupled with the following assessment tools:

- Life Cycle Assessment for the avoidance and minimisation of impacts on health and the environment derived from the generation of fugitive emissions to air, water and land through the complete life cycle of the product system (prevention and precautionary principle),
- Cost-Benefit Analysis for the minimisation of the net social cost and the internalisation of environmental costs through the complete life cycle of the product system (polluter pays principle),
- Multicriteria Decision Analysis for the integration of social acceptability and social equity in decision making process (participatory policy making),
- Multi-commodity Flow Distribution for the optimisation of the material flow distribution that ensures an adequate waste management infrastructure by defining the required number and location of waste management operations (proximity and self-sufficiency principles).

The systematic combination of this four assessment tools ensures that the proposed strategy is not only economically affordable, environmentally effective and socially acceptable but also logistically optimised, as shown in Figure 3-1. Additionally, *SUWAMAS* ensures that the proposed strategy provides sustainable consumption and production patterns.

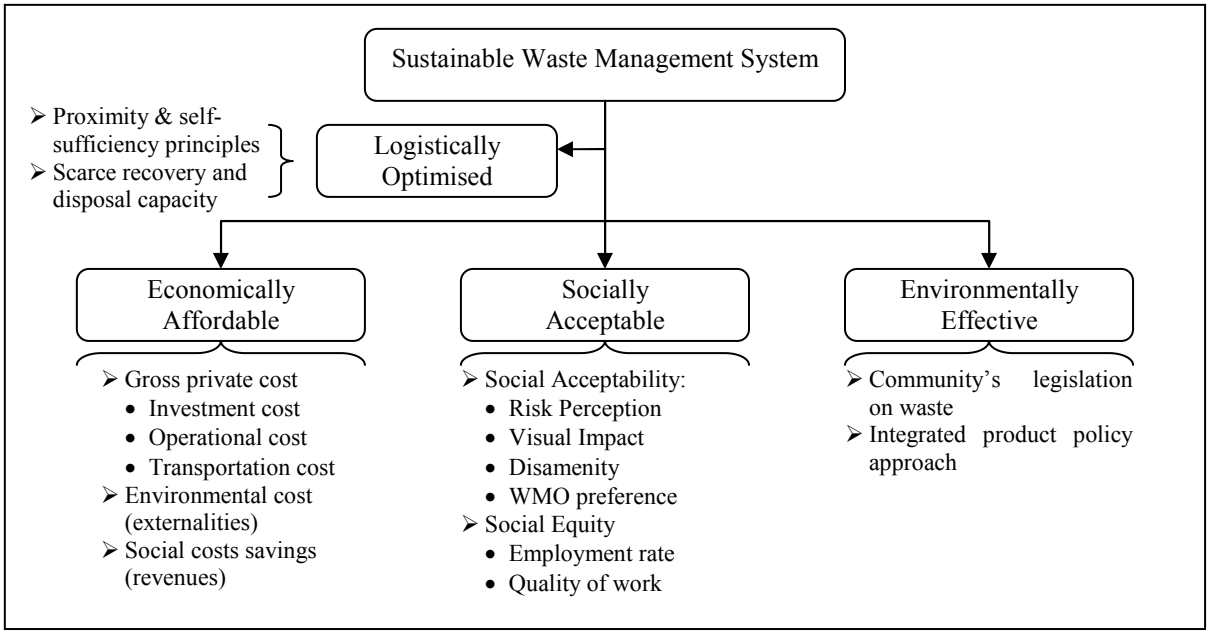


Figure 3-1 Sustainable Waste Management Requirements

Economically affordability is achieved by minimising the net social cost through the life cycle of the product system. The net social cost is the difference between the gross social cost (gross private cost + environmental cost) and the social costs saving associated from the recovery of energy and resources. The gross private costs include transportation, labour and capita costs for operation and maintenance. Environmental costs are externalities and they are assessed considering the principles of "willingness to pay" and the "willingness to accept". Therefore, environmental impacts are internalised as externalities and economically accounted from a social point of view. This economical transformation follows the impact pathway approach and they are represented by predefined life cycle impact assessments such as the EPS 2000, CAFÉ, ExternE or New ExternE. This methodology is explained in chapter 3.4.4.3 and chapter 3.4.4.4.

Social acceptability is reached through the integration of effective public participation in the decision making process of environmental matters. In Europe, public participation is requested by the ratified Aarhus Convention and by the adopted Council Directives on public participation[40] and on public access to environmental information[41]. This framework gives legal provisions on public participation not only in the permitting procedure of environmental operations but also in the development of plans and programmes under the Waste Framework Directive. The public participation framework entered on force by June 2005. As a result, in this model social acceptability is assessed considering the social acceptability and the social equity of every waste management operation. Social acceptability is represented by social preference indicators such as risk perception, visual impact, disamenity and waste management operation preference. On the other hand, social equity is represented by the number and quality of jobs offered within the product system.

Environmental effectiveness is ensured by considering the integrated product policy approach and the community's waste legislation. This approach ensures an eco-efficient solution, which minimises environmental impacts through the entire life cycle of the product system. Additionally, the environmental effectiveness of the product system is achieved through

[40] OJ L 156 of 25.06.2003, p.17
[41] OJ L 41 of 14.02.2003, p.26

sustainable production and consumption patterns by encouraging waste prevention and minimisation of primary and secondary waste. Due to its holistic approach, modelled waste management operations are not subject to the hierarchy of waste. Instead, they are all considered as viable operations without been ranked. The proposed combination of waste management operations is the one that provides the lowest burden to the environment at the lowest cost. Finally, the system is logistically optimised by ensuring that the waste is treated and disposed of as closed as possible to the place where it was generated. The flow distribution of generated primary and secondary waste within the system is restricted to its physical-chemical composition and to the scarce treatment and disposal capacity.

3.2 SUWAMAS

The model is based on a mathematical programming platform. This platform is written in a Lingo[42] environment, whose data sources are taken from an Excel file. Lingo is a modelling language and optimizer, which is used to solve linear and non-linear optimization problems (Lindo 2003a). An integer non-linear mathematical programming model defines the language structure of the solving platform. The model seeks to minimise an objective function, which is subjected to a set of constraints. These constraints are represented by mathematical relationships. The model's constraints define the economical, environmental, social and logistical parameters of the system.

The model finds the most effective sustainable strategy based on the optimisation of the objective function and the system constraints. The optimisation process is divided in three steps as shown in Figure 3-2. Firstly, it is required to define boarders of the waste management system. This is done by introducing all the required information that defines the current state of the waste management infrastructure. Subsequently, the model minimise the objective function as a function of the system constraints with help of the modelled assessment tools. Every tool solves a specific part of the model in a continual improvement sequence. As soon as the optimal solution has been found, then it is send to the excel platform.

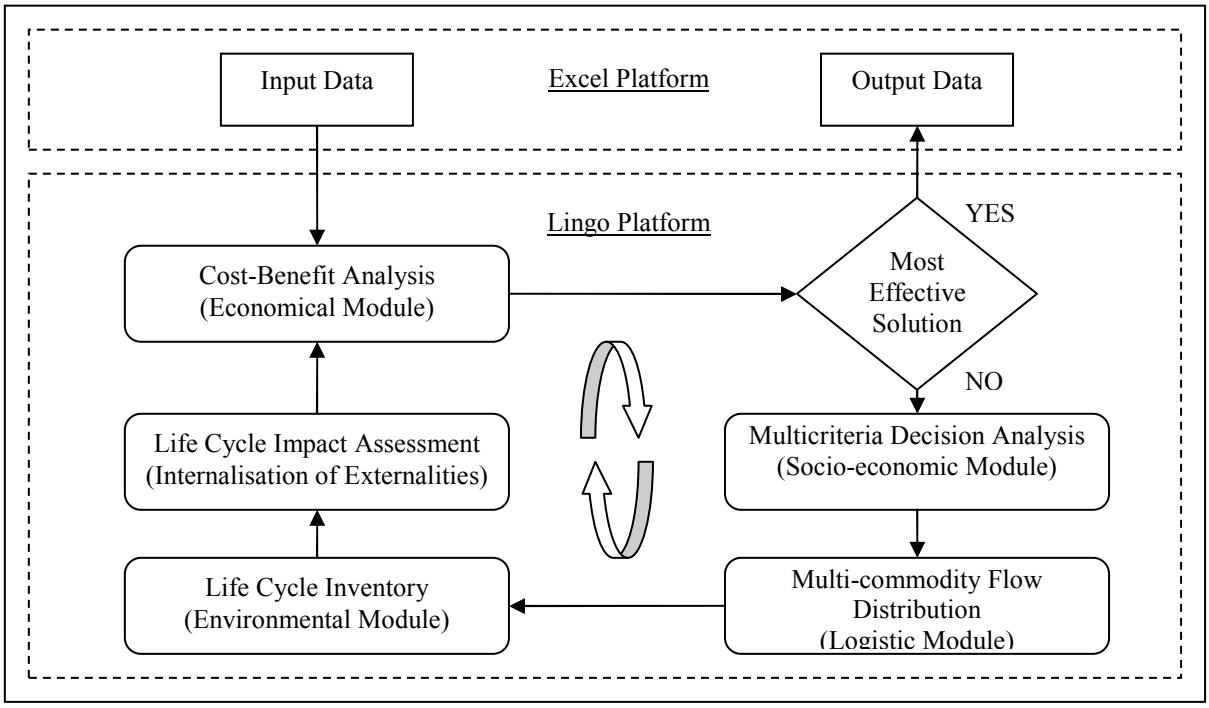


Figure 3-2 *SUWAMAS* Methodology

[42] Operational research software developed by LINDO Systems Inc.

3.2.1 Input Data

The practitioner must define the waste management infrastructure. For this reason, the practitioner is required to introduce the following parameters in the model:

- Country
- Meteorological conditions
- Waste types, source, amount and physical-chemical composition
- Distances between generation points
- Material flow restrictions
- Waste management operation types, installed capacity and location
- Waste management operations choice of technology
- Operational conditions, technical requirements and emission limit values for every waste management operation
- Installed air and water pollution control units
- Transportation costs
- Private costs
- Market prices of recovered material and energy
- Non-market prices for externalities
- Quality criteria for primary and secondary waste
- Quality criteria for recovered material
- Recycling targets
- Pubic preferences

This information is generated from background and forward sources. The practitioner needs to ensure that the input information is of good quality in order to generate reliable results with low uncertainty values.

3.2.2 Output Data

The model produces an extensive output of results. These results are represented and summarized in tables and graphics for better understand. Among the results, the practitioner can find:

- Sustainable material flow distribution of primary and secondary waste fractions
- Total and specific generation of secondary waste
- Total and specific flows of recycled material
- Total and specific flows of recovered material and energy
- Total and specific generation of fugitive emissions to air and water
- Net social cost
- Total and specific gross private cost (disposal and transportation costs)
- Total and specific environmental cost and displaced environmental costs
- Total and specific social costs savings derived from the recovered energy and material

This information is the source for the development of the sustainable waste management indicators.

3.3 OBJECTIVE FUNCTION

The objective function is aimed to minimise the net social cost of the system. It integrates environmental, economical and social issues in the decision making process. It is mathematically expressed by Equation 3-1. Therefore, this objective function is mathematically optimised in the pursuit of development that is *economically affordable, socially equitable and environmentally effective.* This equation is based on the multicriteria decision analysis named weighted product. The model minimise unsustainable production and consumption patterns within the product system based on the sustainable criteria variables

SC_{sci}. Sustainable criteria is represented by a *sci* attribute and weighted by w_{sci}. As a result, the combination of waste management operations that provides the lowest un-sustainability will be the most preferable sustainable strategy for the decision maker. The objective function is restricted by logistical, technical, economical, environmental and social constraints. These constraints are represented by the term $g_h(z)$ and $z=(z_1, z_2, \ldots, z_n)$ is an n-dimensional decision vector, which is composed of *h* real decision variables represented by the variable δ.

Equation 3-1 Objective Function and Constraints

$$\min \prod_{sci} \left(SC_{sci}{}^{w_{sci}} \right)$$

subject to :

$$g_h(z) \le 0, \quad h = 1,2,\cdots,H$$

where :

$$sci = 1...3,$$

$$SC_1 = EcC = \sum_k \left(DC_k + TC - REV_k \right)$$

$$SC_2 = EnC = \sum_k \left[EC_k + DEC_k \right]$$

$$SC_3 = SoC = \sum_k \left(MSS_k \cdot Q_k \right)$$

$$1 = \sum_{sci} w_{sci}$$

In this objective function, economical, environmental and social sustainable criteria are represented by the variables *EcC*, *EnC*, and *SoC*, respectively. Additionally, the weight factor w_{sci} is quantitatively the same for the three sustaianable criteria and with a numeric value equal to 1/3. This value ensues the numeric equilibrium between all the sustainable criteria, e.g. environmental, economical and socal ones. Subsequently, these variables assess their impact of the existing waste management operations (*k*). Economical sustainability considers the optimisation of the gross private cost, which is split into disposal costs (DC_k) and transportation costs (*TC*). Social saving costs or revenues are defined with the variable REV_k. Environmental sustainability is related to the product system externalities. Externalities include environmental costs (EC_k) and displaced environmental costs (DEC_k), which represent the willingness to pay by the society in order to preserve the current state of the environment. Finally, social sustainability is enhanced with the benefit of participatory policymaking. This variable considers public preferences for existing waste management operations.

3.4 PRODUCT SYSTEM CONSTRAINTS

As a difference from other models, *SUWAMAS* does not request the user to define the material flows of the system. Contrary, *SUWAMAS* finds the optimal distribution flow of primary and secondary waste, respecting in every time the system's objectives and constraints. These constraints are restricted to logistic, social, environmental and economical constraints.

3.4.1 Logistic Constraints

Logistic constraints are defined to provide the optimal eco-efficient material flow distribution of primary and secondary wastes within the system. Logistic constraints follow the multi-commodity flow distribution approach. Therefore, the primary waste category *i* generated at the source point *j* is transported from its respective source to its sinks through a defined waste management network. The primary waste will compete for the scarce treatment or disposal capacity of the waste management operation *k*. The waste management network is defined by the system boundaries of the waste management system (Figure 2-1), which now is shown in

Figure 3-3 as a network. For presentation reasons, Figure 3-3 shows exclusively the links between the first and last nodes of generation points, primary waste, waste management operations and secondary waste.

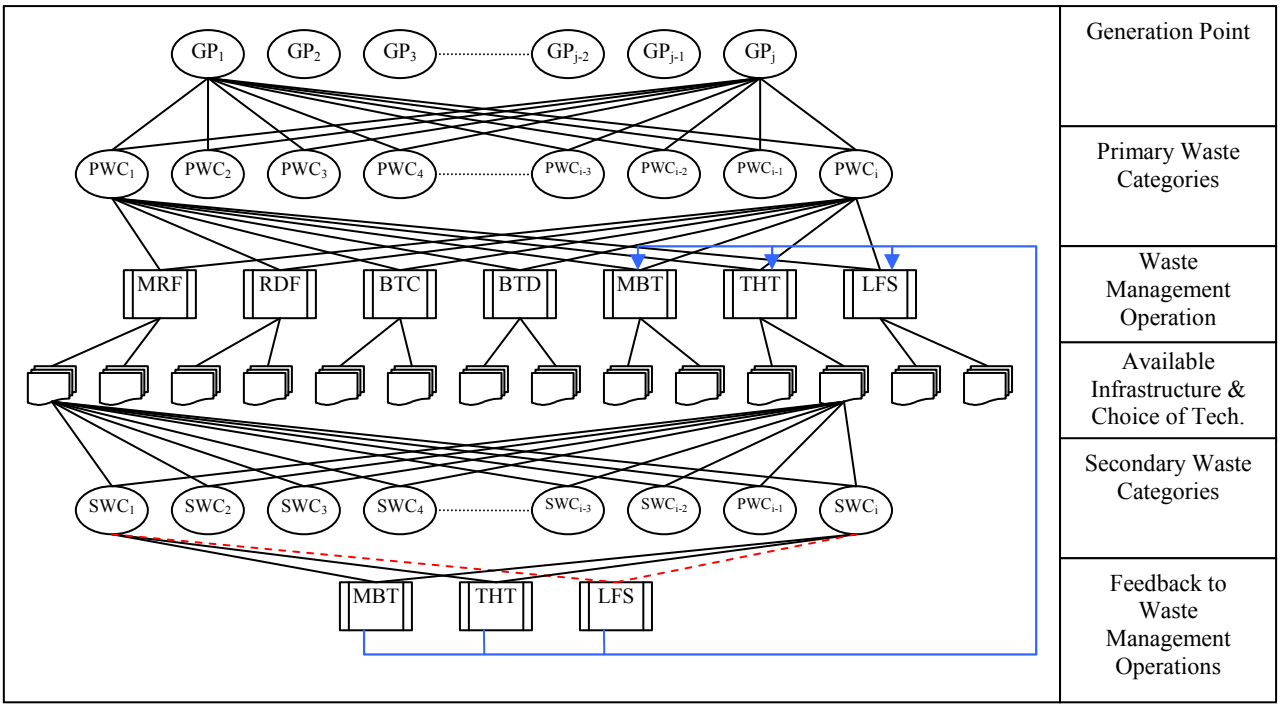


Figure 3-3 Logistical representation of the waste management network

Logistical constraints considered by *SUWAMAS* are material flow restrictions, minimisation of transport distances, material balance and waste management operation treatment/disposal capacity.

3.4.1.1 Material flow restrictions

Material flows within the product system are restricted to the waste management legislation, the choice of technology of the waste management operations and to the physical-chemical composition of the waste category fraction. This logistical restriction is represented by the matrix $MFRX_{k(x),I}$. The criteria followed in these restrictions are *inter alia*:

- Only pre-treated waste can be disposed in a landfill
- Only source-segregated recyclable fractions area suitable for recovery in "clean" material recycling facilities
- Glass, metals and WEEE fractions are accepted only in material recycling facilities
- Only source-segregated biodegradable fractions are suitable for material recovery in biological treatment operations
- "Dirty" material recycling facilities, mechanical-biological treatment and incineration plants are suitable to accept almost all waste fractions categories.

The material-flow-restriction matrix provides default restrictions, which could be modified by the practitioner at any time. Once defined the material flow restrictions of the system, the model defines the waste flow distribution among existing waste management operations that generates the lowest environmental and economical impact to the system.

3.4.1.2 Shortest route (proximity principle)

Generated waste fractions should be treated or disposed of as closely as possible to where they are produced in order to minimise transport of waste. This constrain is achieved by minimising the transportation cost between existing nodes and thus finding the shortest routes between two points as shown in Figure 3-4. This constrain is related exclusively to the transportation distance between generation and disposal points. Therefore, it is required that the practitioner introduce the distance between every source of generation.

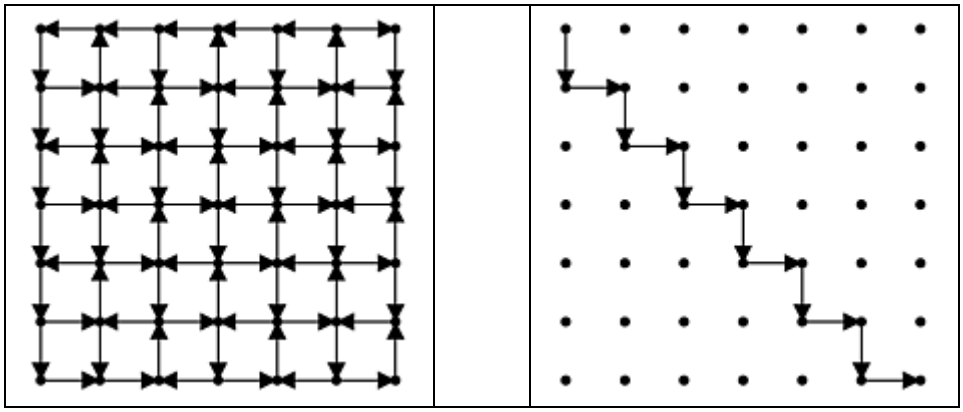


Figure 3-4 Definition of the shortest route

3.4.1.3 Mass balance

The general flow distribution of generated primary waste to the waste management operation is calculated with Equation 3-2. This equation is restricted to the type of waste that is acceptable in every waste management operation $MFRX_{k(x),i}$ and to the decision variable $\delta JXI_{j,k(x),i}$.

Equation 3-2 General primary waste flow distribution from generation point (GP_j) to waste management operation ($WMO_{k(x)}$)

$$QJXI_{j,k(x),i} = QIJ_{i,j} \cdot MFRX_{k(x),i} \cdot \delta JXI_{j,k(x),i}$$

subject to :

$$0 < \delta JXI_{j,k(x),i} < 1$$

Subsequently, the system is balanced with Equation 3-3. This equation secures that the total amount of primary waste generated within the system is the same as the one accepted by existing waste management operations.

Equation 3-3 General primary waste balance from generation point

$$Input = Output$$

$$Input = \sum_{j} QIJ_{i,j} = \sum_{k}\sum_{x}\sum_{j} QJXI_{j,k(x),i}$$

$$Output = \sum_{k} QIK_{i,k} = \sum_{k}\sum_{x}\sum_{j} QJXI_{j,k(x),i}$$

$$\therefore$$

$$\sum_{j} QIJ_{i,j} = \sum_{k} QIK_{i,k}$$

SUWAMAS calculates the inputs of primary waste to every waste management operation as waste category indicators (w) with Equation 3-4. This allows the model to assess the generated primary and secondary waste in one single matrix.

Equation 3-4 General waste category indicator input from generation point

$$QJXW_{k(x),w} = \sum_{i}\sum_{j} QJXI_{j,k(x),i} \cdot MWI_{w,i}$$

The terms *X* and *x* used in Equation 3-2, Equation 3-3 and Equation 3-4 are substituted by the specific waste management operation index (*s, c, a, d, m, t, l*). This allows the model to calculate the specific material input flow of every waste management operation. For example, the material flow of primary waste entering to the Material Recycling Facility units (MRF_s) is calculated with Equation 3-5, balanced with Equation 3-6 and converted to waste category indicators with Equation 3-7. The same procedure applies to the calculation of material flows for the other waste management operations. Due to the similarly of the formulas they are not further written.

Equation 3-5 Primary waste flow distribution from generation point (GP_j) to a Material Recycling Facility (MRF_s)

$$QJSI_{j,s,i} = QIJ_{i,j} \cdot MFRS_{s,i} \cdot \delta JSI_{j,s,i}$$

where:

$$0 < \delta JSI_{j,s,i} < 1$$

Equation 3-6 Primary waste balance at the Material Recycling Facility (MRF_s) from generation point

$$QIK_{i,1} = \sum_{s}\sum_{j} QJSI_{j,s,i}$$

Equation 3-7 Waste category indicator input at the Material Recycling Facility (MRF_s) from generation point

$$QJSW_{s,w} = \sum_{i}\sum_{j} QJSI_{j,s,i} \cdot MWI_{w,i}$$

Subsequently, the treatment of primary waste at the waste management operation *k* generates secondary waste, which requires further treatment or disposal. According to current European waste management strategic drivers, if the secondary waste fulfils quality criteria for landfilling[43] then it will compete for scarce disposal capacity at the landfill (LFS_l), otherwise it will require further treatment and compete for a scarce treatment capacity either in mechanical-biological treatment (MBT_m) or in thermal treatment (THT_t) units. The flow distribution of secondary waste categories between waste management operations is defined with the decision variable $\delta XY_{x,y}$. Similarly, to the decision variable for primary waste flow distribution ($\delta JXI_{j,k(x),i}$), the term *y* represents the type of waste management operation which is allowed to treat secondary waste. Therefore, the term *y* can be substituted with the waste management operation index (*m, t, l*) and defined by the decision variables: $\delta SM_{s,m}$ $\delta ST_{s,t}$ $\delta SL_{s,l}$ $\delta CM_{c,m}$ $\delta CT_{c,t}$ $\delta CL_{c,l}$ $\delta AM_{a,m}$ $\delta AT_{a,t}$ $\delta AL_{a,l}$ $\delta DM_{d,m}$ $\delta DT_{d,t}$ $\delta DL_{d,l}$ $\delta MT_{m,t}$ $\delta ML_{m,l}$ *and* $\delta TL_{t,l}$.. Specific secondary wastes generated in every waste management operation are previously calculated as a function of the primary waste composition, the waste management choice of technology following waste-specific models.

Finally, multi-commodity decision variables for secondary wastes are balanced to ensure the equilibrium of the system as shown in the set Equation 3-8.

[43] EU waste acceptance criteria at landfills are defined by the Council Decision 2003/33/EC. This constrain is further considered in section 3.4.3.5 of this report.

Equation 3-8 Balance of decision variables for secondary waste

Decision variable balance equation

MRFs
$$\sum_m \delta SM_{s,m} + \sum_t \delta ST_{s,t} + \sum_l \delta SL_{s,l} = 1$$

RDF_c
$$\sum_m \delta CM_{c,m} + \sum_t \delta CT_{c,t} + \sum_l \delta CL_{c,l} = 1$$

BTC_a
$$\sum_m \delta AM_{a,m} + \sum_t \delta AT_{a,t} + \sum_l \delta AL_{a,l} = 1$$

BTD_d
$$\sum_m \delta DM_{d,m} + \sum_t \delta DT_{d,t} + \sum_l \delta DL_{d,l} = 1$$

MBT_m
$$\sum_t \delta MT_{m,t} + \sum_l \delta ML_{m,l} = 1$$

THT_t
$$\sum_l \delta TL_{t,l} = 1$$

3.4.1.4 Waste management operation treatment/ disposal capacity

The total input of primary and secondary waste to a waste management operation ($QXW_{k(x),w}$) will be restricted to the maximum treatment or disposal capacity of the operation unit ($PCX_{k(x)}$). This mathematical relationship is given by Equation 3-9, which right parameter of the equation is separately calculated with the set Equation 3-10 for every waste management operation. Similarly, the terms *X* and *k(x)* used in these equations are substituted by the specific waste management operation index (*s, c, a, d, m, t, l*), as required. From the set Equation 3-10 it can be observed that waste management operations named MRF_s, RDF_c, BTD_a and BTD_d accept only primary waste as input flow, while MBT_m, THT_t and LFS_l accept both primary and secondary waste.

Equation 3-9 Treatment capacity constraints

General for waste management operations
$$PCX_{k(x)} > \sum_w QXW_{k(x),w}$$

Substitution example for MRF_s:
$$PCS_s > \sum_w QSW_{s,w}$$

Equation 3-10 Waste category (*w*) input to the waste management operation *k(x)*

Waste Management Operation — Substitution of k(x) term

MRF_s
$$QSW_{s,w} = \sum_j QJSW_{j,s,w}$$

RDFc
$$QCW_{c,w} = \sum_j QJCW_{j,c,w}$$

BTC_a
$$QAW_{a,w} = \sum_j QJAW_{j,a,w}$$

BTD_d
$$QDW_{d,w} = \sum_j QJDW_{j,d,w}$$

MBT_m
$$QMW_{m,w} = \begin{cases} \sum_j QJMW_{j,m,w} + \sum_s QSMW_{s,m,w} + \sum_c QCMW_{c,m,w} + \sum_a QAMW_{a,m,w} \\ + \sum_d QDMW_{d,m,w} \end{cases}$$

THT_t
$$QTW_{t,w} = \begin{cases} \sum_j QJTW_{j,t,w} + \sum_s QSTW_{s,t,w} + \sum_c QCTW_{c,t,w} + \sum_a QATW_{a,t,w} \\ + \sum_d QDTW_{d,t,w} + \sum_m QMTW_{m,t,w} \end{cases}$$

LFS_l

$$QLW_{l,w} = \begin{cases} \sum_j QJLW_{j,l,w} + \sum_s QSLW_{s,l,w} + \sum_c QCLW_{c,l,w} + \sum_a QALW_{a,l,w} \\ + \sum_d QDLW_{d,l,w} + \sum_m QMLW_{m,l,w} + \sum_t QTLW_{t,l,w} \end{cases}$$

3.4.2 Social Constraints

Social constraints are designed to ensure that the proposed sustainable strategy is as well socially acceptable. Thus, social acceptability is reached considering the benefit of public participation in environmental decision-making. This is done in the fulfilment of exiting international agreements (Aarhus Convention) and European legislation (Directives 2003/4/EC on public access to environmental information, Directive 2003/35/EC on public participation and commission proposal COM(2003) 624 on access to justice).

SUWAMAS assesses social constraints considering the social acceptability and the social equity of every waste management operation within the product system. However, social constraints are based on public preferences, which depend on the nature of the waste management operations and on the knowledge the public own over them. Public preferences are a combination of quantitative and qualitative ones. In the one hand, quantitative preferences are easy to quantify and they are based on precise knowledge. On the other hand, qualitative preferences are not based on precise knowledge. Therefore, this knowledge is heterogeneous, uncertain and subjective.

In this model, public preferences or social indicators are represented as linguistic values by means of linguistic variables, which are easily represented with fuzzy numbers. Subsequently, these fuzzy numbers are transformed into crisp values through a fuzzy-to-crisp conversion. Crisp values are then quantitative assessed with the multicriteria decision analysis (MCDA) named fuzzy weighted sum (FWS). This method is selected due its capacity to qualify phenomena related to human perception. This assessment tool is a single synthesising criterion methodology and it is based on the α-cut technique. The α level sets are used to derive fuzzy utilities based on the simple additive weighted method (Guitouni 1998).

3.4.2.1 Linguistic variables

Linguistic variables (Bothe 1995) are characterized by a quintuple (*v, L, X, g, m*). They have a specific name (*v*) and they are expressed by a set of linguistic terms (*L*). Linguistic terms are generated with a syntactic rule or grammar *(g)*, limited by a defined range over a universal set *X* and represented by a fuzzy set membership functions. Every membership function of a fuzzy set A is denoted by μ_A or simply A. Mathematically it is defined on the set $\Re$ of real numbers [0,1] and expressed as: $\mu_A : \Re \longrightarrow [0,1]$ *or* $A : \Re \longrightarrow [0,1]$. The number of linguistic terms will depend on the conversion scale. A semantic rule *(m)* assigns the meaning of every linguistic term *l*, which is a fuzzy set on *X* (*m:l* $\rightarrow$ *f*(X)). For example, the social acceptability indicator "Risk Perception" is represented by a linguistic variable as shown in Figure 3-5. This linguistic variable expresses the social perception for a specific alternative. In this case, the linguistic variable is restricted to a two conversion scale and thus to three linguistic terms named low, medium and high. Every linguistic term is defined by a fuzzy membership function with help of a semantic rule and defined as well on the interval [0,1]. The fuzzy membership functions are limited by a fuzzy restriction [0,1].

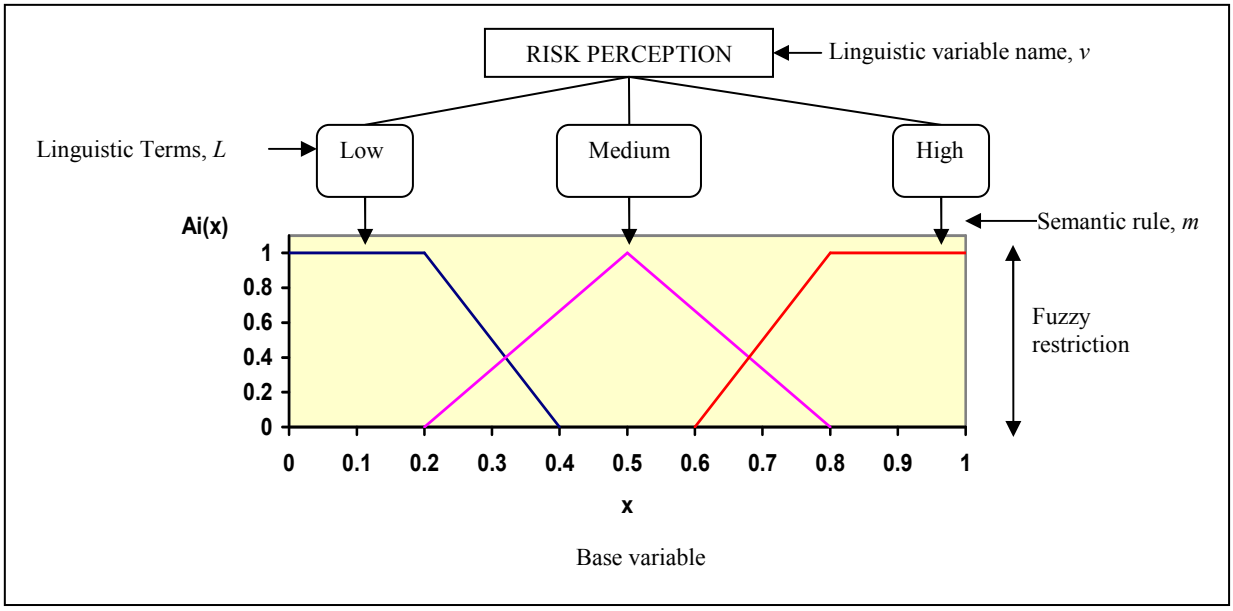
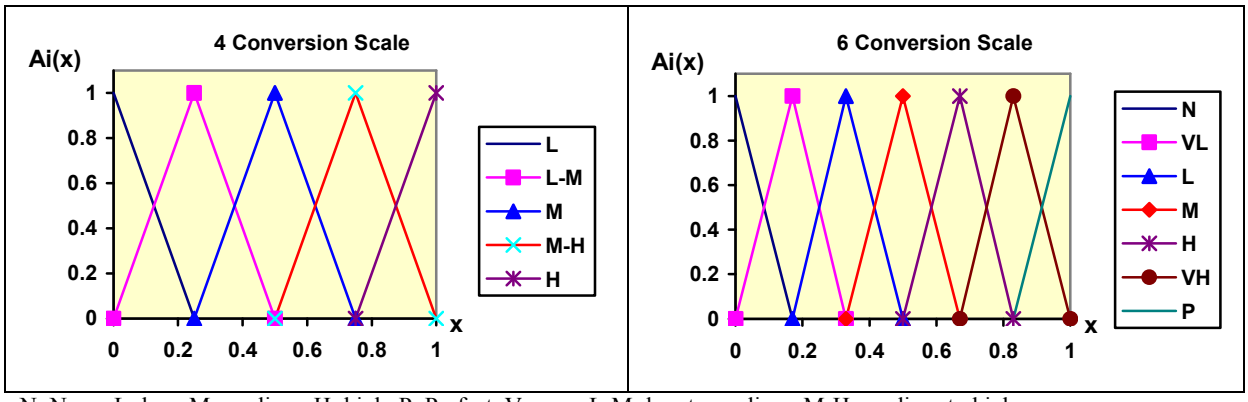


Figure 3-5 Characterisation of linguistic variables

The selection of the conversion scale depends on the number of linguistic terms required to assess the linguistic variable. The higher the linguistic term involved the higher the conversion scale. From Figure 3-6 it can be observed that every linguistic term has a particular fuzzy set value and it differs from scale to scale. For example, the linguistic term "low" in the 4-conversion scale has a total membership score of 0.1, while the same linguistic term in the 6-conversion scale is of 0.3571429. This difference is attributed to the difference of meanings and ranges given to the linguistic term in every conversion scale.



N: None, L: low, M: medium, H: high, P: Perfect, V: very, L-M: low to medium, M-H: medium to high.

Figure 3-6 Typical conversion scale for linguistic variables

3.4.2.2 Fuzzy-to-crisp conversion

The fuzzy-to-crisp conversion is based on the Hwang's mean L-R scoring method (Cheng 2003). In this model is taken the six-conversion scale for the assessment of the social indicators represented as linguistic values by means of linguistic variables. Therefore, every linguistic variable will consist of seven linguistic terms or fuzzy membership functions *A(x)* as shown in Figure 3-7. The set of linguistic terms is a function of the linguistic variable and it is given as follows: $A=\{A_1$=none, A_2=very low, A_3=low, A_4=medium, A_5=high, A_6=very high, A_7=perfect$\}$. For fuzzy-to-crisp conversion purposes, it is required to include as well a maximisation operator (*Amax*) and a minimisation operator (*Amin*), which will allow to determinate the mean value of every membership function.

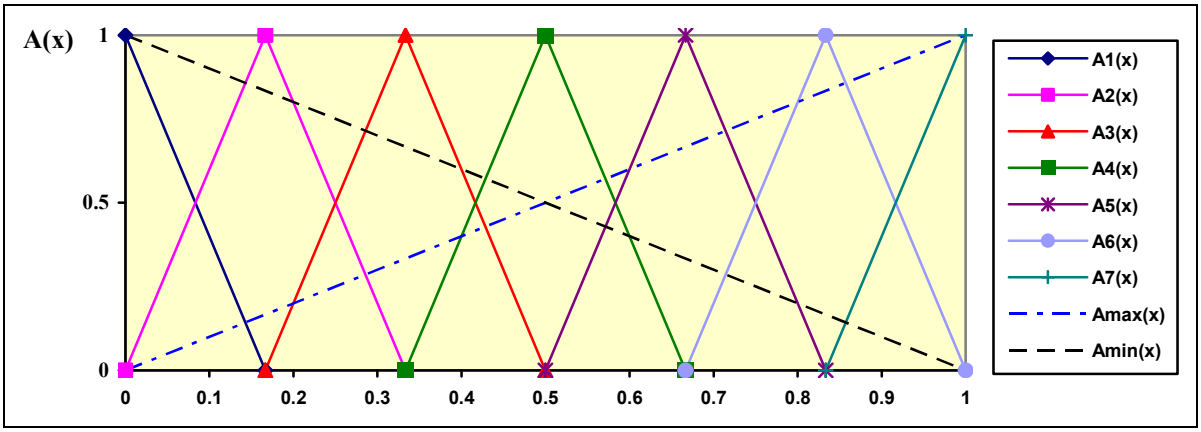


Figure 3-7 Six conversion scale

Every linguistic term *l* is defined by a fuzzy membership function as shown in Equation 3-11. In this equation, it is assumed a base variable range between zero and one. As well it can be seen that it is restricted to an *n* conversion scale, where *n* is equal to six.

Equation 3-11 Membership functions

A_1: N(0,0,1/6)

$$\underset{l=1}{A_l(x)} = \begin{cases} 1 & for\ \ x = 0 \\ n\left(1/n - x\right) & for\ \ (l-1)/n < x < l/n \\ 0, & otherwise \end{cases}$$

A_2: VL(0,1/6,1/3)
A_3: L(1/6,1/3,1/2)
A_4: M(1/3,1/2,2/3)
A_5: H(1/2,2/3,5/6)
A_6: VH(2/3,5/6,1)

$$\underset{l\neq 1,L}{A_l(x)} = \begin{cases} n\left(x - (l-2)/n\right) & for\ \ (l-2)/n < x \le (l-1)/n \\ n\left(1/n - x\right) & for\ \ (l-1)/n < x < l/n \\ 0, & otherwise \end{cases}$$

A_7: P(5/6,1,1)

$$\underset{l=L}{A_l(x)} = \begin{cases} n\left(x - (l-2)/n\right) & for\ \ (l-2)/n < x \le (l-1)/n \\ 1 & for\ \ x = 1 \\ 0, & otherwise \end{cases}$$

Similarly, the maximisation and minimisation membership functions are defined by Equation 3-12.

Equation 3-12 Maximisation and minimisation membership functions

Amax

$$A_{\max}(x) = \begin{cases} x & for\ \ 0 \le x \le 1 \\ 0 & otherwise \end{cases}$$

Amin

$$A_{\min}(x) = \begin{cases} 1-x & for\ 0 \le x \le 1 \\ 0 & otherwise \end{cases}$$

Subsequently, the left and right scores of every membership function are calculated. The left score of every membership function is the intersection between it and the minimising membership function as shown in Equation 3-13. Similarly, the right score of every membership function is the intersection between it and the maximising membership function as shown in Equation 3-14.

Equation 3-13 Left score membership function

$$A_{l,L} = \sup_x \left[A_l(x) \wedge A_{\min(}x)\right]$$

Equation 3-14 Right score membership function

$$A_{l,R} = \sup_x \left[A_l(x) \wedge A_{\max(}x)\right]$$

Finally, the mean score of every membership function is calculated as a function of the left and right scores as shown in Equation 3-15.

Equation 3-15 Mean score membership function

$$A_{l,T} = \frac{\left[A_{l,R} + 1 - A_{l,L}\right]}{2}$$

The calculated left, right and mean scores of every membership function are shown in Table 3-1. These scores represent the fuzzy-to-crisp conversion values for a 6-conversion scale function.

Table 3-1 Mean score for membership functions values following the 6 conversion approach

Membership Function, i	$A_{i,L}$	$A_{i,R}$	$A_{i,T}$
1	1.000000	0.1428571	0.7142857E-01
2	0.8571429	0.2857143	0.2142857
3	0.7142857	0.4285714	0.3571429
4	0.5714286	0.5714286	0.5000000
5	0.4285714	0.7142857	0.6428571
6	0.2857143	0.8571429	0.7857143
7	0.1428571	1.000000	0.9285714

3.4.2.3 Fuzzy weighted sum

Social indicators are evaluated in a social impact matrix as shown in Figure 3-8. This matrix incorporates the point of view of the public for a specific waste management operation. This public preference is the crisp value obtained from the fuzzy-to-crisp conversion and is represented by the impact value $a_{SI,k}$, where SI is the social indicator and k the type of waste management operation.

k		MTS	RDF	BTC	BTD	MBT	THT	LFS
SI_1	w_1	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}
SI_2	w_2	$\ddots$			$\ddots$			
$\vdots$	$\vdots$		$\ddots$			$\ddots$		
SIS_{I-1}	w_{SI-1}			$\ddots$			$\ddots$	$\vdots$
SI_{SI}	w_{SI}	a_{SI1}	a_{SI2}	a_{SI3}	a_{SI4}	a_{SI5}	a_{SI6}	a_{SI7}
MSS_k		MSS_1	MSS_2	MSS_3	MSS_4	MSS_5	MSS_6	MM_7

Figure 3-8 Social impact matrix

For every waste management operation is provided a utility value MSS_k, which is calculated by the addition of the product between the impact score $a_{SI,k}$ and its importance weight w_{SI}. Mathematically, this relation is represented by Equation 3-16. In this model the weight of the social indicators are the ones given in Table 3-2. These values are calculated considering that both social acceptability and social equity have the same importance to the society. Therefore, their weight is the same and equal to 0.5. Smilarly, the weight value of considered social subindicators are the relation between the main social indicator value and the number of subindicator, which belong to assessed social indicator. However, the flexibility of the model allows the practitioner to introduce its own weights for every social indicator.

Equation 3-16 Fuzzy weighted sum

$$MSS_k = \sum_{SI} w_{SI} \cdot a_{SI,k}$$

The waste management operation with the lowest utility value is the most preferable alternative by the public. This preference is taken in consideration in the decision-making process as required by the Aarhus Convention Art 6(8) and incorporated in Equation 3-1.

Table 3-2 Social indicator weights, w_{SI}

Social Indicator	w_{SI}	**Social Indicator**	w_{SI}
Social Acceptability	0.5	Social Equity	0.5
Risk perception	0.125	Job characteristics	0.25
Visual impact	0.125	Job Satisfaction	0.035714
Local disamenity	0.125	Remuneration	0.035714
Stakeholder preference	0.125	Non-pay rewards	0.035714
		Working time	0.035714
		Skills and training	0.035714
		Job content	0.035714
		Match between jobs characteristics and worker characteristics	0.035714
		Work and wider labour market context	0.25
		Gender equality	0.035714
		Health and safety	0.035714
		Flexibility and security	0.035714
		Access to jobs	0.035714
		Work-life balance	0.035714
		Diversity and non-discrimination	0.035714
		Social dialogue and worker involvement	0.035714

3.4.3 Environmental Constraints

Environmental constraints are designed to ensure that the proposed sustainable strategy is as well environmentally effective. Thus, they ensure an eco-efficient solution that promotes effective protection to the environment and to human health by minimising the overall environmental impacts of existing waste management operations at the lowest cost, through the entire life cycle of the product system. Additionally, the model ensures sustainable production and consumption patterns through the prevention and minimisation of primary and secondary waste. Environmental constraints follow current European waste management strategic drivers, which are shown in Figure 3-9.

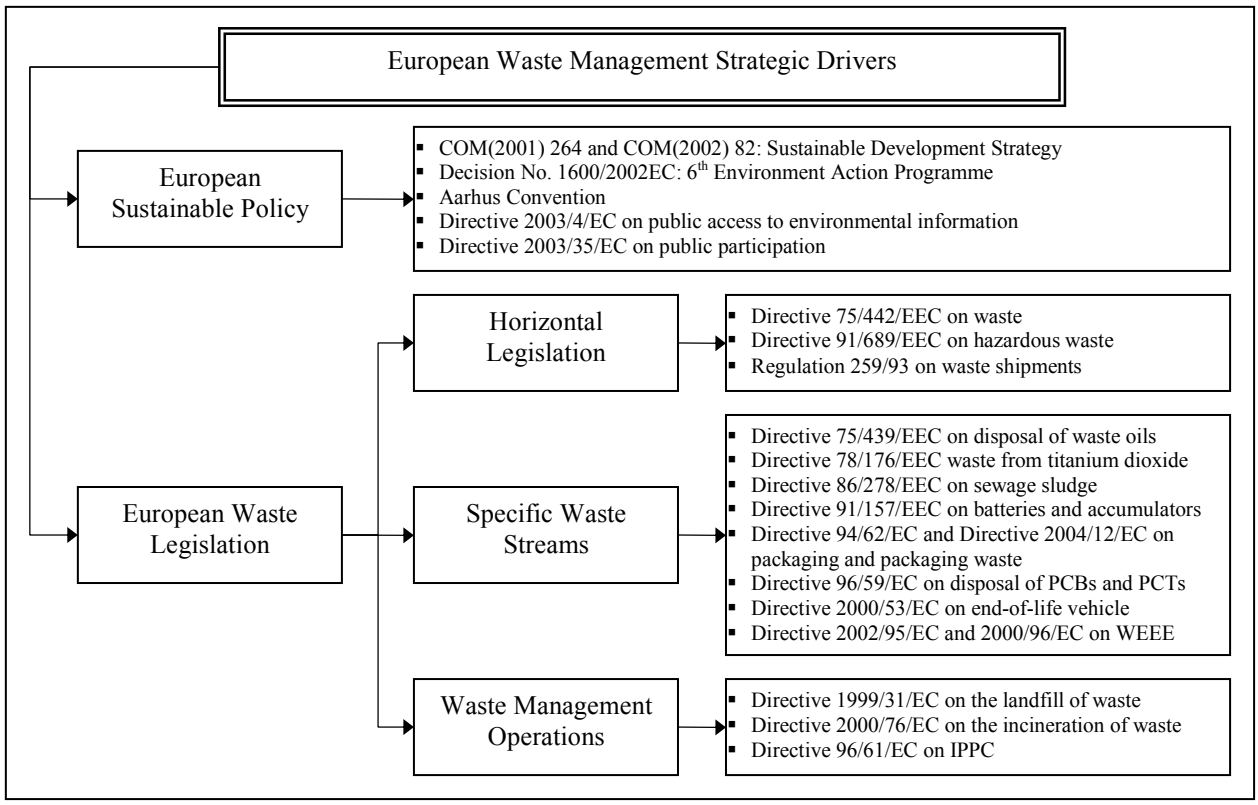


Figure 3-9 European Waste Management Strategic Drivers

3.4.3.1 Allocation of fugitive emissions

Fugitive emissions are accounted and allocated to the year in which they occur.

The model do not analyse the impact of the use of recovered compost-like products for land applications. Therefore, fugitive emissions generated during land applications are neither accounted nor allocated.

3.4.3.2 Choice of technology

Existing waste management operations are assessed considering their type and choice of technology. The life cycle inventory of every waste management operation is calculated through transfer functions and transfer coefficients based on the emission modelling product approach. This means that elementary and intermediate material flows are calculated as a function of the composition of the waste category input, the choice of technology of the waste management operation and the fulfilment of operational conditions and technical requirements imposed by the European framework on waste management operations.

3.4.3.3 Recovery and recycling targets

The European framework on specific waste streams gives provisions for the minimisation, recovery and recycling of waste as key issues to achieve sustainable production and consumption patterns. For the clearest understanding, recycling is defined in Art 3(7) of Directive 94/62/EC on packaging and packaging waste and on Art 3(e) of Directive 2002/96/EC on WEEE as "*the reprocessing in a production process of the waste materials for the original purpose or for other purposes…but excluding energy recovery.*.". On the other hand, recovery is carried out in any applicable operation provided for in Annex IIB to Directive 75/442/ECC. In other words, it is the sum of recycling and energy recovery (COM(2001) 729 final).

Following the scope of this model, only the specific waste streams named "packaging waste" and "waste electrical and electronic equipment, WEEE" are considered for further recovery and recycling options. Therefore, the proposed sustainable strategy ensures that the recovery and recycling rates given in Art 7.2 of the Directive 2000/96/EC on WEEE and on Art 6.1 of the Directive 2004/12/EC on packaging and packaging waste are respected. Recovery and recycling targets for WEEE and packaging waste are shown in Table 3-3 and Table 3-4, respectively. Opposed to the hierarchy of waste, Art 6.3 of Directive 2004/12/EC gives provisions for the encouragement of energy recovery over material recycling due to its higher environmental and cost-benefit viability following the integrated product policy approach. Finally, in accordance with these two directives, recovery and recycling targets of WEEE must be met by 31 December 2006, and for packaging waste by 31 December 2008.

Table 3-3 Recovery and recycling targets for WEEE, Directive 2002/96/EC

Categories of electrical and electronic equipment covered in ANNEX IA to Directive 2002/96/EC	Recovery	Recycling
Large house appliances (1), Automatic dispensers (10)	Min. 80%	Min. 75%
IT and telecommunications equipment(3), Consumer equipment (4)	Min. 75%	Min. 65%
Small house appliances (2), Lighting equipment (5), Electrical and electronic tools (6), Toys, leisure and sport equipment (7), Monitoring and controlling instruments (9)	Min. 70%	Min.50%
Gas discharge lamps		Min. 80%

Table 3-4 Recovery and recycling targets for packaging waste, Directive 2004/12/EC Art 6.1

	Recovery	Recycling	Glass (GL)	Paper and board (PAP)	Metals (FE/ALU)	Plastics	Wood (FOR)
Jun. 2001	50% - 65%	25% – 45%	15%	15%	15%	15%	
Dec. 2008	55% – 80%	Min. 60%	60%	60%	50%	22.5%	15%

GL, PAP, FE/ALU and FOR are the official abbreviations for packaging material as stated in the Commission Decision (97/129/EC) of 28 January 1997 establishing the identification system for packaging material pursuant to European Parliament and Council Directive 94/62/EC on packaging and packaging waste.

3.4.3.4 Waste management operations fugitive emissions limit values

In order to prevent or to limit as far as possible the environmental impacts existing waste management operations, the model restricts them to the emission limit values given by the European framework on waste management operations. Waste incineration plants are regulated by the Directive 2000/76/EC, while other waste management operations (mechanical and biological treatment) are covered by IPPC Directive. On the one hand, Directive 2000/76/EC gives statutory provisions. On the other hand, the IPPC Directive grants permit to work only if they operate based on the Best Available Technologies (BAT) concept through the non-biding (BAT) Reference document (BREF) code WT[44]. Therefore, the model restricts the amount of generated fugitive emissions to the ones establish in this framework and shown in Table 3-5.

[44] JRC-IPTS (2005). Reference Document on Best Available Techniques for the Waste Treatments Industries, August 2005

Table 3-5 Waste management operations fugitive emissions limits values

FEA		RDF	BTA	BTD	BTC / BTD	MBT	THT
		IPCC	IPPC	IPPC	BW D	30th BImSchV	200/76/EC
		g/Gg	g/Gg	g/Gg	mg/m^3		mg/m^3
Carbon dioxide	CO_2	81E3 -98E3	98 - 563	2E5 - 5.2E5			
Methane	CH_4	411	411 - 2000				
Nitrous oxide	N_2O		11 - 110	0		100 g/Mg	n/a
Hydrofluorocarbons	HFCs						
Perfluorocarbons	PFCs			(0.4-4)E-08			
Sulphur hexafluoride	SF_6						
Sulphur dioxide	SO_2	25-85		2.5-30	500		50
Nitrogen dioxide	NO_2	70-215	100	10-72.3	500		200
Ammonia	NH_3	0	5 - 3700				n/a
Hydrogen chloride	HCl			0.011	30		10
Hydrogen sulphide	H_2S			0.033	5		
NMVOC	NMVOC	8-36	0.7 - 600	0.0023			10
Dioxins & Furans	PCDD/F		0.1 ng/m^3			0.1 ng/m^3	0.1 ng/m^3
PAH	PAH						
Carbon monoxide	CO	40-725		72.3	650		50
Particulates, < 2.5 µm	PM2.5				Σ=50		10
Particulates,	PM						
Particulates, >10 µm	PM10	0-5	163 - 186				
Cadmium	Cd	1.15E-03		9.4E-07			Σ = 0.05
Thallium	Tl	1.15E-03					
Mercury	Hg	1.70E-02		6.9E-7			0.05
Antimony	Sb						Σ = 0.5
Arsenic	As						
Lead	Pb			8.5E-7			
Chromium	Cr			1.1E-07			
Cobalt	Co						
Copper	Cu						
Manganese	Mn						
Nickel	Ni						
Vanadium	V						
FEW							
Biological oxygen demand	BOD	21					
Chemical oxygen demand	COD	40-530					
Nitrogen Total	N-tot	230					
Phosphorous Total	P-tot						
Mercury	Hg						0.03 mg/l

RDF : EU (IPPC Directive, BREF code WT, Adapted from Table 3.131 & Table 3.132 page 244)
BTA: EU (IPPC Directive, BREF code WT, Table 3.21 page 151)
BTD: EU (IPPC Directive, BREF code WT, Table 3.18 page 147)
MBT: DE (30th BImSchV)
THT: EU (Directive 2000/76/EC on Incineration of waste); (IPPC Directive, BREF code WI, Table 3.8 Page 156)

3.4.3.5 Waste acceptance criteria at landfills

Art 6(a) of Directive 1999/31/EC on the landfill of waste establishes that only waste that has been subjected to treatment can be landfilled. Moreover, the acceptability of waste at landfills is restricted to the waste acceptance criteria of the relevant landfill class as set out in section of the Annex to Council Decision 2003/33/EC[45]. The European and German waste acceptance criteria at landfills is shown in Table 3-6. It is interesting to observe that the German acceptance criteria allows a higher organic content (18%) from waste that is subjected to prior treatment in a MBT unit than the one required by the European acceptance criteria (5%). Therefore, the EU acceptance criteria jeopardise the objective of MBT units in Germany. Other criteria values are as expected below the European ones.

[45] Council Decision 2003/33/EC of the 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC. OJ L 11, 16.01.2003.

Table 3-6 Quality criteria for the disposal of secondary waste

			Council Decision 2003/33/EC		AbfAbIV		
		Dry matter	Inert Waste	Non-Hazardous Waste	MSWI → LCI	MSWI → LCII	MBT → LCII
I. Organic component of dry residue in original substance determined as							
Loss on ignition	LOI	%w			≤ 3	≤ 5	-
Total organic carbon	TOC	%w	≤ 0.03	≤ 5	≤ 1	≤ 3	≤ 18
Higher Heating Value	Ho	kJ/kg					≤ 6.000
II. Biological degradability of dry substances							
Respiration activity	AT_4	mgO_2/g					≤ 5
Gas formation rate	GB_2	l /kg					≤ 20
III. Eluate Criteria							
Water soluble content	H_2O	%w			≤ 3	≤ 6	≤ 6
Cadmium	Cd	mg/l	≤ 0.02	≤ 0.3	≤ 0.05	≤ 0.1	≤ 0.1
Thallium	Tl	mg/l					
Mercury	Hg	mg/l	≤ 0.002	≤ 0.03	≤ 0.005	≤ 0.02	≤ 0.02
Antimony	Sb	mg/l	≤ 0.1	≤ 0.15			
Arsenic	As	mg/l	≤ 0.06	≤ 0.3			
Lead	Pb	mg/l	≤ 0.15	≤ 3	≤ 0.2	≤ 1	≤ 1
Chromium	Cr	mg/l	≤ 0.1	≤ 2.5	≤ 0.05	≤ 0.1	≤ 0.1
Cobalt	Co	mg/l					
Copper	Cu	mg/l	≤ 0.6	≤ 30	≤ 1	≤ 5	≤ 5
Manganese	Mn	mg/l					
Nickel	Ni	mg/l	≤ 0.12	≤ 3	≤ 0.2	≤ 1	≤ 1
Vanadium	V	mg/l					

3.4.3.6 Quality criteria of compost-like products

Currently, there is not a European directive that provides either operational conditions, technical requirements or quality criteria for the use on land of compost-like products (compost, digestate and stabilised biowaste) recovered from the biological treatment of waste. It was expected that the Biowaste Directive would do so, but for unclear reasons, it has been withdrawn and so far, there are no indications for further developments. The latest document developed by the Commission in this area is the working document on biological treatment of biowaste[46], which suggests quality criteria for compost-like products. As an alternative quality criteria for compost-like products, the model is restricted to the provisions imposed by voluntary quality assurance system for compost RAL-GZ 251 established by the German Compost Quality Assurance Organisation (Bundesgütegemeinschaft Kompost, BGK). The quality criteria of this assurance system fulfil the requirements of the statutory German Biowaste Ordinance (Bioabfallverordung - BioAbfV) and the Fertiliser Ordinance (Düngemittelverordnung – DÜmV). Both ordinances provide quality criteria for the use on land of treated and untreated biowaste and mixed wastes. BioAbfV limits the amount of harmful substances (heavy metals, impurities), while the DÜmV indicates the minimum amount of nutrients (primary: N, P, K & secondary: Ca, Mg, Na, S) required as a secondary raw material fertiliser. Finally, the quality criteria from mentioned documents are shown in Table 3-7.

3.4.3.7 Quality criteria for refuse derived fuel

So far has not been recognised an official European standard on the quality for refuse derived fuels. Quality requirements are normally imposed by the cement industry and power stations. The RDF quality is restricted to its calorific value and chemical composition (Cl, S, N, moisture, ashes and heavy metal). Therefore, the Technical Committee CEN/TC 343 of the European Committee for Standardisation is developing a set of standards related to the definition, description and requirements for solid recovered fuels in Europe. These standards are expected to be available between 2006 and 2007. On the other hand, there are voluntary

[46] DG ENV.A.2/LM/biowaste/ 2nd draft. Brussels, 12 February 2001.

quality assurance systems, which provide limits to the RDF composition. The German quality label RAL-GZ 724 and the Finnish standard SFS 5875 are the most representative quality-assurance systems. Similarly, the European Union for Responsible Incineration and Treatment of Special Waste (EURITS) has developed criteria for RDF consumed by the cement industry, which has been criticised as too stringent. Finally, even though that the RDF quality is not subject to the IPPC Directive, the BREF WT provides a range of compositions of RDF in Europe. The user can decide which quality assurance system the model should use to restrict the composition of generated RDF within the boundaries of the product system. The quality requirements of mentioned quality assurance systems are shown in Table 3-8.

Table 3-7 Quality criteria for fresh and mature compost

		Dry matter	Biowaste Directive 2nd Draft			BioAbfV / DÜmV		RAL-GZ251	
Compost type			Class 1	Class 2	SOM	SOM	SOM	Fresh	Mature
Decomposition degree								II or III	IV or V
Water content	H_2O	%						< 45	< 35
Organic content	C	%	> 30	> 30	> 30			> 30	> 15
Cadmium	Cd	mg/kg	0.7	1.5	5	1.5	1	1.5	1.5
Thallium	Tl	mg/kg							
Mercury	Hg	mg/kg	0.5	1	5	1	0.7	1	1
Antimony	Sb	mg/kg							
Arsenic	As	mg/kg							
Lead	Pb	mg/kg	100	150	500	150	100	150	150
Chromium	Cr	mg/kg	100	150	600	100	70	100	100
Cobalt	Co	mg/kg							
Copper	Cu	mg/kg	100	150	600	100	70	100	100
Manganese	Mn	mg/kg							
Nickel	Ni	mg/kg	50	75	150	50	35	50	50
Vanadium	V	mg/kg							
Impurities > 2 mm (Glass, plastic, metals)	Imp	%	< 0.5	< 0.5	< 3	< 0.5		< 0.5	< 0.5
Gravel and stones > 5 mm		%	< 5	< 5	-	< 5		< 5	< 5

Maximum application rate of 20 Mg of stabilised organic waste per hectare in a period of 3 years, BioAbfV §6 Par. 1(1,2)
Maximum application rate of 30 Mg of stabilised organic waste per hectare in a period of 3 years, BioAbfV §6 Par. 1(3)
BioAbfV §4 Par.4(1)
BioAbfV §4 Par.4(2)

Table 3-8 Quality criteria for refuse derived fuels

Parameter			EURITS Criteria	RAL-GZ 724	SFS 5875	IPPC BREF WT[1]
Higher heating value	Ho	MJ/kg	15	16		10 – 40
Nitrogen	N	%	0.7		1 – 2.5	0.5 – 0.8
Sulphur	S	%	0.4		0.2 – 0.5	0.02 – 0.6
Chlorine	Cl	%	0.5		0.15 – 1.5	<0.01 – 1.77
Ash content	Ash	%	5			0.7 – 20
Cadmium	Cd	mg/kg	10	4	1 - 5	0.16 – 6
Thallium	Tl	mg/kg	-	1		<0.1 – 0.8
Mercury	Hg	mg/kg	2	0.6	0.1 – 0.5	<0.02 – 1
Antimony	Sb	mg/kg	10	25		1 – 39
Arsenic	As	mg/kg	10	5		<0.4 –160
Lead	Pb	mg/kg	200	190		2.4 – 300
Chromium	Cr	mg/kg	200	125		2.5 – 226
Cobalt	Co	mg/kg	200	6		0.4 – 7.4
Copper	Cu	mg/kg	200	350		6.8 –1340
Manganese	Mn	mg/kg	200	250		22 – 590
Nickel	Ni	mg/kg	200	80		<2.5 -40
Vanadium	V	mg/kg	200	10		2.3 - 10.2

[1] IPPC BREF WT, Table 3.142 pages 253-257

3.4.4 Economical Constraints

The economical constraints are the input parameters of the objective function. Thus, they are designed to ensure that the proposed sustainable strategy is not only economically affordable but also that it satisfies waste management objectives at the least overall costs to society. These constraints guarantee the optimal net social costs of the product system. The net social cost is the difference between the gross social costs and the social costs savings (revenues) associated to the revenues and displacement of recovered energy and resources. The gross social cost integrates the gross private cost (e.g. transportation, labour and capital cost for operation and maintenance of existing waste management operations) and the environmental cost (e.g. externalities). This approach considers that generated and displaced fugitive emissions pay the full costs of their impact based on shadow prices. As a result, the model restricts economically the system to its gross private costs, environmental costs and social costs savings.

3.4.4.1 Disposal costs

Disposal costs (DC_k) is part of the gross private cost. This cost is a function of the plant treatment capacity ($PTCX_{k(x)}$) and of the waste category fraction, which is treated or disposed on site. When the treatment cost is exclusively function of the plant treatment capacity then it follows the economy of scale principle. Treatment costs are given as fee gates. These costs include fixed capital costs ($CCX_{k(x)}$) and operating costs ($OCX_{k(x)}$). Capital costs include site costs, planning costs and construction/plant development costs, while operation costs exclude the cost of residue disposal, staff costs and income from sales of recovered resources. Capital costs are the present worth of the series of future equal annual payments ($AX_{k(x)}$) at a discount rate r at the end of each year over a period of t years. For the economical evaluation, it is assumed a discount rate of 4%[47] and a working period of 20 years. Finally, annual treatment costs are calculated with Equation 3-17.

Equation 3-17 Treatment Costs

$$DC_k = \sum_x Q_{k(x)} \cdot \left(OCX_{k(x)} + AX_{k(x)}\right)$$

where:

$$AX_{k(x)} = CCX_{k(x)} \cdot \left[\frac{r(1+r)^t}{(1+r)^t - 1}\right]$$

3.4.4.2 Transportation costs

Transportation costs (TC) belongs as well to the gross private cost. Transportation costs are based on the price recommendations given by the KURT tables (Kostenorientierte Unverbindliche Richtsatz – Tabellen). These tables provide price recommendations based on the weight of a product transported and the travelled distance from point j to point j'. The model makes use specifically of Table III, which considers an average transportation capacity of 29 ton. Mathematically this is represented by Equation 3-18. If the practitioner has specific transportation costs, they should be taken instead.

Equation 3-18 Transportation Costs

$$TC = \sum_x \sum_j \sum_i \left[QJXI_{j,k(x),i} \cdot \left(0.0704 \cdot DJX_{j,j(x)} + 6.3446\right)\right] + \sum_y \sum_x \sum_w \left[QXYW_{k(x),k(y),w} \cdot \left(0.0704 \cdot DXY_{j(x),j(y)} + 6.3446\right)\right]$$

[47] The discount rate of 4% is recommended by the SEC(2005) 791. 15.06.2005. Impact Assessment Guidelines and it corresponds to the average real yield on longer-term government debt in the EU since 1980.

3.4.4.3 Environmental costs - Externalities

Environmental costs or externalities are derived from the generation and displacement of fugitive emissions to air and water. Externalities are marginal social costs, which are normally not taken into account in decisions by market players (IPPC 2005b). They represent the willingness to pay (WTP) to avoid negative effects on the environment. Externalities are based on the life cycle impact assessment of the life cycle inventory. Additionally, they are accounted and allocated to the year in which they occur. Various methodologies or characterisation models have been developed, which assigned marginal cost values to specific fugitive emissions. The most representative ones are *inter alia*:

- Environmental priority strategy in product design, EPS-2000 (Steen 1999a, Steen 1999b)
- ExternE (EC 1999b)
- BeTa database (Holland 2000)
- Cost benefit analysis in the clean air for Europe (CAFE) programme (EC 2004a)
- New ExternE (EC 2004b)

These methodologies follow the "impact pathway approach" and they are considered as damage methods. In general, they trace generated fugitive emissions through dispersion and environmental chemistry models. The impacts of the generated fugitive emissions on sensitive receptors are assessed with exposure-response functions and finally an economical value is given using the willingness to pay and willingness to accept approach. The external social costs proposed from these methodologies are shown in Table 3-9.

The EPS-2000 methodology follows the ISO-14042 guidelines on life cycle impact assessment. Therefore, generated fugitive emissions are classified in damage impact categories, which subsequently are characterised in five damage impact categories or areas of protection (at damage or endpoint level). These areas of protection include human health, abiotic stock resources (resources), biotic stock resources or biodiversity (flora and fauna), ecosystem production capacity (production) and cultural and recreational values (aesthetic values). Default characterisation factors are calculated using empirical, equivalency and mechanistic models. These methods include a fate, exposure, effect and damage analysis. Finally, weighting is done via valuation. Weighting represents the willingness to pay to avoid changes, considering the present state of the environment. Weighting factors or impact indices are applied directly to the fugitive emission and expressed in ELI (Environmental Load Index) per kg substance. This unit does not represent a real market value but it can be assumed that one ELU correspond to one ECU (one Euro, 1 €). On the other hand, Externalities reported in the CAFE programme are only related to human health and it excludes impacts on ecosystems and cultural heritage for the monetisation of externalities. Similarly, the BeTa database estimates exclusively marginal environmental costs of air pollution in Europe related to human health and crop production externalities. Both the CAFE programme and the BeTa database are an update of the ExternE methodology. Both methodologies are limited to SO_2, NO_2, NH_3, VOCs and $PM_{2.5}$ emissions.

The default characterisation method used in this model is the Environmental Priority Strategy in product design, EPS2000. Firstly, it is based on ISO-14042 and it satisfies the goal and scope of this model. Secondly, it is not limited to a certain type of fugitive emission and its better environmental relevance makes it easier to communicate the environmental impact of the system. Finally, it is a comprehensive and user-friendly methodology. However, the practitioner has the possibility to select another characterisation methodology from the database of the model. After the selection of the characterisation method, the accounted

fugitive emissions to air and water originated by every waste management operation ($FEAX_{fea,k(x)}$ and $FEWX_{few,k(x)}$) are internalised using Equation 3-19.

Equation 3-19 Environmental costs or Externalities

$$EC_k = \sum_x \left[\sum_{fea} \left(FEAX_{fea,k(x)} \cdot ELI_{fea} \right) + \sum_{few} \left(FEWX_{few,k(x)} \cdot ELI_{few} \right) \right]$$

Table 3-9 Marginal environmental costs, €/kg

FEA		EPS-2000	CAFE[1]	BeTa[2]	ExternE[3]	New ExternE[4]
Carbon dioxide	CO_2	0.108			0.019	0.019
Methane	CH_4	2.72			0.437	0.44[c]
Nitrous oxide	N_2O	33.48			5.62	5.62[c]
Hydrofluorocarbons	HFCs	1340				
Perfluorocarbons	PFCs	697				
Sulphur hexafluoride	SF_6	2760			421.80	421.80[c]
Sulphur dioxide	SO_2	3.27	11	5.2	4.268	3.524
Nitrogen dioxide	NO_2	2.13	8.2	4.2	2.084	3.021
Ammonia	NH_3	1.96	21			
Hydrogen chloride	HCl	2.13				
Hydrogen sulphide	H_2S	4.96				
NMVOC	NMVOC	2.14	2.1	2.1	0.134	1.124
Dioxins & Furans	PCDD/F	2.14			1097338	
PAH	PAH	64300				
Carbon monoxide	CO	0.331			0.06	0.06[c]
Particulates, < 2.5 μm	PM2.5	72	51	14	33.19[c]	45.16[c]
Particulates,	PM	54				
Particulates, >10 μm	PM10	36			19.872	27.042
Cadmium	Cd	10.2			345000	39
Thallium	Tl	0				
Mercury	Hg	61.4				
Antimony	Sb	0				
Arsenic	As	95.3				80
Lead	Pb	2910				1600
Chromium	Cr	76.9				29-34
Cobalt	Co	0				
Copper	Cu	0				
Manganese	Mn	0				
Nickel	Ni	0				4
Vanadium	V	0				
FEW						
Biological oxygen demand	BOD	0.00201				
Chemical oxygen demand	COD	0.00101				
Nitrogen Total	N-tot	-0.381				
Phosphorous Total	P-tot	0.055				
Mercury	Hg	0				

[1] EU25 (excluding Cyprus) averages values

[2] EU15 average values for urban populations (cities of 1 million people)

[3] ExternE. EC (1999). Externalities of Energy. Vol 9: Fuel cycles for emerging and end use technologies, transport & waste. Table 3.4, Table 3.5, Table 3.6 page 500-501

[4] New ExternE. EC (2004). New elements for the assessment of external costs from energy technologies. Final report to the European Commission, DG Research, Technological Development and Demonstration (RTD) September 2004

[C] Calculated parameters:

The impact category of $PM_{2.5}$ is 1.67 higher than the corresponding PM_{10} → $PM_{2.5}$= 1.67 PM_{10} (ExternE 1999)

Global warming gases are multiplied by the externality of CO_2 times is global warming potential (New Ext 2004)

3.4.4.4 Displaced Environmental Costs

Displaced environmental costs are as well externalities, which are accounted considering the amount of resources used and recovered within the system. Displaced environmental costs are proportional to the amount of displaced fugitive emissions ($DFEAX_{fea,k(x)}$ and $DFEWX_{few,k(x)}$)

and to the amount of displaced goods. Consequently, used resources will have a positive flow, while recovered material will have a negative one. Displaced environmental costs are calculated with Equation 3-20.

Equation 3-20 Displaced Environmental costs

$$DEC_k = \sum_x \left[\sum_{fea} \left(DFEAX_{fea,k(x)} \cdot ELI_{fea} \right) + \sum_{few} \left(DFEWX_{few,k(x)} \cdot ELI_{few} \right) \right]$$

3.4.4.5 Revenues from recovered material

Product system benefits are obtained from the commercialisation of recovered material and energy. The type of recovered material depends on the system recycling targets, recovery efficiencies and the choice of technology installed in every waste management operation. The mechanical treatment sub-models *MRF* and *RDF* calculate the potential recovery and recycling amount of metals, paper, glass cullets, wood chips, refuse-derived fuel (RDF) and valuable plastics (PET, LDPE, HDPE, PVC, PP, PS, PU, mixed plastics). The biological treatment sub-models *BTC* and *BTD* estimate the potential recovery amount of fresh and mature compost. Similarly, the mechanical-biological treatment sub-model *MBT* estimates the potential recovery of refuse-derived fuel and metals. Market prices for recovered and recycled materials are trade values obtained from the Global Recycling Network[48] database.

3.4.4.6 Revenues from recovered energy

The European Directive 2001/77/EC[49] promotes the electricity production from renewable energy sources. Based on this Directive, the German government has transposed it into national law and it is represented by the Renewable Energy Sources Act[50] (Erneuerbare-Energien-Gesetz, EEG). This law establishes a direct price support mechanism for renewable energy sources at national level. The fee paid for the generated electricity depends on several factors such as the energy source, the size of the installation and a degression factor, which depends on the year of commissioning. This mechanism provides a continual incentive to improve the efficiency and reduce costs. Considered energy sources include hydropower, landfill gas, sewage treatment and mine gas, biomass, solar radiation, geothermal and wind energy. However, following the scope of this study, the model considers exclusively those renewable sources directly related with the management of municipal solid waste. This fee is paid by grid operators for the feed-in of electricity to the grid system generally for a 20-year period. Selected fees are shown in Table 3-10. In this table can be seen that EEG provides additional fees or bonuses according to the type of technology employed. These bonuses can be used cumulatively. Additionally, the Renewable Energy Sources Act (EEG) is supported by the Ordinance on Generation of Electricity from Biomass (Biomass Ordinance: 8.2.1 Biomassverordnung – BiomasseV). This ordinance considers biological waste, waste wood not containing hazardous substances and biogas produced from anaerobic fermentation of biomass as biomass sources. On the other hand, mixed municipal solid waste, waste wood containing hazardous substances, PCP, sewage sludge, textiles animal carcasses, landfill gas an sewage treatment gas are not considered as biomass sources. The model is restricted to this biomass definition for the application of the EEG's direct price support mechanism.

[48] http://www.grn.com

[49] Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market. OJ L 283,27.10.2001 p. 33

[50] Renewable Energy Sources Act (EEG) as amended on 21 July 2004.

Table 3-10 Direct price support mechanisms for electricity produced from renewable energy sources

Energy Source	Capacity Range	Fee paid, ct/kWh	Degression	Bonus a	Bonus b	Bonus c	Bonus d
Landfill gas	< 500 kW	7.67	1.5%			+ 2	
Sewage biogas	< 5 MW	6.65	1.5%			+ 2	
Biomass	<150 kW	11.5	1.5%	+ 6	+ 2.5	+ 2	+ 2
	150-500 kW	9.9	1.5%	+ 6	+ 2.5	+ 2	+ 2
	0.5- 5 MW	8.9	1.5%	+ 4	+ 2.5	+ 2	+ 2
	> 5 MW	8.4	1.5%	+ 4	+ 2.5	+ 2	+ 2

Bonus a when is produced from plants (phytomass), manure or a combination of both
Bonus b when electricity is generated from wood.
Bonus c when electricity is generated within a Combined Heat and Power unit.
Bonus d when electricity is generated within a Combined Heat and Power unit and the biomass is treated in a thermo-chemical gasification or dry fermentation.
Sources: BMU(2004): EEG

Well managed waste management operations such as anaerobic biological, thermal and landfill units are suitable to obtain revenues from the sale of recovery energy produced from renewable sources. Therefore and considering this legal framework, recovered energy coming from renewable energy is then calculated with Equation 3-21 together with the fees given in Table 3-10.

Equation 3-21 Revenues from the sales of recovery energy

$$B_{SRE} = \sum_{k}\sum_{x} RE_{k(x)} \cdot \left(EFP_{ES,CR} + \sum_{i} Bonus_i \right)$$

where:

B_{SRE} Total benefit from the sales of recovered energy; [M€]
$RE_{k(x)}$ Total amount of energy recovered in the waste management operation *k(x)*; [kWh]
$EFP_{ES,EC}$ Energy Price Matrix restricted to the source of energy *ES* and capacity range *CR* of *k(x)*; [ct/kWh]
$Bonus_i$ Additional bonus type *i*

4 MECHANICAL RECYCLING

4.1 PROCESS DESCRIPTION

Mechanical recycling is defined in the Communication COM(2001) 729 final as "*the reprocessing of waste material, for the original purpose or for other purposes excluding energy recovery or disposal, without changing the chemical structure of the processed material*". Following the previous definition, in this model are considered mechanical recycling facilities (MRF) that sort and condition exclusively the following waste categories:

1. paper and cardboard
2. glass
3. lightweight packaging
4. metals
5. waste wood
6. waste electrical or electronic equipment (WEEE)
7. construction and demolition waste (C&D waste)
8. textiles
9. refuse derived fuel / solid recovered fuel (RDF/SRF)

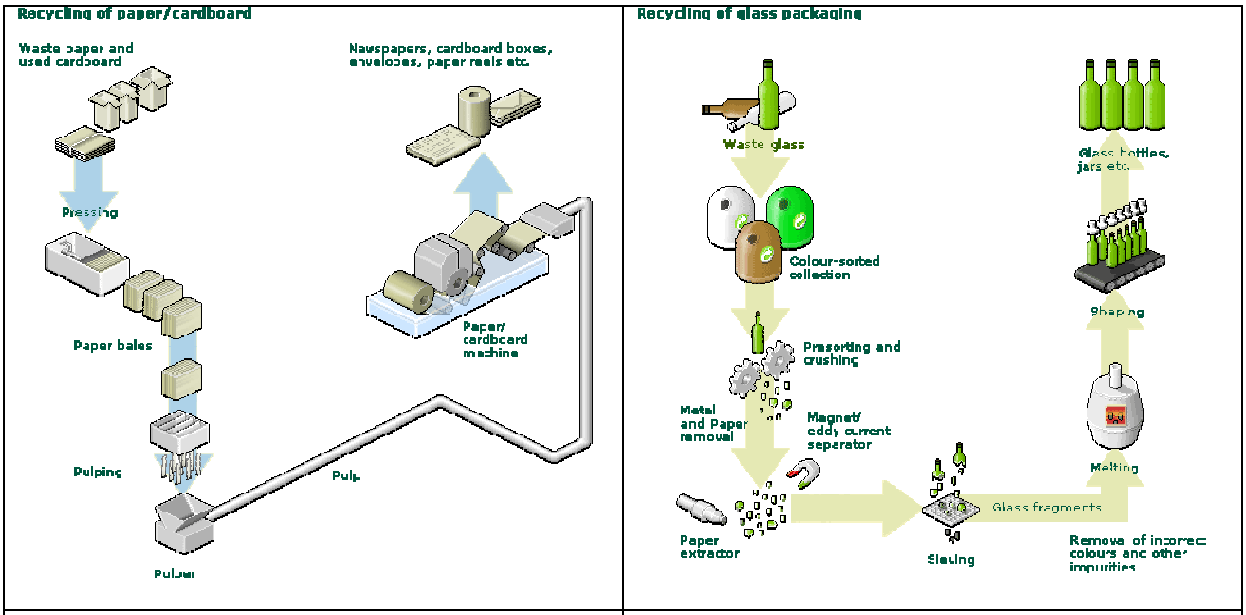
Every mechanical recycling facility recovers a specific waste category. The process sequence is function of the material to be recovered. Individual process sequences are explained in the following sections.

4.1.1.1 Paper and cardboard MRF

The post-consumer collected paper fraction is sent to the paper-MRF, where it is split into cardboard, deinking fraction (e.g. newspapers and magazines) and impurities such as glass, metals and textiles. Impurities are either landfilled or incinerated. After sorting, both the cardboard fraction and the deinking fraction are pressed into bales. In the one hand, the cardboard bales are sent to the paper-mill where the cardboard is transformed into a pulp product. This pulp product is then sent to the paper machine, where new paper is manufactured from it. On the other hand, the deinking fraction is a high quality fraction, which is firstly deinked before it can be sent to the paper-mill. This recycling sequence is shown in Figure 4-1 (a).

4.1.1.2 Glass MRF

The post-consumer collected glass fraction is separated and collected at source in green, brown and clear glass fractions. Separation by colour is a key factor for the effective recycling of glass. Collected glass is directly sent to the glass-MRF, which is normally installed as an integrated part of a glass factory. Post-consumer collected glass is firstly clean and crushed. Impurities such as paper or metals are removed by means of a paper extractor and a magnet/eddy current separator, respectively. Subsequently, the crushed glass is sorted in cullets, where incorrect colours and impurities are removed. Finally, the glass cullets are conditioned in the melting furnace from where the resulting product is used as raw material for the manufacturing of glass-finished products. This recycling sequence is shown in Figure 4-1 (b).



a) Paper and cardboard | b) Glass

Figure 4-1 MRF for a) paper & cardboard and b) glass waste fractions (DSD 2006)

4.1.1.3 Lightweight packaging MRF

The post-consumer collected lightweight packaging fraction is send to the packaging-MRF. In this waste management operation, the lightweight fraction is sorted into aluminium, tinplate, composites, plastic materials and non-recyclable materials. The material distribution of this waste fraction is shown in Table 4-1. The installed choice of technology is extensive and it varies from plant to plant. However, the basic technology consists of a combination between sorting and conditioning. In the sorting section, the input waste is screened by means of screen drums or vibration screens. This section segregates the fine fraction from the coarse fraction. Ferrous and non-ferrous materials are sorted as well through magnetic and eddy-current separators, respectively. Subsequently, the coarse fraction is split in both lightweight and heavy fractions by means of air separation units. In the one hand, the heavy fraction is sorted either manually or optically in material groups such as paper, PET, polystyrene (PS) and composite material. These fractions are either reduced in size by means of chopping, crushing and grinding units or simple pressed into bales. Alternatively, the light fraction undergoes further segregation. For example, when using the SORTEC technology, the light fraction enters to a hydro-pulping section, where it is split into paper fibres, plastics and aluminium-plastic composites (DSD 2006, ACRR 2004). Floating paper fibres are collected from the pulper tank, while the aluminium is segregated using an eddy-current separator. Finally, the remainder plastic fractions such as PS and PVC are sorted by type based on their density in a centrifuge. The SORTEC process is shown in Figure 4-2.

Table 4-1 Lightweight packaging waste composition fraction

	Total	Mixed Plastic	PE	PP	PS	PET	Film < DinA4	Film > Din A4	Impurities
Tinplate	0.348								
Aluminium	0.057								
Beaker (tubs)	0.088	0.1	0.375		0.375				0.15
Bottles	0.078		0.57	0.075		0.205			0.15
Film < Din A4	0.071	0.85					0.047		0.103
Film > Din A4	0.124	0.385						0.615	
Plastic composites	0.013	0.834							0.166
Mixed Plastic	0.08	0.195	0.108	0.247	0.148	0.022			0.28
Mixed paper	0.019								
Cartons for liquids	0.122								

Source: (BIfA 2004, UBA 2001)

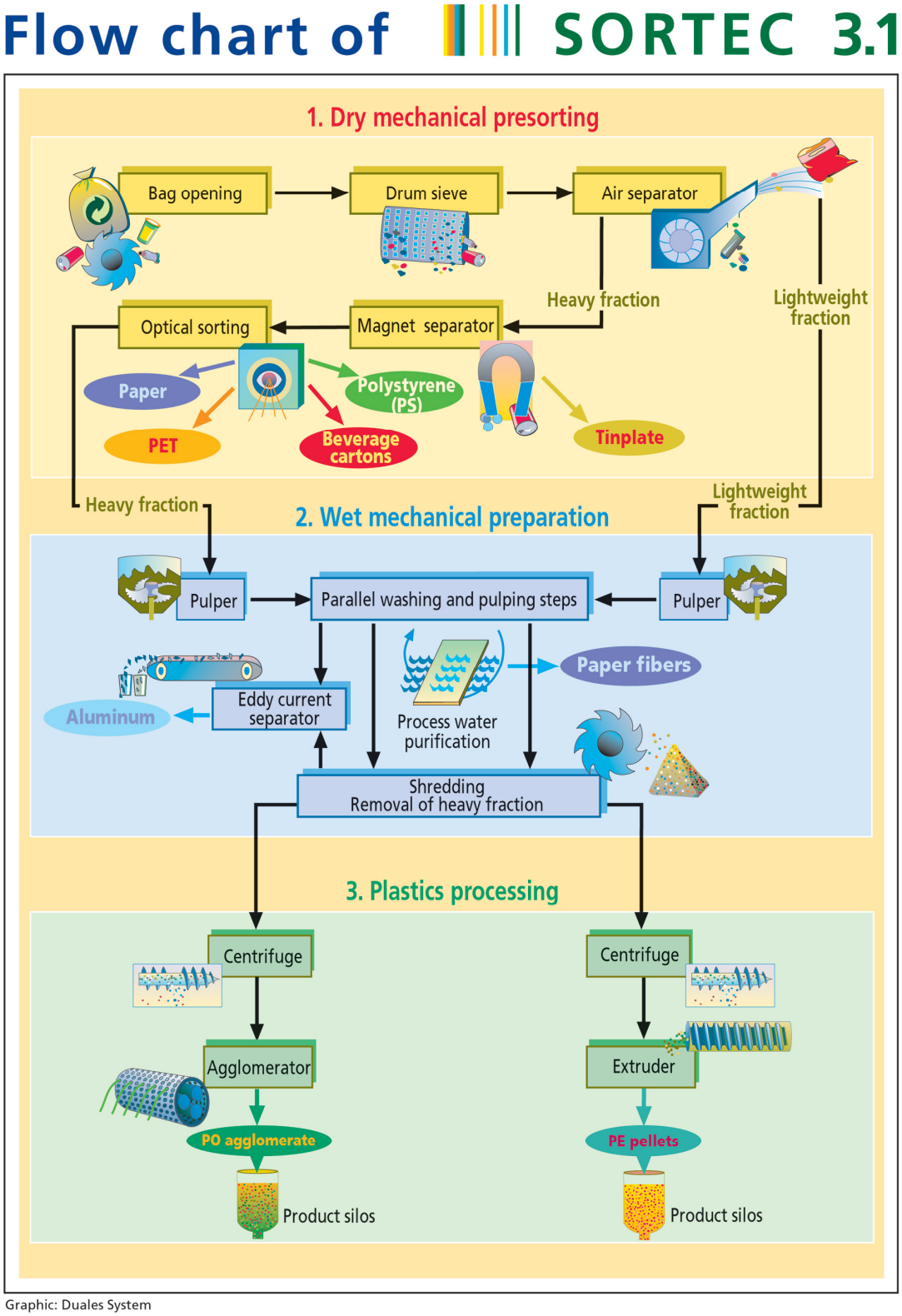
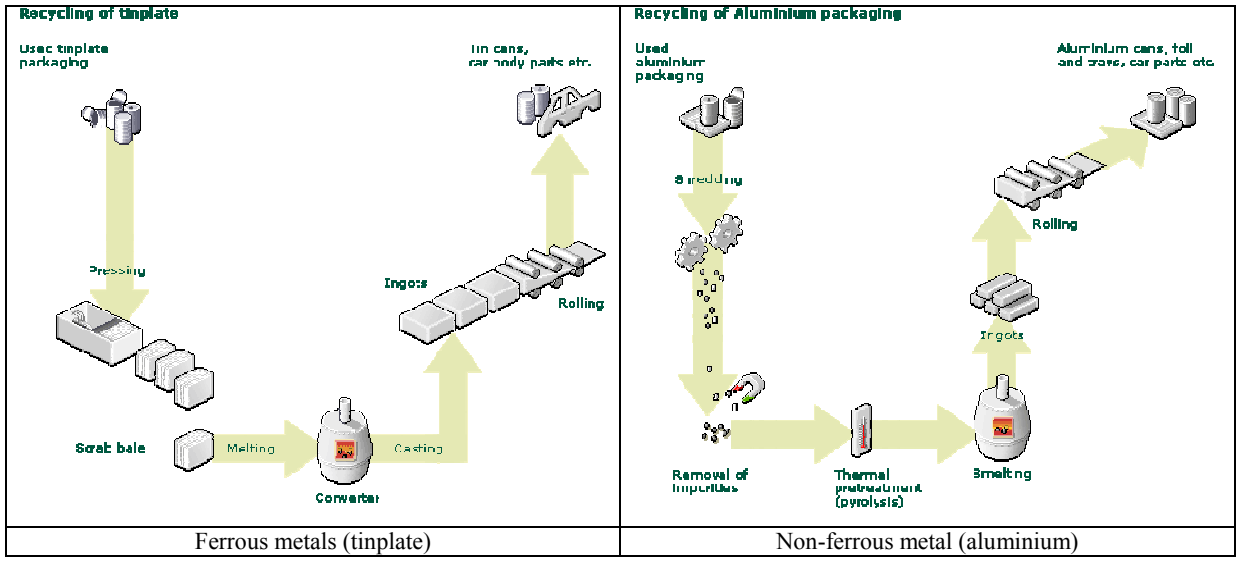


Figure 4-2 SORTEC technology (DSD 2006)

a. Ferrous metals (tinplate)
Post-consumer scrap metals consist of iron and steel. This waste fraction is mechanically sorted by means magnetic separation installations in order to increase its value. The sorted ferrous fraction is then shredded and subsequently impurities are removed from the stream. Around 2% of the plant output consists of these residues, which are landfilled (MUNLV 2001). Subsequently, the ferrous fraction is cleaned and pressed in blocks. Pressed metal bocks can be melted together with raw iron and with the surplus material that arises during the production of iron and steel.

b. Non-ferrous metals (aluminium)
Post-consumer scrap aluminium is segregated from the lightweight packaging waste fraction in the sorting plant. This is done by means of eddy current installations. Likewise, to the ferrous recycling process, the aluminium is shredded. After shredding, metallic impurities are removed and contrary to the ferrous process, they represent around 12% of the plant output (MUNLV 2001). Once the non-ferrous material is sorted, it is cleaned and pressed in blocks. Then, aluminium is melted and cast into ingots. Finally, these ingots are used as raw material for the manufacturing aluminium finished products.



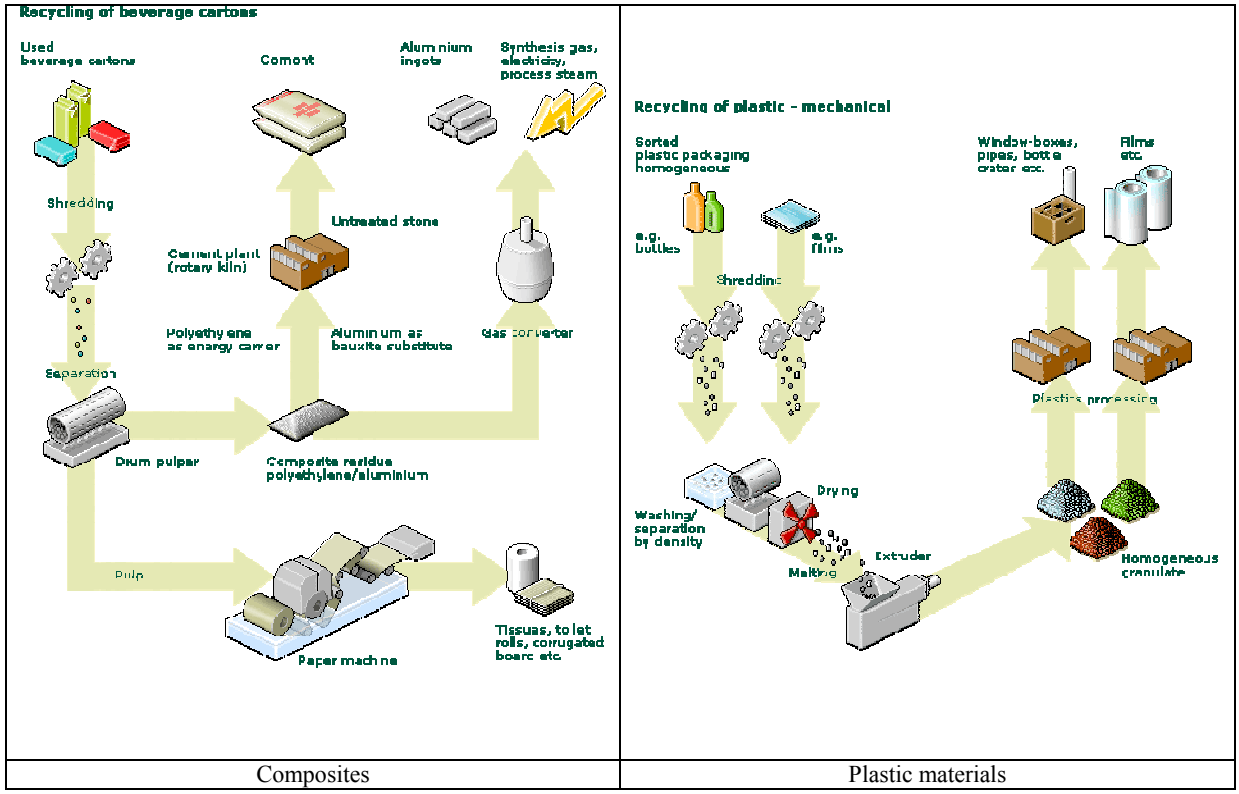
Ferrous metals (tinplate)	Non-ferrous metal (aluminium)

Figure 4-3 MRF for ferrous and non-ferrous fractions (DSD 2006)

c. Composites
Composite packaging are a polymer matrix composite, which consists typically of 76% paper, 20% polyethylene (HDPE or PET) and 4% aluminium foil (TetraPak 2003). In the MRF, collected composites are separated and pressed into bales. These bales are sent then to the recycling plant, where it is shredded. The shredded material is subsequently conveyed to a drum pulper. In this unit operation, paper fibres separate from the composite material. This pulp product is then sent to the paper machine, where new paper is manufactured from it. On the other hand, the remaining mixture of polyethylene and aluminium has two possible recycling routes. It could be used by the cement industry, where polyethylene is an energy recovery source and the aluminium is a cement additive. Alternatively, this composite fraction could be sent to a gasification plant, where the polyethylene undergoes feedstock recovery and the aluminium is recovered in pure form.

d. Plastic materials
Sorted lightweight plastics are used for mechanical recycling, feedstock recycling and energy recovery (DSD 2006, Smith 2001, Hogg 2001). Mechanical recycling processes are used to

reprocess the plastic into new plastic valuable products. Firstly, impurities such as metals are removed from the sorted plastic before it is shredded and washed. Subsequently, the different plastic fractions are further segregated by means of a density separator. In this step, valuable plastic fractions such as polypropylene, polystyrene and polyethylene are segregated. Segregated fractions are conveyed to an extruder where they are melted into homogeneous granulates. This product is sent to a plastic processing facility and used as raw material for the manufacturing of plastic finished products. On the other hand, feedstock recycling and energy recovery take place in both incineration and co-incineration plants. Both feedstock recycling and energy recovery do not take place in mechanical recycling facilities as defined by the COM(2001) 729. Thus, they are not considered within this module.



Composites	Plastic materials

Figure 4-4 MRF for composite and plastic material fractions (DSD 2006)

4.1.1.4 Waste Wood

Post-consumer waste wood can be transformed into wood chips or pellets as valuable products. These products can be used as refused derived fuel in power and cement plants. The recovery process includes size reduction, magnetic separation and size classification. Firstly, the waste wood is reduced on size by means of shredders, crushers or hammer mills. Then, exiting metallic impurities are removed by means of a magnet unit. Finally, the conditioned wood is sorted according its grain distribution in vibration screens.

4.1.1.5 Waste electrical or electronic equipment, WEEE

In the WEEE-MRF, the waste electrical and electronic equipment is segregated in product-groups (refrigerators, household big equipment, IT equipment, u-electronic and electro-domestics. Every product-group is recycled with different methods. It is not purpose of this model to explain and analyse all of them. Therefore, the model bases its analysis on the composition of this waste fraction. The average composition of WEEE is estimated to be 47% ferrous metals, 22% plastic, 6% glass, 4% non-ferrous metals and 26% inert material (Smith 2001). From this composition, only the ferrous and non-ferrous metal fractions are recovered

after shredding (MUNLV 2001). Remaining materials such as plastics are either landfilled or incinerated.

4.1.1.6 Construction and demolition waste, C&D waste

Construction and demolition waste (C&D waste) are sorted at source. Once sorted, they are sent to the C&D-MRF where the mineral fraction is recovered. The process starts with the size reduction of the input fraction by means of an impact or jaw crusher. Reduced materials are classified in different mineral fractions, which can be recycled and used as construction material. Ferrous materials are removed through magnetic separation, while residues are segregated either manually or through air separation units. The recovered mineral fraction is around 65% of the plant output. Other recovered materials include wood (7%), metals (1.55%), paper (0.5%) and plastics (0.2%). Finally, around 25% of the plant out is considered as sorting residue and it is landfilled (MUNLV 2001).

4.1.1.7 Textiles

Textiles are collected from textile banks or via kerbside collection. If the recovered textiles are in good state, they are exported and reused. Charitable organizations and commercial establishments collect this waste fraction. Otherwise, they are processed by the wiper manufacture, yarn manufacture or for flock production.

4.1.1.8 RDF/SRF

Specific high calorific waste categories such as household waste, bulky waste, similar to h.w. commercial waste, lightweight packaging waste, textiles, paper and cardboard have the potential to be transformed into solid fuels. Commercially they are known as refuse derived fuel (RDF) or solid recovered fuel (SRF). The RDF is a lower grade, heterogeneous fuel material generated without quality control, while the SRF is a fuel material generated to fulfil defined specifications. These high calorific products are used as fuel substitute in co-incineration plants such as power plants, cement plants, blast furnace and in industrial combustion units.

The RDF/SRF process starts with the pre-size reduction of the input material by means of a coarse crusher or mill. In this section, impurities (e.g. glass) and hazardous material are removed from the waste stream. Subsequently, it is further reduced on size by means of a co comminuting drum, cutting mill or a contact crusher. The required grain distribution of the recovered material is ensured with a trommel screen. Ferrous and non-ferrous materials are separated by means of magnetic and eddy current separators, respectively. Then, the conditioned waste is washed, mixed and homogenized. Finally, this product is pressed into bales. This recycling process must ensure that the produced RDF/SRF is a high-calorific and homogenous material. The final product should have a low content of hazardous components and low content of ashes. For handling reasons, it should have as well gut transportation, dosing and storage properties.

4.2 MRF SUB-MODEL

The mechanical recycling facility submodel (MRF) assesses the life cycle of selected waste categories. Waste categories are codified according to its entry in the European Waste Catalogue (EWC) as defined by the Commission Decision 94/3/EC. Every MRF unit is categorised according to the type of desired recyclable product. This categorisation is defined by the variable $MRFT_s$, which is shown in Table 4-2. A mechanical recycling facility whose $MRFT_s$ is between one and eight are named “clean” MRF units because they accept exclusively source-separated recyclable materials. Otherwise, when $MRFT_s$ is equal to nine,

then they are named "dirty" MRF because they accept unsegregated waste fractions such as mixed municipal solid waste, bulky waste or similar to household waste commercial waste.

Table 4-2 MRF categorisation

$MRFT_s$	Recyclable material
1	Paper and cardboard
2	Glass
3	Lightweight packaging
4	Metals
5	Waste wood
6	Waste electrical or electronic equipment (WEEE)
7	Construction and demolition waste (C&D waste)
8	Textiles
9	Refuse derived fuel / Solid recovered fuel (RDF/SRF)

The primary waste category that is accepted in every MRF is restricted by the variable $MRFT_s$. Table 4-3 shows the restrictions given for every mechanical recycling unit, where X corresponds to the accepted primary waste category.

Table 4-3 Accepted waste categories subject to mechanical recycling

EWC	Primary waste category, *i*	$MRFT_s$								
		1	2	3	4	5	6	7	8	9
200301	Mixed municipal waste (household waste)	-	-	-	-	-	-	-	-	X
200301	Similar to h.w. commercial waste	-	-	-	-	-	-	-	-	X
200307	Bulky waste	-	-	-	-	-	-	-	-	X
170904	Mixed construction and demolition waste	-	-	-	-	-	-	X	-	-
200101	Paper and cardboard	X	-	-	-	-	-	-	-	X
200102	Glass	-	X	-	-	-	-	-	-	-
200139	Lightweight packaging	-	-	X	-	-	-	-	-	X
200140	Metals	-	-	-	X	-	-	-	-	-
200138	Waste wood	-	-	-	-	X	-	-	-	X
200135	WEEE containing CFC	-	-	-	-	-	X	-	-	-
200136	WEEE without CFC	-	-	-	-	-	X	-	-	-
200110	Clothes and textiles	-	-	-	-	-	-	-	X	X

Material flows within these waste management operations are calculated based on waste-specific and process-specific models. In the one hand, "clean" MRF units are assessed with process-specific equations. Therefore, "clean" MRF units are assessed as "black boxes", where the main internal process size reduction, impurities removal, sorting of recyclable material and conditioning. The internal material and energy flows are calculated as a function of the mechanical recycling type, the composition of the input primary waste and its recovery efficiency. Required information is derived from background sources such as Ecoinvent (Althaus 2004, Doka 2003, Hischier 2004, Werner 2003), UBA (UBA 2000) and (Smith 2001). On the other hand, "dirty" MRF units are assessed with waste-specific equations. Material and energy flows in "dirty" MRF are subjected to the mechanical recycling type, the composition of the input primary waste, the sorting process and the quality criteria of the desired recovered product. Both "clean" and "dirty" MRF estimate as well the amount of fugitive emissions to air and water, secondary waste and energy consumption. The system boundaries of both MRF types are shown in Figure 4-5 and Figure 4-6, respectively.

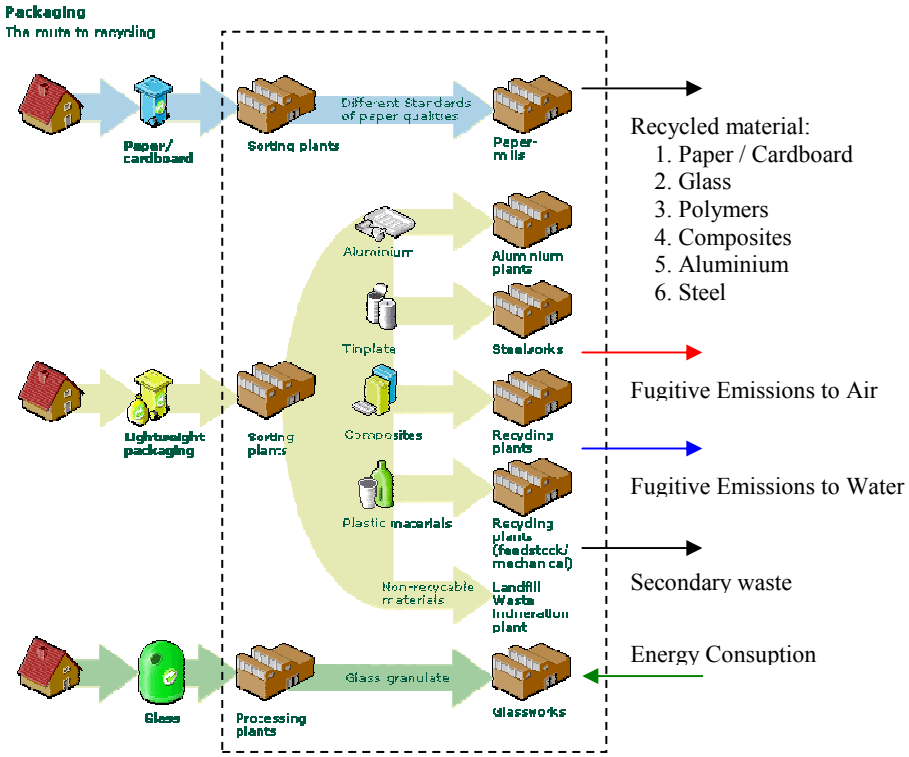


Figure 4-5 "Clean" MRF system boundaries, e.g. paper & cardboard, lightweight packaging and glass

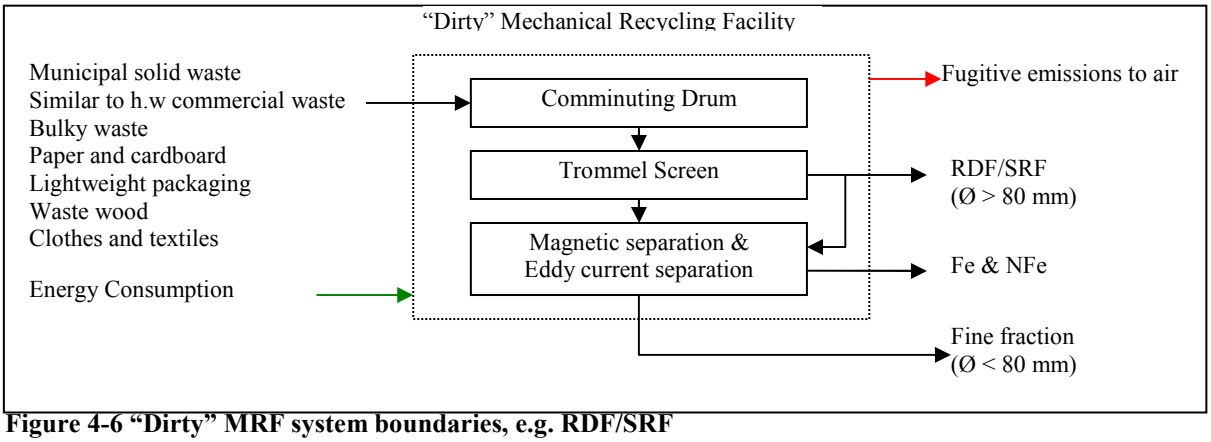


Figure 4-6 "Dirty" MRF system boundaries, e.g. RDF/SRF

4.2.1 MRF Internal Process

4.2.1.1 Material Input

According to the multi-commodity flow distribution approach, the waste category w generated at the source point j will compete for the scarce and finite treatment capacity of the mechanical recycling facility s. Every MRF is restricted to accept only the waste category defined by the material-flow-restriction matrix $MFRS_{s,i}$. The individual material flow distribution is calculated using Equation 4-1. The input of every MRF is defined with the variable $m_{j,s,w}$. This variable is calculated in advance as showed in subchapter 3.4.1, which is related to logistic constraints.

Equation 4-1 MFR waste category *w* input acceptance

$$m_{s,w} = \sum_{j} m_{j,s,w}$$

subject to :

$$m_s = \sum_{w} m_{s,w}$$

$$PTC_s > m_s$$

where:

$m_{s,w}$	Total waste category w material flow entering to the material recycling facility *s*, Gg
$m_{j,s,w}$	Waste category w generated at point j and entering to the material recycling facility *s*, Gg
m_s	Total amount of waste accepted for conditioning in the material recycling facility *s*, Gg
PTC_s	Plant treatment capacity *s*, Gg

4.2.1.2 "Clean" Mechanical Recycling Facilities

"Clean" mechanical recycling facilities are modelled with process-specific equations, whose transfer coefficients are based on background sources such as Ecoinvent (Althaus 2004, Doka 2003, Hischier 2004, Werner 2003), UBA (UBA 2000) and (Smith 2001). The total amount of recovered and rejected material is calculated as a function of the primary waste input composition and the type of mechanical recycling facility. It is assumed that existing mechanical recycling facilities accept exclusively the primary waste *i*, which correspond to their recovery line process. Recyclable materials are limited by the integer variable $SOR_{s,w}$, which defines the material that undergoes segregation. If the input waste fraction corresponds to the type of mechanical recycling facility, then this material is segregated as valuable product. Otherwise, it is an impurity and rejected as secondary waste. Additionally, the recovery process is subject to the recovery efficiency of the process, which is defined by the variable ηREC_w and values shown in Table 4-4.The final composition of both recovered and rejected material in a "clean" mechanical recycling facility is calculated with Equation 4-2 and Equation 4-3, respectively.

Equation 4-2 "clean" MRF sorted material

$$mSOR_{s,w} = m_{s,w} \cdot SOR_{s,w} \cdot \eta REC_w$$

and

$$SOR_{s,w} = \begin{Bmatrix} 0 & if\ MRFT_s \neq w \\ 1 & if\ MRFT_s = w \end{Bmatrix}$$

Equation 4-3 "clean" MRF secondary waste

$$mSW_{s,w} = m_{s,w} \cdot \left(1 - SOR_{s,w} \cdot \eta REC_w\right)$$

where:

$mSOR_{s,w}$	Waste category *w* sorted at the mechanical recycling facility *s*, [Gg]
$mSW_{s,w}$	Process rejects *w* generated at the mechanical recycling facility *s*, [Gg]
$m_{s,w}$	Mass flow of the waste category fraction *w* which enters to the mechanical recycling facility *s*, [Gg]
$SOR_{s,w}$	Integer variable that defines which waste fraction *w* is sorted as end product in the mechanical recycling facility *s*, [-]

Table 4-4 MRF recovery efficiency (sorting + conditioning)

	$\eta RECw$		$\eta RECw$
Paper and board (Blue bin)	0.7230	Waste Wood	1
Glass (Green bin)	0.9259	Waste electrical or electronic equipment	1
Lightweight packaging (Yellow bin)	1	Construction and demolition waste	1
Aluminium	0.7893	Refuse derived fuel	1
Ferrous metal	1		

Adapted from Ecoinvent (Althaus 2004, Doka 2003, Hischier 2004, Werner 2003), UBA (UBA 2000) and (Smith 2001)

Finally, the potential amount of recyclable material is calculated with the set of process-equations defined by Equation 4-4. This set of equations depends on the sorting efficiency of previous operations.

Equation 4-4 MRF recyclable material

Rcm	*rcm*	
Mixed scrap iron & steel (Fe)	1	$mRCM_1 = \sum_s \left(mSOR_{s,1} + mSOR_{s,8} \cdot MWEEC_1 \right)$
Metals - NFe as Al.	2	$mRCM_2 = \sum_s \left(mSOR_{s,2} + mSOR_{s,8} \cdot MWEEC_2 + mSOR_{s,12} \cdot MCPC_3 \right)$
Metals – Mixed	3	$mRCM_3 = \sum_s mSOR_{s,3}$
Paper	4	$mRCM_4 = \sum_s \left(mSOR_{s,4} + mSOR_{s,12} \cdot MCPC_1 \right)$
Glass cullets	5	$mRCM_5 = \sum_s mSOR_{s,5}$
Clothes and textiles	6	$mRCM_6 = \sum_s mSOR_{s,6}$
Wood chips	7	$mRCM_7 = \sum_s mSOR_{s,7}$
Polyethylene Terephthalate, PET	8	$mRCM_8 = \sum_s mSOR_{s,9} \cdot MPPC_1$
High density polyethylene, HDPE	9	$mRCM_9 = \sum_s mSOR_{s,9} \cdot MPPC_2 + \sum_s mSOR_{s,12} \cdot MCPC_2$
Polyvinyl chloride, PVC	10	$mRCM_{10} = \sum_s mSOR_{s,9} \cdot MPPC_3$
Low density polyethylene, LDPE	11	$mRCM_{11} = \sum_s mSOR_{s,9} \cdot MPPC_4$
Polypropylene, PP	12	$mRCM_{12} = \sum_s mSOR_{s,9} \cdot MPPC_5$
Polystyrene, PS	13	$mRCM_{13} = \sum_s mSOR_{s,9} \cdot MPPC_6 + mSOR_{s,10}$
Polyurethane, PU	14	$mRCM_{14} = \sum_s mSOR_{s,9} \cdot MPPC_7$
Mixed Plastic	15	$mRCM_{15} = \sum_s mSOR_{s,9} \cdot MPPC_8 + mSOR_{s,11}$
Mixed Composites	16	$mRCM_{16} = \sum_s mSOR_{s,13}$
Construction mineral material	17	$mRCM_{17} = \sum_s mSOR_{s,20}$
RDF/SRF	18	$mRCM_{18} = \sum_s \sum_w mOF_{s,w}$

4.2.1.3 "Dirty" Mechanical Recycling Facilities

"Dirty" mechanical recycling facilities are modelled with waste-specific equations. In this model, these waste management operations are focused on the recovery of RDF/SRF. Thus, the following sequence applies only to MRF whose $MRFT_s$ are equal to nine. Basically, "dirty" MRF consist of three main mechanical operations (Gendebien 2003, MUNLV 2001). These operations are size reduction (e.g. comminuting drum), grain distribution (e.g. trommel screen) and recovery of recyclable material (e.g. metals). The mathematic sequence of this waste management operation is described as follows.

4.2.1.3.1 Comminuting Drum

This device is a rotating drum, where soft organic material break down to smaller particles with a diameter smaller than 80 mm while inert materials such as plastic, textiles and metals do not suffer any size reduction. Any glass material content in the input flow is reduced in size as well. The integer variable (SOM_w) is used to represent which waste category w is subject to comminution. Soft organic material will have a SOM_w value equal to one; otherwise, it is equal to zero.

4.2.1.3.2 Trommel Screen

After the comminution drum, the waste is screened in a trommel screen. The model considers a trommel screen with one opening size of 80 mm, where input waste material is divided in two fractions named fine fraction (Φ<80 mm) and oversized fraction (Φ>80 mm). The fine fraction contains not only impurities such as glass, but also a high percent of organic material, which is suitable for biological treatment. The oversized fraction will consist mainly of mixed plastics, textiles, paper and board or similar non-biodegradable materials. The oversized fraction is a high calorific fraction, which can be used as refuse derived fuel (RDF). Fine and oversized fraction are calculated with Equation 4-5 and Equation 4-6, respectively.

Equation 4-5 MRF Fine Fraction

$$mFF_{s,w} = m_{s,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w\right)$$

Equation 4-6 MRF Oversized Fraction

$$mOF_{s,w} = m_{s,w} \cdot \left(1 - SOM_w\right) \cdot \left(1 - WPD_w\right)$$

where:

$mFF_{s,w}$	Fine Fraction mass flow from the mechanical recycling facility s, [Gg]
$mOF_{s,w}$	Oversized Fraction mass flow from the mechanical recycling facility s, [Gg]
$m_{s,w}$	Mass flow of the waste category fraction w which enters to the mechanical recycling facility s, [Gg]
SOM_w	Integer variable for the waste category w that is subject to comminution For the waste category w, which is soft organic material then, SOM_w is equal to 1, otherwise to 0.
WPD_w	Waste Particle Distribution fraction lower than 80 mm for the waste category w

The oversized fraction must fulfil exiting quality criteria for refused derived fuel in order to be commercialised. Currently, there is not available an international standard that defines these parameters. Therefore, the practitioner must select a voluntary quality assurance system, which fits better to his/her necessities. Typical voluntary assurance systems are among others the German quality label RAL-GZ 724, the Finish standard SFS 5875, the EURITS criteria or the recommendations given by the Waste Treatment BREF. These voluntary assurance systems restrict not only the calorific value of the produced RDF, but also its ash, sulphur, chlorine and heavy metal content. These values are shown as a dry base composition in Table 3-8. The selected voluntary assurance system is then defined by the variable $RDFR_{cc}$. In this variable, the calorific value is not considered. Thus, the calorific value of the RDF is defined by the variable $RDFcv_s$ and calculated with the ultimate analysis equation derived by Dulong. This equation is as defined by Equation 2-1 and Equation 2-2. Finally, generated refuse derived fuel are restricted to fulfil the selected voluntary assurance system, as defined by Equation 4-7.

Equation 4-7 RDF quality criteria constrain

$$for\ cc = \text{S, Cl, Ash and heavy metals}:$$

$$\sum_w m_{s,w} \cdot \left(1 - SOM_w\right) \cdot \left(1 - WPD_w\right) \cdot MCC_{w,cc} < RDFR_{cc} \cdot \sum_w m_{s,w} \cdot \left(1 - SOM_w\right) \cdot \left(1 - WPD_w\right) \cdot \left(1 - MCC_{w,H_2O}\right)$$

$$and$$

$$RDFcv_s \geq RDFcv$$

4.2.1.3.3 Metals separation

Ferrous metals are recovered from the waste input by means of a magnet unit, while aluminium by means of an eddy-current separator. Both recovery units are commonly suspended above the fine and oversized conveyor belt. It is assumed that the total metal input is separated and recovered from the feedstock stream and calculated with Equation 4-8.

Equation 4-8 Metal separation

$$for\ w = 1..3:$$

$$Metal_{s,MET} = m_{s,w}$$

where:

$Metal_{s,MET}$	Metal mass flow type *MET* separated and recovered from the mechanical recycling facility *s*, [Gg]
MET	Metal type: 1 = metal, 2 = aluminium, 3 = mix

4.2.2 Secondary Waste

In the one hand, secondary waste generated in "clean" MRF consist *inter alia* of rejected paper and board, plastic and rubber, glass, wood, textiles, inert material, scrap metals or sorted constriction and demolition materials. On the other hand, secondary wastes produced in "Dirty" MRF consist on the fine fraction diverted from the trommel screen. Generated secondary waste can be disposed in a landfill or in an incineration plant. However, this secondary waste fraction can be landfilled only if it fulfils the waste acceptance criteria as defined in the section of the Annex to Council Decision 2003/33/EC. Additionally, following the multi-commodity flow distribution approach, the secondary waste generated in the mechanical recycling facility *s* will compete for scarce disposal capacity in the thermal treatment *t* and in the landfill *l*. The material flow distribution to the landfill *l* is restricted to the integer variable $LFRS_s$. Subsequently, the material flow of this waste fraction to acceptable waste management operation is calculated with Equation 4-9. This equation is subject to the decision variable $\delta SX_{s,x}$, where *X* and *x* are substituted with the specific waste management operation index (*T,L*) and (*t,l*), respectively.

Equation 4-9 MRF secondary waste flow distribution

$$mSWST_{s,t} = \begin{Bmatrix} \sum_w \left[m_{s,w} \cdot \left(1 - \eta REC_{MRFT_s,w}\right) \right] \cdot \delta ST_{s,t} & \text{for "clean" MRF} \\ \sum_w \left[m_{s,w} \cdot \left(SOM_w + (1\text{-}SOM_w) \cdot WPDw\right) \right] \cdot \delta ST_{s,t} & \text{for "dirty" MRF} \end{Bmatrix}$$

$$mSWSL_{s,x} = \begin{Bmatrix} \sum_w \left[m_{s,w} \cdot \left(1 - \eta REC_{MRFT_s,w}\right) \right] \cdot \delta SL_{s,l} \cdot LFRS_s & \text{for "clean" MRF} \\ \sum_w \left[m_{s,w} \cdot \left(SOM_w + (1\text{-}SOM_w) \cdot WPDw\right) \right] \cdot \delta SL_{s,l} \cdot LFRS_s & \text{for "dirty" MRF} \end{Bmatrix}$$

Subsequently, the material distribution flow to the landfill is restricted with Equation 4-10.

Equation 4-10 MRF secondary waste flow restriction to landfill

$$LFRS_s = \begin{Bmatrix} 0 & if \sum_w \left[mSW_{s,w} \cdot MCC_{w,C} \right] > LFC_C \cdot \sum_w \left[mSW_{s,w} \cdot \left(1 - MCC_{w,H_2O}\right) \right] \\ & or \\ & if \sum_w \left[mOF_{s,w} \cdot MCC_{w,C} \right] > LFC_C \cdot \sum_w \left[mOF_{s,w} \cdot \left(1 - MCC_{w,H_2O}\right) \right] \end{Bmatrix}$$

Finally, decision variables and secondary waste flows are balanced to ensure the equilibrium of the system. This is represented with Equation 4-11.

Equation 4-11 MRF decision variable and secondary waste balance

$$1 = \sum_t \delta ST_{s,t} + \sum_l \delta SL_{s,l}$$

and

$$\sum_w mSW_{s,w} = \sum_t MSWST_{s,t} + \sum_l MSWSL_{s,l}$$

4.2.3 Fugitive Emissions to Air (FEA_s) and to Water (FEW_s)

Fugitive emissions to air and water depend on the type of waste category that is sorted and conditioned on site. The following MRF are assessed separately based on their specific life cycle inventory of both sorting and conditioning activities. These inventories are obtained from different background sources such as Ecoinvent (Althaus 2004, Doka 2003, Hischier 2004, Werner 2003), UBA (UBA 2000) and (Smith 2001).

4.2.3.1 Paper and cardboard

Inventoried environmental impacts from the segregation of paper in sorting plants are only energy consumption, as shown in Table 4-5. Energy consumption is related to the use of lift-trucks and heating of buildings. This process section does not generate fugitive emissions to water.

Table 4-5 MRF: Paper sorting

Input	Unit	Mean value	Output	Unit	Mean Value
Recovered paper and board	**kg**	**1**	**Sorted paper and board**	**kg**	0.8503
Electricity medium voltage	kWh	4.5493E-03			

Adapted from (Hischier 2004), (UBA 2000)

Subsequently, the sorted paper is transported to a paper mill, whose conditioning process has a greater impact due to generated fugitive emissions to water and energy consumption. The inventory of environmental impacts from the recycling of sorted paper is shown in Table 4-6.

Table 4-6 MRF: Paper recycling with deinking

Input	Unit	Mean value	Output	Unit	Mean Value
Sorted paper and board	**kg**	**1**	**Recycled paper**	**kg**	0.85034014
Electricity medium voltage	kWh	6.7177E-01	BOD	kg	3.4941E-04
Heat: heavy fuel oil	MJ	0.0000E+00	COD	kg	2.9146E-03
Heat: natural gas	MJ	0.0000E+00	N.tot	kg	1.7897E-04
Heat consumption total	MJ	8.1973E+00	P.tot	kg	2.7386E-06

Adapted from (Hischier 2004), (UBA 2000)

Finally, the inventory of environmental impacts from the recycling process of paper in a MRF is given by Table 4-7.

Table 4-7 MRF Paper

Input	Unit	Mean value	Output	Unit	Mean Value
Recovered paper and board	**kg**	**1**	**Recycled paper**	**kg**	0.7230
Electricity medium voltage	kWh	5.7576E-01	BOD	kg	2.9710E-04
Heat: heavy fuel oil	MJ	0.0000E+00	COD	kg	2.4783E-03
Heat: natural gas	MJ	0.0000E+00	N.tot	kg	1.5218E-04
Heat consumption total	MJ	6.9702E+00	P.tot	kg	2.3286E-06

Adapted from (Hischier 2004), (UBA 2000)

4.2.3.2 Glass

The recovery of the glass fraction in mechanical recycling facilities does not have inventoried environmental impacts neither to air nor to water. Indirect emissions are derived from the consumption of energy as shown in Table 4-8.

Table 4-8 MRF Glass sorting

Input	Unit	Mean value	Output	Unit	Mean Value
Recovered glass (all colours)	**kg**	**1**	**Glass cullets (all colours)**	**kg**	**0.9259**
Electricity medium voltage	kWh	3.4722E-03		kg	

Adapted from (Hischier 2004)

Subsequently, the glass cullets are sent to a glasswork where they are recycled into useable glass. In this process, the glass cullets are melted and cooled in glass containers previous its packaging and palletting. The inventoried environmental impacts related to the recycling of glass cullets into glass are related to energy consumption and fugitive emissions to air. This inventory is shown in Table 4-9.

Table 4-9 MRF Glass recycling

Input	Unit	Mean value	Output	Mean Value, kg	Output	Mean Value, kg
Glass cullets (all colours)	**kg**	**1**	**Recycled glass (all colours)**			**1.6**
Electricity medium voltage	kWh	2.538E-01	CO_2	5.008E-01	HCl	2.704E-05
Diesel	kg	2.096E-03	CH_4	1.430E-07	NMVOC	2.485E-05
Heat: heavy fuel oil	MJ	1.624E+00	N_2O	6.992E-07	PCDD/F	1.256E-16
Heat: natural gas	MJ	5.325E+00	SO_2	1.186E-03	PAH	1.616E-11
Heat consumption total	MJ	6.948E+00	NO_2	1.390E-03	CO	1.120E-05
			NH_3	4.192E-08	PM	2.896E-06

Adapted from (UBA 2000)

Finally, the inventory of environmental impacts from the recycling process of paper in a MRF is given by Table 4-10.

Table 4-10 MRF Glass

Input	Unit	Mean value	Output	Mean Value, kg	Output	Mean Value, kg
Recovered glass (all colours)	**kg**	**1**	**Recycled glass (all colours)**			**1.48144**
Electricity medium voltage	kWh	2.3847E-01	CO_2	4.6369E-01	HCl	2.5036E-05
Diesel	kg	1.9407E-03	CH_4	1.3240E-07	NMVOC	2.3009E-05
Heat: heavy fuel oil	MJ	1.5037E+00	N_2O	6.4739E-07	PCDD/F	1.1629E-16
Heat: natural gas	MJ	4.9304E+00	SO_2	1.0981E-03	PAH	1.4963E-11
Heat consumption total	MJ	6.4332E+00	NO_2	1.2870E-03	CO	1.0370E-05
			NH_3	3.8814E-08	PM	2.6814E-06

Adapted from (Hischier 2004) and (UBA 2000)

4.2.3.3 Lightweight packaging

Inventories environmental impacts for the mechanical segregation of recovered lightweight packaging are not only energy consumption but also fugitive emissions to air and water. The life cycle inventory of the segregation of lightweight packaging is shown in Table 4-11. Recovered material, which consists of aluminium, tinplate, composites and plastic materials, are transported to the corresponding industries for either mechanical or feedstock recycling. In this module, we consider only the life cycle inventory of mechanical recycling of every type of recovered material. Feedstock recycling is analysed in the thermal treatment module.

Table 4-11 MRF lightweight packaging

Input	Unit	Mean value	Output, kg	Mean Value	Output, kg	Mean Value
Glass cullets	**kg**	**1**	**AIR**		**WATER**	
Electricity medium voltage	kWh	1.5728E-01	CO_2	3.710E-02	BOD_5	6.530E-15
Diesel	kg	0.0000E+00	CH_4	6.980E-05	COD	2.150E-13
Heat: heavy fuel oil	MJ	1.7514E-01	N_2O	1.180E-06	N-tot	2.940E-13
Heat: natural gas	MJ	3.4424E-02	SO_2	1.170E-04		
			NO_2	1.560E-04		
			NH_3	1.900E-07		
			HCl	4.000E-06		
			NMVOC	1.410E-06		
			PCDD/F	1.240E-15		

			PAH	2.334E-10		
			CO	3.920E-05		
			PM_{10}	1.730E-05		
			Cd	2.440E-04		
			As	1.970E-04		
			Cr	2.870E-04		
			Ni	9.460E-03		

Adapted from (UBA 2000)

4.2.3.4 Metals

a. Steel:

Inventoried environmental impacts for the mechanical segregation of recovered metal are energy consumption and emission of dust. The inventory of this recycling process is shown in Table 4-12.

Table 4-12 MRF Steel

Input	Unit	Mean value	Output	Unit	Mean Value
Recovered metal	**kg**	**1**	**Secondary sorted iron/steel**	**kg**	**1**
Electricity medium voltage	kWh	1.00E-02	Total Particulates, PM	kg	2.90E-05
Heat: heavy fuel oil	MJ	0	• <$PM_{2.5}$: 32%	kg	9.28E-06
Heat: natural gas	MJ	0	• PM_{10} < x >$PM_{2.5}$: 48%	kg	1.392E-05
Heat consumption total	MJ	0	• >PM_{10} : 20%	kg	5.8E-06

Adapted from (Althaus 2004), (UBA 2000)

b. Aluminium:

Inventoried environmental impacts to air for the mechanical recovery of aluminium are energy consumption, dust and hydrogen chloride. This inventory is shown in Table 4-13.

Table 4-13 MRF: Sorting of recovered aluminium

Input	Unit	Mean value	Output	Unit	Mean Value
Recovered Aluminium	**kg**	1	**Secondary sorted aluminium**	**kg**	0.81300813
Electricity medium voltage	kWh	5.2033E-02	Hydrogen chloride	kg	8.9431E-06
Heat: heavy fuel oil	MJ	1.3496E-01	Total Particulates, PM	kg	2.3577E-05
Heat: natural gas	MJ	8.2927E-01	• <$PM_{2.5}$: 32%	kg	7.5447E-06
Heat consumption total	MJ	9.6423E-01	• PM_{10} < x >$PM_{2.5}$: 48%	kg	1.1317E-05
Water	m^3	0	• >PM_{10} : 20%	kg	4.7154E-06

Adapted from (Althaus 2004), (UBA 2000)

After sorting, the sorted aluminium undergoes mechanical conditioning, which leads as well to energy consumption, dust and different inorganic emissions. This process is carried out in melting and allowing facilities. The respective inventory of mechanical conditioning of secondary sorted aluminium is shown in Table 4-14. Finally, the emission inventory for the mechanical recycling of aluminium is shown in Table 4-15. Additionally, neither sorting nor conditioning activities generated fugitive emissions to water.

Table 4-14 MRF: Conditioning of sorted aluminium

Input	Unit	Mean value	Output	Unit	Mean Value
Secondary sorted aluminium	**kg**	**1**	**Secondary aluminium billets**	**kg**	0.9709
Electricity medium voltage	kWh	2.7961E-01	Ammonia	kg	1.9417E-05
Heat: heavy fuel oil	MJ	4.9806E-01	Hydrogen sulphide	kg	2.7184E-06
Heat: natural gas	MJ	8.0291E+00	Hydrogen chloride	kg	3.9806E-06
Heat consumption total	MJ	8.5272E+00	Total Particulates, PM	kg	2.3301E-05
Water	m^3	7.7282E-03	• <$PM_{2.5}$: 32%	kg	7.4563E-06
			• PM_{10} < x >$PM_{2.5}$: 48%	kg	1.1184E-05
			• >PM_{10} : 20%	kg	4.6602E-06

Adapted from (Althaus 2004), (UBA 2000)

Table 4-15 MRF Aluminium

Input	Unit	Mean value	Output	Unit	Mean Value
Recovered aluminium	kg	1	**Secondary aluminium billets**	kg	0.789349593
Electricity medium voltage	kWh	2.79E-01	Ammonia, NH_3	kg	1.58E-05
Heat: heavy fuel oil	MJ	5.40E-01	Hydrogen sulphide, H_2S	kg	2.21E-06
Heat: natural gas	MJ	7.36E+00	Hydrogen chloride, HCl	kg	1.22E-05
Heat consumption total	MJ	7.90E+00	Total Particulates, PM	kg	4.25E-05
Water	m^3	6.28E-03	· <$PM_{2.5}$: 32%	kg	1.36E-05
			· PM_{10} < x >$PM_{2.5}$: 48%	kg	2.04E-05
			· >PM_{10} : 20%	kg	8.50E-06

Adapted from (Althaus 2004), (UBA 2000)

4.2.3.5 Waste wood

Inventoried environmental impacts for the conditioning of waste wood into wood chips/pellets are energy consumption and dust emission. Dust emissions are generated in the size reduction section. This life cycle inventory is shown in Table 4-16. Energy consumption is estimated to be around 20 kWh per Mg dried matter.

Table 4-16 MRF waste wood

Input	Unit	Mean value	Output	Unit	Mean Value
Waste wood	**kg**	**1**	**Wood chips/pellets**	**kg**	1
Electricity medium voltage	kWh	20E-03	Total particulates, PM	kg	

Adapted from (Werner 2003)

4.2.3.6 Waste electrical or electronic equipment (WEEE)

a. WEEE without CFC: Inventoried environmental impacts for the conditioning of waste electrical or electronic equipment are only energy consumption. Energy consumption is estimated to be around 40 kWh per Mg of WEEE (Smith 2001).

b. WEEE containing CFC: WEEE such as refrigerators and freezers contain CFCs. This material is present in the refrigerant gas and in the insulation foam, as CFC12 and CFC11 respectively. Additionally, the weight fraction of CFC12 and CFC11 is of 4.03E-3 and 1.34E-02 kg per kg of WEEE containing CFC, respectively. In the recycling process, all the refrigerant gas is collected but it escapes after disposal. Similarly, 60% of the insulation foam is released as gas during recycling and landfill operations, while the remainder has been released during the life time of the product (Smith 2001, ICER 2000). Thus in this model it is assumed that all the CFC is emitted to the atmosphere. The global warming potential of CFC12 is 8100 and from CFC11 is of 3800. Consequently, then the recycling process of one WEEE containing CFC emits to the atmosphere 83.7365 kg of CO_2-eq. Mechanical recycling of both WEEE containing CFC and without CFC have an average energy consumption of 40 kWh per Mg of WEEE, as shown in Table 4-17.

Table 4-17 MRF WEEE

Input	Unit	Mean value	Output	Unit	Mean Value
WEEE containing CFC	**kg**	**1**	**F(WEEE composition)**		
Electricity medium voltage	kWh	40E-03	CFC as CO_2-eq	kg	83.7365

Adapted from (Smith 2001)

4.2.3.7 Construction and demolition waste (C&D waste)

Inventoried environmental impacts for the conditioning of construction and demolition waste are energy consumption and dust emission. Dust is generated only when mineral construction waste fraction such as concrete, brick, cement and gypsum are crushed. The life cycle inventory for the sorting and conditioning of C&D waste is shown Table 4-18.

Table 4-18 MRF C&D waste

Input	Unit	Mean value	Output	Unit	Mean Value
Recovered metal	**Kg**	**1**			
Electricity medium voltage	kWh	3.7E-03	Total Particulates, PM	kg	1.5665E-4
Heat: heavy fuel oil	MJ		• <$PM_{2.5}$: 10.17%	kg	1.5931E-5
Heat: natural gas	MJ		• PM_{10} < x >$PM_{2.5}$: 38.76%	kg	6.0717E-5
Heat consumption total	MJ		• >PM_{10} : 51.07%	kg	8.0000E-5

Adapted from (Doka 2003)

4.2.3.8 Textiles

The recovery of the textile fraction in mechanical recycling facilities does not have inventoried environmental impacts neither to air nor to water.

4.2.3.9 Refuse derived fuel / solid recovered fuel (RDF/SRF)

Inventoried environmental impacts from the conditioning of refuse derived fuel are related to energy consumption. Under normal operation conditions, this waste management operation consumed between 50 and 80 kWh per Mg of dry input waste, as indicated in Table 4-19.

Table 4-19 MRF RDF

Input	Unit	Mean value	Output	Unit	Mean Value
Mix waste	**kg**	**1**	**RDF/SRF**	**kg**	**F(input waste)**
Electricity medium voltage	kWh	(5-8)E-02			

Adapted from (Greenpeace 2003), (IPPC 2005a)

4.2.4 Energy consumption

Energy consumption depends on the type of mechanical recycling facility. Typical energy consumption values are shown in Table 4-20. Consequently, the total amount of energy that is consumed in these waste management operations is calculated with a process-specific model, which is defined by Equation 4-12.

Equation 4-12 MRF energy consumption

$$EU_{s,ES} = EF_{MRFT_s,ES} \cdot \sum_{w} m_{s,w}$$

where:

$EU_{s,ES}$ Total energy type *ES* consumed by mechanical recycling facility *s*
$EF_{MRFTs,ES}$ Emission factor of energy type *ES* consumed by the mechanical recycling facility *s* type *MRFTs*
ES Energy source (ES=1…3: electricity, diesel, heat)

Table 4-20 MRF energy consumption

Eui		Fe	NFe-Al	Mix-Fe	Paper	Glass	Plastic	Wood	WEEE	Construction
Power	kWh/Mg	10.00	279.00	144.50	575.76	238.47	157.28	20.00	40.00	3.70
Diesel	Mg/Mg	0.00	0.00	0.00	0.00	1.94	0.00	0.00	0.00	0.00
HFO	MJ/Mg	0.00	540.00	270.00	0.00	1,503.70	0.00	0.00	0.00	0.00
HNG	MJ/Mg	0.00	7,360.00	3,680.00	6,970.16	4,930.40	0.00	0.00	0.00	0.00

HFO: heat fuel oil; HNG: heat natural gas
Adapted from (Althaus 2004, Doka 2003, Hischer 2004, Werner 2003, Smith 2001 and UBA 2000)

4.2.5 Costs

4.2.5.1 Treatment Cost

The treatment costs for mechanical recycling facilities depend on several factors such as:

- Range of materials being processed
- Scale

- Degree of automatism
- Quality of input materials
- Quality of end products
- Market prices for recovered materials
- Disposal costs of rejects

The diversity of recycling technologies and the number of recovery lines make impossible to define a common treatment costs scheme for the existing MRF. As a result, in this model the recycling cost is not estimated as a function of the choice of technology or treatment capacity of the plant, but to existing licenses fees imposed by recycling organisations such as the Duales-System-Deutschland (DSD). The overall system for the collection, sorting and recovery of recyclables is financed with the licenses fees paid by trade and industry for the right to use the Green Dot (DSD 2006). These license fees apply exclusively to selected recyclables. They are calculated based on the material that makes up the complete registered pack and the corresponding material prices (DSD 2006). As a result, the final treatment costs is calculated by multiplying the total amount of primary waste entering to the MRF with its respective individual licence fee, as shown in Equation 4-13. Individual license fees are given in Table 4-21. The practitioner can modified this default values as required.

Table 4-21 MRF treatment costs

Primary waste *i*	*ILFi*	(Smith 2001)	(DSD 2006) Germany
		€/Mg	€/Mg
Paper and board	200101	410-470	180.00
Glass	200102	34	76.00
Lightweight packaging	200139	845-915	1,350.00
Aluminium	200140	945	756.00
Ferrous metal	200140	22	280.00
Waste Wood	200138		102.00
WEEE containing CFC	200135	180-2445	970.00
WEEE without CFC	200136		970.00
Clothes and textiles	200110	1180	102.00
Construction and demolition waste	170904		-

Equation 4-13 MRF treatment costs

$$TC_s = \sum_i ILF_i \cdot m_{s,i}$$

where:

TC_s Treatment costs at the mechanical recycling facility *s*
ILF_i Individual license fee for the primary waste *i*
$m_{s,i}$ Material flow input of the primary waste *i* entering to the mechanical recycling facility *s*

The main disadvantage of MRF is their higher cost in comparison with other waste management operations. Therefore, economic and market-based instruments are used to promote recycling.

4.2.6 Benefits

4.2.6.1 Recovered Energy

Mechanical recycling facilities do not recover energy in any sense.

4.2.6.2 Recovered Material

Mechanical recycling facilities are suitable to recover a big spectrum of valuable products. Moreover, recovered materials in MRF should be considered as tradable goods as they substitute the use of primary resources at a lower environmental impact. In the one hand, "clean" MRF are able to recover and recycle materials such as paper, glass, plastics, composites, metals (ferrous and non-ferrous), wood pellets and textiles. Considered plastic fractions include PET, HDPE, PVC, LDPE, PP, PS, PU and mixed plastics. The benefit from the recovery of this material is determined by their market prices and their commercialisation. On the other hand, "dirty" MRF are able to recover RDF/SRF. The benefit of this recovered material depends on its composition, which is determined by its calorific value and for its water, ash, sulphur and chlorine content. The physical composition of the RDF recovered in "dirty" MRF was previously defined by the variables $mOF_{s,w}$. Only RDF/SRF that fulfils existing quality criteria (e.g. RAL-GZ 724, SFS 5875 and the EURITS criteria) can be commercialised as a fuel substitute in co-incineration plants. In the secondary material market, solid fuels have low or negative revenue. RDF is accepted by co-incineration plants by paying a fee gate between 0 and 40 €/Mg. SRF may have a fee gate between -30€/Mg and 35€/Mg (LCA IWM 2005). Finally, the total revenues from the sale of recovered material are calculated with Equation 4-14. This equation makes use of the individual market prices for recovered materials as given in Table 4-22.

Table 4-22 Market prices of recycled material, €/Mg

Rcm	$PRCM_{rcm}$	[GRN 2005] Jun 2005	GRN Address
Mixed scrap iron & steel (Fe)	125.86	Steel & iron scrap recycling	http://www.grn.com/a/0460.html
Metals - NFe as Al.	492.87	Aluminium scrap recycling	http://www.grn.com/a/0403.html
Metals – Mixed	125.86	Scrap metal recycling	http://www.grn.com/a/0400.html
Paper	15.53	Waste paper recycling	http://www.grn.com/a/1200.html
Glass cullets	24.84	Glass and Fiberglas recycling	http://www.grn.com/a/0900.html
Polyethylene Terephthalate, PET	766.68	PET recycling	http://www.grn.com/a/1001.html
High density polyethylene, HDPE	638.90	HDPE recycling	http://www.grn.com/a/1002.html
Polyvinyl chloride, PVC	474.61	Vinyl recycling	http://www.grn.com/a/1003.html
Low density polyethylene, LDPE	565.88	LDPE recycling	http://www.grn.com/a/1004.html
Polypropylene, PP	565.88	PP Polypropylene recycling	http://www.grn.com/a/1005.html
Polystyrene, PS	474.61	PS Polystyrene Recycling	http://www.grn.com/a/1006.html
Polyurethane, PU	621.00	Polyurethane foam recycling	http://www.grn.com/a/1025.html
Mixed Plastic	18.25	Mixed sortable plastic scrap	http://www.grn.com/specs/gr100796.html
Mixed Composites	-		
Wood chips	15.00	Wood recycling	http://www.grn.com/a/1100.html
Mixed WEEE scrap	9.94	Electronic recycling	http://www.grn.com/a/0300.html
Construction mineral material	0.00	Mineral recycling	http://www.grn.com/a/0800.html
Clothes and textiles	0.00	Textiles and leather recycling	http://www.grn.com/a/1400.html
RDF	00 – 40		(LCA IWM 2005)
SRF	-30 – 35		(LCA IWM 2005)

Equation 4-14 MRF revenues from recovered material

$$\text{for } k = 1\,(\text{MRF}):$$

$$BRM_k = \sum_s \left(mRCM_{s,rcm} \cdot PRCM_{rcm} \right)$$

where:

BRM_k Benefit form the sale of recycled material *rcm* produced in the mechanical recycling facility *s*
$mRCM_{s,rcm}$ Material flow of recycled material *rcm* recovered in the mechanical recycling facility *s*
$PRCM_{rcm}$ Market price of the recycled material *rcm*

4.2.6.3 Displaced resources and emissions

Displaced resources and emissions derive from the potential recovery of recyclable material such as paper, glass, plastics, composites, metals (ferrous and non-ferrous), wood pellets,

textiles and RDF. Considered plastic fractions include PET, HDPE, PVC, LDPE, PP, PS, PU and mixed plastics. In the one hand, in this model is assumed that recyclables materials will have a substitution rate equal to 1:1. This means that one mass unit of recyclable material will substitute one mass unit of the same material produced exclusively with virgin raw materials.

On the other hand, RDF is used in co-incineration operations as substitute of conventional sources of energy such as coal, fuel oil and natural gas (Gendebien 2003). The potential amount of energy that can be recovered from this material is related to its calorific value. The calorific value of this material is calculated as a function of its macro-chemical composition with the ultimate analysis equation derived by Dulong (Kathiravale 2003) and defined by Equation 2-1. Finally, the potential amount of recovered energy will be proportional to the amount of displaced fugitive emissions associated to the country-specific power plant technology and on the fuel source that is used to generate the same amount of energy.

5 BIOLOGICAL TREATMENT: COMPOSTING

5.1 PROCESS DESCRIPTION

Composting is the aerobic decomposition and biodegradation of biodegradable waste under controlled conditions, which produce a stable, odourless, humus-like product rich in organic matter suitable for soil improvement. The microorganisms that carried out this process include bacteria, fungi and actinomycetes.

The variety of composting technologies is extensive but it can be well represented by three main systems that are the non-reactor, the enclosed reactor and the in-vessel reactor system. These systems are further divided according to the installed aeration system and the turning equipment as shown in Table 5-1.

Table 5-1 Aerobic biological treatment process types

Turning Method	Non-Reactor System, NRS	Enclosed Reactor System, ERS	In-Vessel Reactor System, IVRS
Static	aerated static pile (ASP) naturally ventilated pile	aerated static pile (ASP)	box, container, tunnel
Agitated	aerated agitated pile naturally ventilated pile	tunnel, aerated agitated pile	box, container, tunnel, vertical-flow
Dynamic	-	-	rotating drum, vertical-flow

The non-reactor system is the basic composting technology currently employed and it is represented by the windrow composting. Biodegradable waste is piled in non-enclosed long triangular cross section rows (windrows) where it is decomposed and biodegraded. According to the employed technology, windrows can be either static or agitated piles, with or without forced aeration. Composting duration is between one to twelve weeks, time that defines the final compost quality (BGK 2005). However, this technology is being progressively abandoned because its fugitive emissions to air are not controlled and they do not fulfil existing maximum emission levels to air imposed by national and international laws such as the 30th Federal Immission Control Ordinance on biological treatment of waste (30. BImSchV) in Germany.

Enclosed and in-vessel reactor systems confine the input biodegradable waste within a building, container or vessel. These systems minimised the thermal exchange with the atmosphere and speed up the composting process due to its optimised turning system (static, agitated or dynamic), forced aeration, moisture content and temperature control. Currently, there are different technologies in used such as the aerated static pile, box, container, tunnel, rotating drum and the vertical flow reactor.

5.2 BTA SUB-MODEL

The aerobic biological treatment sub-model (BTA) assesses the life cycle of exclusively biodegradable municipal solid waste fractions. Accepted fractions or waste categories for aerobic biological treatment are shown in Table 5-2 and they are codified according to its entry in the European Waste Catalogue (EWC) adopted with Commission Decision 94/3/EC. Compost sludge will be treated only if the sewage sludge complies with the limits for sludge use in agriculture, as set by the Sewage Sludge Directive 86/278/EEC.

As shown in Figure 5-1, sub-model starts when selected waste categories enters to the waste management facility and ends not only when they are transformed into a valuable end product but also when they are emitted as a fugitive emission to air, water and land. Valuable products such as metals and compost are recovered and commercialised in exiting markets. Secondary

wastes such as the oversized fraction are collected for further treatment prior to landfilling as required by the Landfill Directive 1999/31/EC. Acceptable treatments include mechanical-biological and thermal treatment.

Table 5-2 Accepted waste categories subject to aerobic biological treatment

EWC	Waste category, *w*
200101	Separately collected paper and cardboard from MSW
200107	Separately collected wood from MSW
200108	Biowaste: organic biodegradable kitchen waste
200201	Greenwaste: biodegradable waste from gardens, parks and cemeteries
200302	Waste from markets
200303	Street-sweeping waste
200306	Waste from sewage cleaning

The life cycle inventory of the aerobic treatment process is calculated using product and process-specific model. The life cycle inventory is assessed with the life cycle impact assessment method named Environmental Priority Strategy in product design (EPS).

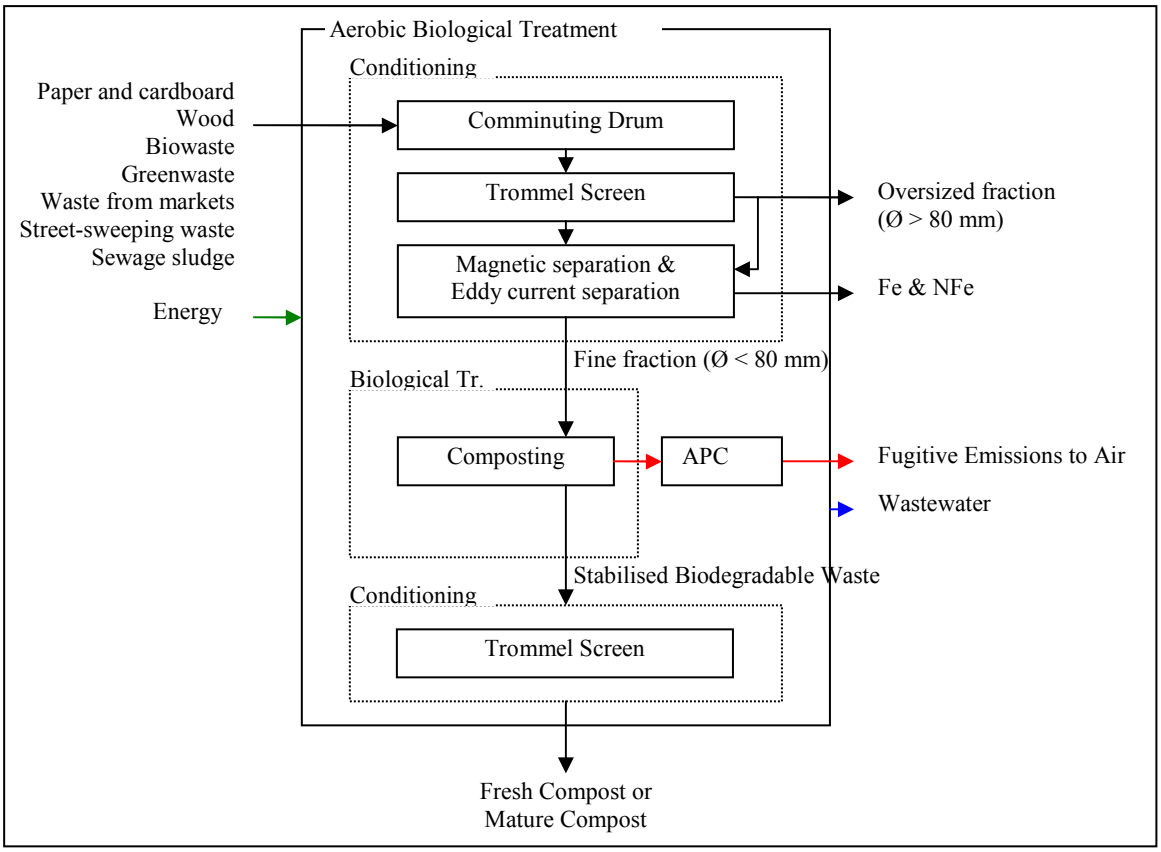


Figure 5-1 Aerobic biological treatment

Every waste management facility is unique so as well its process treatment sequence. However, most of them consist of three main sections that are the front-end pre-conditioning, biological treatment and final conditioning. This sub-model considers this treatment sequence as standard.

5.2.1 BTA Internal Process

5.2.1.1 Material input

According to the multi-commodity flow distribution approach, the waste category *w* generated at the source point *j* will compete for the scarce and finite network capacity of the aerobic biological treatment plant *a*, which is restricted to accept only biodegradable waste category types. Individual material flow distribution is calculated using Equation 5-1. The biodegradable waste flow distribution ($m_{j,a,w}$) is calculated in advance as showed in subchapter 3.4.1, which is related to logistic constraints.

Equation 5-1 BTA waste category *w* input acceptance

$$m_{a,w} = \sum_{j} m_{j,a,w}$$

subject to :

$$m_a = \sum_{w} m_{a,w}$$

$$PTC_a > m_a$$

where:

$m_{a,w}$	Total waste category *w* material flow entering to the aerobic biological treatment unit *a*, [Gg]
$m_{j,a,w}$	Waste category *w* generated at point *j* and entering to the aerobic biological treatment unit *a*, [Gg]
m_a	Total amount of waste accepted for treatment in aerobic biological treatment *a*, [Gg]
PTC_a	Plant treatment capacity *a*, [Gg]

5.2.1.2 Mechanical Treatment: Front-end pre-conditioning

5.2.1.2.1 Comminuting Drum

This device is a rotating drum, where soft organic material break down to smaller particles with a diameter smaller than 80 mm while inert materials such as plastic, textiles and metals do not suffer any size reduction. Any glass material content in the input flow is reduced in size as well. The integer variable (SOM_w) is used to represent which waste category *w* is subject to comminution. Soft organic material will have a SOM_w value equal to 1, otherwise it is equal to zero.

5.2.1.2.2 Trommel Screen

After the comminution drum, the waste is screened in a trommel screen. The model considers a trommel screen with one opening size of 80 mm, where input waste material is divided in two fractions named fine fraction (Φ<80 mm) and oversized fraction (Φ>80 mm). The fine fraction contains a high percent of organic material, which is suitable for biological treatment. The oversized fraction will consist mainly of impurities such as mixed plastics, textiles, paper and board or similar non-biodegradable materials, which require further treatment prior landfilling. Fine and oversized fraction are calculated with Equation 5-2 and Equation 5-3, respectively.

Equation 5-2 BTA Fine Fraction

$$mFF_{a,w} = m_{a,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w\right)$$

Equation 5-3 BTA Oversized Fraction

$$mOF_{a,w} = m_{a,w} \cdot \left(1 - SOM_w\right) \cdot \left(1 - WPD_w\right)$$

where:

$mFF_{a,w}$	Fine Fraction mass flow from aerobic biological treatment *a*, [Gg]
$mOF_{a,w}$	Oversized Fraction mass flow from aerobic biological treatment *a*, [Gg]
$m_{a,w}$	Mass flow of the waste category fraction *w* which enters to the aerobic biological treatment *a*, [Gg]
SOM_w	Integer variable for the waste category *w* that is subject to comminution For the waste category *w*, which is soft organic material then, SOM_w is equal to 1, otherwise to 0.
WPD_w	Waste Particle Distribution fraction lower than 80 mm for the waste category *w*

5.2.1.2.3 Metals separation

Ferrous metals are recovered from the waste input by means of a magnet unit, while aluminium by means of an eddy-current separator. Both recovery units are commonly suspended above the fine and oversized conveyor belt. It is assumed that the total metal input is separated and recovered from the feedstock stream and calculated with Equation 5-4.

Equation 5-4 Metal separation

$$for\ w = 1..3:$$

$$Metal_{a,MET} = m_{a,w}$$

where:

$mMetal_{a,MET}$	Metal mass flow type *MET* separated and recovered from the aerobic biological treatment unit *a*, [Gg]
MET	Metal type: 1 = metal, 2 = aluminium, 3 = mix

5.2.1.3 Aerobic biological treatment: composting

Based on the chemical composition and on the degradability potential of the fine fraction, it is possible to calculate the amount of potential degradable material *(PDM)* subject to aerobic biodegradation. This approach follows the default method (Tier 1), which is recommended by the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000). The potential degradable material is calculated with Equation 5-5. This equation is restricted with the integer variable $BDR_{cc,}$ which fixes water, inert material and heavy metals input into the substrate.

Equation 5-5 Potential Degradable Material, $PDM_{a,cc}$

$$PDM_{a,cc} = \sum_{w} \left[m_{a,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right) \cdot DOC_w \cdot DOCF_a \cdot MCC_{w,cc} \cdot BDR_{cc} \right]$$

Similarly, the chemical composition of the generated compost is calculated with Equation 5-6 as a dry basis. Similarly, Equation 5-6 calculates the compost composition in a wet basis considering the desire final percent of total solids. The standard RAL-GZ 251 from the German Composting Organisation (Bundesgütegemeinschaft Kompost e.V.) defines a minimum value of total solids equal to 60% (BGK 2005). Composting residence time will determinate the final compost quality and the grade of waste biodegradation. Aerobic biological treatments with a residence time between one and four weeks will produce fresh compost, which is hygienic, fractionated compost with a decomposition degree II or III. Finally, composting residence time between five and twelve weeks generates mature compost, which is hygienic, biologically stable and fractioned compost with a decomposition degree IV or V.

Equation 5-6 Compost composition, dry basis

$$Compost_{a,cc} = \sum_{w} \left[m_{a,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right) \cdot MCC_{w,cc} \cdot \left(MF_{cc} - DOC_w \cdot DOCF_a \cdot BDR_{cc} \right) \right]$$

Equation 5-7 Compost weight, wet basis @%TS

$$Compost_a = \frac{100}{\%TS} \left\{ \sum_{cc} \sum_{w} \left[m_{a,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right) \cdot MCC_{w,cc} \cdot \left(MMF_{cc} - DOC_w \cdot DOCF_a \cdot BDR_{cc} \right) \right] \right\}$$

The value of the dissimilated organic carbon fraction (*DOCF*) for aerobic processes is different to one form anaerobic processes. For aerobic processes, it can be calculated with Equation 5-8 as a function of the composting residence time. This equation is a modification of the one proposed by (MUNLV 1998. Thus, if it is assumed that the composting residence time required to produce fresh compost is of four weeks then its $DOCF_a$ will be equal to 0.2061. Similarly, for the generation of mature compost with a residence time of twelve weeks the expected $DOCF_a$ is equal to 0.4996.

Equation 5-8 Degradable organic dissimilated fraction for aerobic biological treatments, Adapted from (MUNLV 1998)

$$DOCF_a = 1 - \exp^{(-0.0577 \cdot CRT_a)}$$

where:

$PDM_{a,cc}$	Mass flow of the chemical compound *cc* which is potentially degradable in the aerobic biological treatment *a*; [Gg]
DOC_w	Degradable organic carbon fraction of the waste category fraction *w*; -
$DOCF_a$	Degradable organic carbon dissimilated fraction as a function of the composting residence time ; -
CRT_a	Composting retention time in weeks; -
$MCC_{w,cc}$	Matrix [waste category fraction *w* vs. chemical compound *cc*] ; -
BDR_{cc}	Integer variable that represents which chemical compound is subject to biological degradation. ; - For *cc* equal to water, inert material and heavy metals then BDR_{cc} is equal to 0, otherwise equal to 1.
MF_{cc}	Integer variable for setting the equation as moisture free basis; - For *cc* equal to water MF_{cc} is equal to 0, otherwise equal to 1.
MMF_{cc}	Integer variable for setting the equation as moisture & heavy metals free basis; - For *cc* equal to water and heavy metals, MMF_{cc} is equal to 0, otherwise equal to 1.
%TS	Percent total solids; %
MW	Molecular weight; g/gmol

5.2.1.4 Product preparation, fine conditioning

Stabilised biodegradable waste or compost is screened before being used by the existing market share. In the case of mature compost, there are three main fractions obtained after screening, which are named fine compost, coarse compost and screen overflow. These fractions represent the 60-70%, the 20-30% and the 10% of the rot output, respectively (ASA 2004). Fine and coarse compost can be used as a substitute of virgin soil. The screen overflow can be recycled as structural material for the composting process or as a final landfill cover.

5.2.2 Secondary Waste

The front-end pre-conditioning section segregates the oversized fraction, which consists mainly of inorganic impurities. This rejected fraction required further treatment before it could finally be disposed in a landfill. Recommended treatment technologies include mechanical-biological treatment and thermal treatment.

Following the multi-commodity flow distribution approach, the oversized fraction will compete for scarce and finite network capacity and it will be restricted to its organic component of dry residue in original substance for its final disposal in landfills as shown in Equation 5-9. In order to keep the balance within the system is required to fix two mass balance equations, one for the decision variables (Equation 5-10) and one for the distributed oversized fraction (Equation 5-11).

Equation 5-9 BTA oversized fraction distribution flow within the system

$$mOF_{a,m} = \sum_w \left[m_{a,w} \cdot (1 - SOM_w) \cdot (1 - WPD_w) \right] \cdot \delta AM_{a,m}$$

$$mOF_{a,t} = \sum_w \left[m_{a,w} \cdot (1 - SOM_w) \cdot (1 - WPD_w) \right] \cdot \delta AT_{a,t}$$

$$mOF_{a,l} = \sum_w \left[m_{a,w} \cdot (1 - SOM_w) \cdot (1 - WPD_w) \right] \cdot \delta AL_{a,l} \cdot LFRA_a$$

where:

$$LFRA_a = \begin{cases} 0 & if \sum_w \left[Maw \cdot MCC_{w,C}\right] > LFC_C \cdot \sum_w \left[Maw \cdot \left(1 - MCC_{w,H_2O}\right)\right] \\ 1 & if \sum_w \left[Maw \cdot MCC_{w,C}\right] \leq LFC_C \cdot \sum_w \left[Maw \cdot \left(1 - MCC_{w,H_2O}\right)\right] \end{cases}$$

$$and: Maw = m_{a,w} \cdot (1 - SOM_w) \cdot (1 - WPD_w)$$

Equation 5-10 BTA decision variables mass balance

$$1 = \sum_m \delta AM_{a,m} + \sum_t \delta AT_{a,t} + \sum_l \delta AL_{a,l}$$

Equation 5-11 BTA oversized fraction mass balance

$$mOFa = mOF_{a,m} + mOF_{a,t} + mOF_{a,l}$$

where:

m,t,l	Mechanical-biological unit m, thermal treatment unit t, landfill l; -
$\delta AX_{a,x}$	Decision variable which determinates the fraction of the oversized fraction generated in aerobic biological unit a and transported to units m ,t, l; -
LFR_a	Oversized fraction transportation restriction to landfill generated in unit a; -
$LFCC$	Landfill disposal limit criteria for organic component of dry residue; -
$mOF_{a,(m,t,l)}$	Oversized fraction material flow distribution from unit a to unit (m,t,l) ; Gg

5.2.3 Fugitive Emissions to Air, FEA_a

5.2.3.1 FEAa generation

Fugitive emissions to air generated during the aerobic treatment of biodegradable waste include the following ones:

- Carbon dioxide
- Trace gases such as ammonia, methane and some volatile organic compounds, which are produced in anaerobic zones within the rot
- Bio-aerosols, which are generated when the composting material is turned
- Odours, which are mainly produced by organic and inorganic sulphurated compounds, nitrogenous compounds, volatile acids, aldehydes and ketones
- Dust, which is generated during chipping and grinding activities, from wind entrainment of static uncovered windrows and as a result of compost turning, curing, screening, storage and loading

Under optimal aerobic conditions, the potential degradable material *(PDM)*, which was calculated with Equation 5-5, will be transformed by the aerobic bacteria into raw gas following the biochemical Reaction 5-1. However, this biochemical process is not completely achieved due to the presence of anaerobic zones within the rot. This occurs when the rot is built incorrectly, the rot is not well aerated, the temperature is too high or when the moisture level is not optimal. Under these circumstances, it has been documented that between 1 and 1.7%, with an average of 1.35% of the potential degradable carbon is emitted as methane. Additionally, around 0.05% of the potential degradable carbon is as well converted into carbon monoxide. On the other hand, approximately 1.2% of the potential degradable nitrogen is emitted as ammonia and 0.5% as nitrous oxide. Remaining potential degradable material is oxidised to low-energy compounds such as NO_3^-, SO_4^{-2} and the remainder is synthesized into cellular material (Nemecek 2004, Coe 2004, Soyez 2002, Beck-Friis 2001, Hellebrand 1998, Garibay 2001, LfU 1997, Hellmann 1997, Rösch 1996, Garibay 1996, Angerer 1999, Häusler 1998).

Reaction 5-1 Biochemical aerobic degradation

$$C_cH_hO_oN_nS_sCl_l + O_2 + nutrients \xrightarrow{bacteria} cCO_2 + (0.5h - 1.5n - s - 0.5l)H_2O + nNH_3 + sH_2S + lHCl$$

Compounds shown in the right-hand side of Reaction 5-1 are calculated stoichiometrically with Equation 5-12. On the other hand, selected trace gases are calculated with Equation 5-13. For both equations, waste-specific coefficients are shown on Table 5-3. Figures for other emissions than the ones listed in this table have not been identified by this study.

Equation 5-12 Potential degradable material-specific emission model

$$m_{a,FEA} = PDM_{a,CC} \cdot \frac{MW_{FEA}}{MW_{CC}} \cdot EF_{FEA}$$

substituting *FEA*:

$$m_{a,CO_2} = PDM_{a,C} \cdot \frac{MW_{CO_2}}{MW_C} \cdot EF_{CO_2}$$

Equation 5-13 Potential degradable material process-specific emission model

$$m_{a,FEA} = EF_{FEA} \cdot \sum_w \left[m_{a,w} \cdot \left(SOM_w + (1 - SOM_w) \cdot WPD_w \right) \right]$$

substituting *FEA*:

$$m_{a,Cd} = EF_{Cd} \cdot \sum_w \left[m_{a,w} \cdot \left(SOM_w + (1 - SOM_w) \cdot WPD_w \right) \right]$$

Table 5-3 Non-reactor system raw gas emission inventory

			Biowaste	Green waste	Sludge	mix MSW
Methane	CH_4	kg/ kg_{in}	1.00 %C	1.70 %C	1.67E-02	3.03E-02
Nitrous oxide	N_2O	kg/ kg_{in}	0.50 %N	0.50 %N		2.92E-05
Sulphur dioxide	SO_2	kg/ kg_{in}				6.36E-05
Nitrogen dioxide	NOx	kg/ kg_{in}	3.81 %N	3.81 %N		
Ammonia	NH_3	kg/ kg_{in}	1.20 %N	1.20 %N	1.40E-03	6.11E-04
Hydrogen chloride	HCl	kg/ kg_{in}				1.69E-06
Hydrogen sulphide	H_2S	kg/ kg_{in}			1.10E-4	2.34E-10
Non-methane volatile organic compounds	NMVOC	kg/ kg_{in}	1.55E-03	2.75E-03	1.56E-03	2.15E-03
Dioxins & Furans	PCDD/F	kg/ kg_{in}				10E-14
Polycyclic aromatic hydrocarbons	PAH	kg/ kg_{in}				
Carbon monoxide	CO	kg/ kg_{in}	0.05 %C	0.04 %C		
Particulates, 2.5mm <PM < 10mm	PM	kg/ kg_{in}	3.50E-05			
Cadmium	Cd	kg/ kg_{in}				2.30E-09
Thallium	Tl	kg/ kg_{in}				1.18E-08
Mercury	Hg	kg/ kg_{in}				1.66E-08
Antimony	Sb	kg/ kg_{in}				2.35E-08
Arsenic	As	kg/ kg_{in}				3.63E-09
Lead	Pb	kg/ kg_{in}				2.25E-08
Chromium	Cr	kg/ kg_{in}				2.28E-08
Cobalt	Co	kg/ kg_{in}				4.48E-09
Copper	Cu	kg/ kg_{in}				1.27E-08
Manganese	Mn	kg/ kg_{in}				5.53E-08
Nickel	Ni	kg/ kg_{in}				1.14E-07
Vanadium	V	kg/ kg_{in}				2.38E-08

[a] $\%CO_2$=100-($\%CH_4$-%CO)

Sources:

Biowaste: (Beck-Friis 2001), (Coe 2004), (Hellmann 1997), (Rösch 1996), (Soyez 2002), (Hellebrand 2001)

Greenwaste: (Garibay 2001), (Hellebrand 1998)

Sludge: (Garibay 1996)

MSW: (Angerer 1999), (Häusler 1998), (IPPC 2005), (LCA-IWM 2005)

5.2.3.2 FEAa controlled emission

5.2.3.2.1 Non-reactor system

Non-reactor system units do not have installed APC units on site and therefore its raw gas is uncontrolled emitted to the atmosphere. The inventory data of fugitive emissions to air from non-reactor systems is calculated using Equation 5-14. This equation considers that the APC removal efficiency (η_{APC}) is equal to zero due to the lack of control systems. This equation is used not only for non-reactor systems but also for enclosed ones. The η_{APC} value is a process-specific factor which depends on the aerobic biological treatment type, which is then restricted to the integer variable BTA_a. This variable is used as a variable vector used in the matrix $\eta_{APC:FEA,BTAa}$.

Equation 5-14 Raw gas process-specific emission model

$$FEA_{a,FEA} = m_{a,FEA} \cdot \left(1 - \eta_{APC:FEA,BTA_a}\right)$$

where:

$$BTA_a = \begin{Bmatrix} 1 & if\ a = NRS : non-reactor\ system \\ 2 & if\ a = ERS : enclosed\ reactor\ system \end{Bmatrix}$$

5.2.3.2.2 Enclosed and in-vessel reactor system

In enclosed and in-vessel reactor systems, the raw gas is effectively collected and treated by utilizing state-of-the-art composting technology and air pollution control units. It is common practice that the collected raw gas is treated in a biofilter before it is emitted to the atmosphere. Thus, fugitive emissions are significantly reduced in comparison with a non-reactor system. Under optimal operational conditions, biofilters can achieve good removal efficiencies. Typical removal efficiencies are shown in Table 5-4. In particular, organic compounds oxidize to carbon dioxide and water, while ammonia oxidizes into nitrates and the existing sulphide trace gases into sulphates as shown in Reaction 5-2.

Reaction 5-2 Biochemical reactions carried out in the biofilter

$H_2S+2O_2 \rightarrow BIO \rightarrow SO_4^{-2}+2H^+$
$NH_3+H_2O \rightarrow BIO \rightarrow NH_4^+ + OH^-$
$2NH_4^+ + 3O_2 \rightarrow BIO \rightarrow 2NO_3^- + 8H^+$
Organic volatile compounds + $O_2 \rightarrow BIO \rightarrow CO_2+H_2O$

(Soyez 2002), (Cuhls 1999) and (LfU 1997) have noticed that ammonia degraded in biofilters is oxidised into nitrous oxide, N_2O, and nitrogen oxide, NO. From the nitrogen mass balance shown in Figure 5-2, it is estimated that 22% of the total ammonia is oxidised to nitrous oxide, while 38% is oxidised to nitrogen oxide. These values are used as typical ones in Equation 5-15.

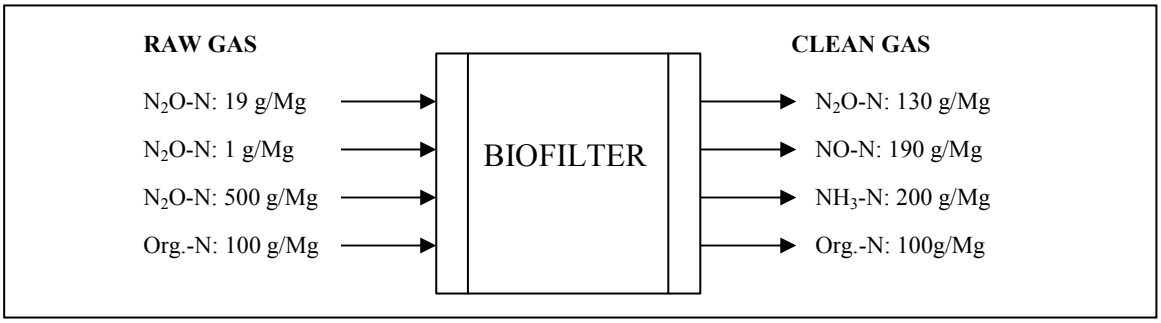


Figure 5-2 Nitrogen mass balance for a typical biofilter unit

The inventory data of fugitive emissions to air from enclosed and in-vessel reactor systems are calculated as well with Equation 5-14. As difference with NRS, ERS and IRS have installed APC units. Thus, they are subject to the APC removal efficiency values given in Table 5-4. Figures for other removal efficiencies than the ones listed in this table have not been identified by this study. Specific raw gases such as carbon dioxide, nitrous oxide and nitrogen dioxide are separately calculated with Equation 5-15. This equation follows the material specific emission modelling approach.

Equation 5-15 Raw gas material specific emission model

CO_2 $$FEA_{a,CO_2} = m_{a,CO_2} + m_{a,CH_4} \cdot \eta_{APC:CH_4,BTA_a} \cdot \frac{MW_{CO_2}}{MW_{CH_4}} + m_{a,CO} \cdot \eta_{APC:CO,BTA_a} \cdot \frac{MW_{CO_2}}{MW_{CO}}$$

N_2O $$FEA_{a,N_2O} = m_{a,N_2O} + m_{a,NH3} \cdot 0.22 \cdot \frac{MW_{N_2O}}{MW_{NH_3}}$$

NO_2 $$FEA_{a,NO_2} = m_{a,NO_2} + m_{a,NH3} \cdot 0.38 \cdot \frac{MW_{NO_2}}{MW_{NH_3}}$$

Table 5-4 APC-biofilter removal efficiency, %

η_{APC}, %	CH_4	CO	N_2O	NH_3	H_2S	NMVOC	PCDD/F	Odour
(Pitschke 2004)	50			95	-	-	-	95-99
(Soyez 2002)				90	-	83	40	-
(Adler 2001)				-	93-100	90	-	>95
(LCA-IWM 2005)	50		40	90	0	82	40	
(Entsorga 2005)				95		83		
In this study, fraction	0.50	0.50	0.40	0.95	0.95	0.83	0.40	0.95

5.2.4 Fugitive Emissions to Water, FEW_a

For non-reactor systems, leachate generation depends on the water content in the waste and the rainfall of the area. On the other hand, in enclosed and in-vessel reactor systems leachate generation is only a function of the waste moisture. For both systems, leachate generation is calculated with Equation 5-16, which is a water balance equation.

Equation 5-16 Water Balance Method for Aerobic Biological Units

$$WW_a = Leachate_a + P_a \cdot A_a + BWP_a$$

$$where:$$

$$Leachate_a = mFF_{a,H2O} \cdot DOC_{a,w} \cdot DOCF_a$$

$$A_a = RP_a \cdot \sum_w \frac{mFF_{a,w}}{\rho_{waste} \cdot h_{windrow}}$$

$$BWP_a = (1 - RP_a) \cdot MW_{H_2O} \cdot \left(\frac{0.5 \cdot PDM_{a,H}}{MW_H} - \frac{1.5 \cdot PDM_{a,N}}{MW_N} - \frac{PDM_{a,S}}{MW_S} - \frac{0.5 \cdot PDM_{a,Cl}}{MW_{Cl}} \right)$$

$$RP_a = \begin{cases} 1 & \text{if } BTC_c = \text{Non Reactor System} \\ 0 & \text{if } BTC_c = \text{Enclosed Reactor System} \end{cases}$$

where:

$mFF_{a,H2O}$	Fine fraction moisture content; Gg
A_a	Composting Area; m^2
P_a	Precipitation rate: mm H_2O y^{-1}= 1 m^{-2} y^{-1} ; mmH_2O
$\rho_{compost}$	Average compost density: $\rho_{compost}$ = 380 kg m^{-3}; kg m^{-3}
$h_{windrow}$	Average windrow height. $h_{windrow}$ = 1.8 m; m

BWP_a Biochemical water production; Gg
WW_a Wastewater; Gg
RPa Integer restriction variable; [0,1]

Some considerations need to be taken in order to use Equation 5-16. For non-reactor systems the biochemical produced water leaves the windrow as steam, so it is not accounted for the leachate generation ($BWP_a=0$). To calculate the amount of infiltrated rainfall infiltrated in the windrow, it is assumed an average compost density of 380 kg m^{-3} and an average windrow height of 1.8 m (EPA 1995). On the other hand, in enclosed and in-vessel reactor systems there is not input of rainwater (P_a=0). The water that is biochemical produced condenses in the walls of the container or vessel and this condensate is joined with the leachate flow. Equation 5-16 produces comparable results to the ones given in Table 5-5.

Table 5-5 Average wastewater discharged from selected enclosed composting technologies, l/Mg

	(Bidlingmaier 2000)			(Pitschke 2004)			Average
	Leachate A	Condensate B	Wastewater C=A+B	Leachate A	Condensate B	Wastewater C=A+B	Wastewater
	l/Mg	l/Mg	l/Mg	l/Mg	l/Mg	l/Mg	l/Mg
ERS: Tunnel	0-20	30-100	30-120	10-50	30-100	40-150	30-150
IVRS: Box	60-100	30-300	90-400	-	220-300	220-300	90-400
IVRS: Container	60-100	30-300	90-400	60-100	30-60	90-160	90-400
IVRS: Rotating drums	0-30	-	0-30	0-30	-	0-30	0-30
ERS & IVRS average wastewater discharge	-	-	-	-	-	-	150

No product specific model has been identified in this study able to predict the composition of leachate as a function of the waste categories subject to aerobic biological treatment. Therefore, this model quantifies the leachate composition of representative compounds with Equation 5-17 and the process-specific coefficients given in Table 5-6.

Equation 5-17 Fugitive emission to water

$$FEW_{a,FEW} = WW_a \cdot EF_{a,FEW}$$

Table 5-6 Average values from selected compounds founded in wastewater (leachate + condensate) from composting units without water treatment, g/l

	Source	(Bidlingmaier 2000)		(Pitschke 2004)		(IPCC 2005)		In this study, $EF_{a,FEW}$	
	Range	min-max	Aver	NRS	ERS	min-max	Aver	NRS	ERS
	Units	g/l	g/l	g/l	g/l	g/l	g/l	g/l	g/l
Biological Oxygen Demand	BOD_5	10-46	17	0.650	7.165	0.020-0.025	0.0225	0.650	7.165
Chemical Oxygen Demand	COD	18-68	35	1.5	15.940	0.12-0.20	0.16	1.5	15.940
Total Nitrogen	N-tot	0.5-2	1.140	0.203	0.145	0.07	0.07	0.203	0.145
Total Phosphorous	P-tot	0.08-0.26	0.120	0.025	0.025	0.001-0.003	0.002	0.025	0.025
Mercury	Hg	-	-	-	-	0	0	-	-

5.2.5 Energy consumption

Energy consumption will depend on the employed composting choice of technology. In this study, it is assumed that non-reactor systems (windrow) will have an average energy consumption of 0.5 kWh electricity and 4.68 l of diesel per Mg of waste. On the other hand, enclosed and in-vessel reactor units will consume in average 30kWh electricity per Mg of waste. In comparison with non-reactor systems, enclosed systems have a higher energy demand due to added energy consumption from process control units (temperature, humidity), air extractors and air pollution control units. These values are based on typical German and

Austrian composting units. Energy consumed by aerobic biological treatment units are calculated using Equation 5-18 and the process-specific coefficients given in Table 5-7.

Equation 5-18 BTA Energy consumption

$$EU_{a,ES} = EF_{BTA_a,ES} \cdot \sum_{w} m_{a,w}$$

subject to:

$$BTA_a = \begin{Bmatrix} 1 & if\ a = NRS : non-reactor\ system \\ 2 & if\ a = ERS : enclosed\ reactor\ system \end{Bmatrix}$$

where:

$EU_{a,ES}$ Total energy type *ES* consumed by aerobic biological treatment unit *a*
$EF_{BTAa,ES}$ Emission factor of energy type *ES* consumed by aerobic biological treatment type *BTAa*
ES Energy source

Table 5-7 Energy requirements from selected composting systems

Source	Choice of Technology	Electricity medium voltage	Diesel	Heat: Heavy fuel oil	Heat: Natural Gas
		kWh/Mg	MJ/Mg	MJ/Mg	MJ
(Hogg 2002)	ERS	50	38.4	-	-
OWARE	NRS	-	15	-	-
OWARE	ERS	27	5	-	-
(Pitschke 2004)	NRS	0.5	168	-	-
(Pitschke 2004)	ERS	30	-	-	-
(Rösch 1996)	IVRS: Box	19.5	-	-	-
(Rösch 1996)	IVRS: Tunnel	36.75	-	-	-
(Rösch 1996)	IVRS: Drum	18	-	-	-
(Smith 2001)	NRS	-	192	-	-
(Smith 2001)	ERS	40	0	-	-

*NRS: Non-reactor system, ERS: Enclosed reactor system, IVRS: In-vessel reactor system
Functional unit: 1-ton mix biodegradable waste.
Diesel (38.4 MJ/L, 48MJ/kg); Heavy fuel oil (42 MJ/kg); Natural gas (52 MJ/kg)

5.2.6 Costs

5.2.6.1 Treatment Cost

Aerobic biological treatment costs are affected by diverse parameters such as the:

- Source segregation efficiency
- Choice of technology
- Scale
- Plant capital costs (cost of land acquisition, planning costs and construction/plant development costs)
- Plant operation costs (plant utilisation rate)
- Revenues from stabilised organic material

The variety of treatment costs is extensive (Auksutat 1998, Crowe 2002, Hogg 2002, Hogg 2001, Pitschke 2004, Rösch 1996, Smith 2001, Steinfeld 2002). However, when one accounts for choice of technology and scale, there is a degree of convergence in the treatment costs. Typical aerobic biological treatment costs are given in Table 5-8.

For general planning purpose, the model uses Equation 5-19, which is a process-specific treatment cost equation. This equation is a function of the treatment technology and the plant treatment capacity.

Table 5-8 BTA Treatment Cost, €/Mg

Source	Min	Max	Aver	Comments
(Auksutat 1998)	56	102	79	ERS and IVRS. Include the cost of residue disposal and none income from sales.
(Crowe 2002)	30.25	79.16	-	NRS as a function of the plant treatment capacity (*PTC*): (*) € / Mg = 522.9 $PTC^{-0.254}$; $R^2 = 0.9794$ Scale: 2,000-100,000 Mg
(Crowe 2002)	62.87	160.96	-	ERS and IVRS as a function of the plant treatment capacity (*PTC*): (*) € / Mg = 1137.4 $PTC^{-0.2553}$; $R^2 = 0.9715$ Scale: 2,000-100,000 Mg
(Hogg 2001)	40	60		IVRS Scale: 20,000 Mg
(LCA-IWM 2005)	25	86	-	General treatment cost as a function of the plant treatment capacity (PCT): €/Mg = 908.02 $PCT^{-0.3131}$ Scale: 2,000 – 120,000 Mg
(Rösch 1996)	36	138	87	ERS and IVRS. Include the cost of residue disposal.
(Smith 2001)	-	-	35	NRS
(Smith 2001)	-	-	50	ERS
(Steinfeld 2002)	38	48	43	NRS. Include the cost of residue disposal and income from sales.
(Steinfeld 2002)	67	87	77	ERS and IVRS. Include the cost of residue disposal and income from sales.

Treatment costs are gate fees and include capital costs (site costs, planning costs and construction/plant development costs) and operating costs excluding the cost of residue disposal, staff costs, income from sales and residue/by product.

Equation 5-19 Aerobic biological treatment cost

a. Non-rector system

$$TC_a = \begin{cases} 75.85 & if\ PTC_a < 2{,}000 \\ 522.9 \cdot PTC_a^{-0.254} & if\ 2{,}000 < PTC_a < 100{,}000 \\ 28.08 & if\ PTC_a > 100{,}000 \end{cases}$$

b. Enclosed and in-vessel reactor system

$$TC_a = \begin{cases} 163.37 & if\ PTC_a < 2{,}000 \\ 1137.4 \cdot PTC_a^{-0.2553} & if\ 2{,}000 < PTC_a < 100{,}000 \\ 60.17 & if\ PTC_a > 100{,}000 \end{cases}$$

5.2.7 Benefits

5.2.7.1 Recovered Material

Recovered material consists mainly of stabilised organic material and less proportion can be as well the recovery of metals.

The final market price, use and market shares of compost are affected by several market drivers. These include the source of raw materials, compost quality criteria, type of application, local marketing strategies for composted products and existing legislation. Additionally, drivers such as local cropping conditions and existing animal husbandry will influence as well the final use of compost. Market shares of compost vary considerable from country to country as shown in Table 5-9. In general, high quality compost may be used in agriculture, horticulture, landscaping and home gardening, while low quality compost might be used as a landfill cover or in land reclamation projects.

Even though compost prices are strongly influenced by mentioned drivers, when one accounts for compost quality criteria, there is a degree of convergence in the compost price. (MUNLV 1999) reports price ranges for fresh compost from zero to 15 €/Mg, with a median value 5 €/Mg. For mature compost the price range goes from zero to 50 €/Mg, with a median value of 17.5 €/Mg. Finally, for mulch compost there is a price range between 5 and 30 €/Mg. The

model assumes that generated fresh and mature compost are used for land reclamations projects and agricultural applications, respectively. Final compost prices are fixed to its quality and the total benefit obtained from its sale is calculated using Equation 5-20.

Table 5-9 Market shares of compost sales in selected European countries, %

Compost use	Austria	Belgium	Germany	Denmark	Italy	Netherlands	Market size
Landscaping	30	24	25	19	30	30	Large
Landfill restoration	5	5	-	13	-	-	Small
Agriculture	35	5	43	10	20	40	Very big
Horticulture	5	6	5	3	-	-	Medium
Earth works	5	33	10	-	50	-	Medium
Hobby gardening	20	18	14	48	-	20	Large
Export	-	9	-	-	-	-	Very small
Miscellaneous	-	-	3	7	-	10	-

Adapted from Barth 2000 and (HOGG 2002)

Equation 5-20 Benefits from the sale of compost as a function of its quality

$$BCom_a = Compost_a \cdot P_{compost} \cdot CF_{tpa-ktpa}$$

$$s.t.:$$

$$P_{compost} = \begin{Bmatrix} 5\ €/\text{ton} & \text{for fresh compost} \\ 17.5\ €/\text{ton} & \text{for mature compost} \end{Bmatrix}$$

where:

$BCom_a$	Total benefit from the sale of compost; €/ Gg
$P_{compost}$	Compost price as a function of its quality, €/ Mg
CF_{tpa-Gg}	Conversion factor from Mg to Gg. CF = 1000; -

On the other hand, if there is presence of metals in the waste input flow, they can be as well separated and recovered. This waste management operation can obtain revenues as well from the segregation and commercialisation of recovered metal. Metal prices drivers vary considerable from region to region. Therefore, in order to have a point of reference, the metal prices are trade values given by the Global Recycling Network (GRN). Finally, the total benefit from the recovery of metals is calculated with Equation 5-21.

Equation 5-21 BTA revenues from recovered metals

$$BMET_a = Metal_{a,MET} \cdot P_{MET}$$

where

$$P_{MET} = \begin{Bmatrix} 126\ €/\text{ton} & \text{if MET} = 1 \\ 493\ €/\text{ton} & \text{if MET} = 2 \\ 126\ €/\text{ton} & \text{if MET} = 3 \end{Bmatrix}$$

5.2.7.2 Recovered Energy

There is no energy recovery from aerobic biological treatment plants.

5.2.7.3 Displaced resources and emissions

Mature compost produced from source separated biodegradable waste can be used as a sustainable substitute of mineral fertilisers. Mineral fertilisers are chemical compounds that provide essential nutrients for plant growth and are categorised according to its nutrient content (nitrogen, phosphorous and potassium).

Based on the compost quality is possible to determinate the potential amount and type of substituted mineral fertiliser. In this study is assumed that the mineral fertiliser being

displaced is the nitrogen-based fertiliser ammonium nitrate (NH_4NO_3). It is assumed as well that the compost's nitrogen content displaces an equal quantity of bounded nitrogen to soil from the substituted mineral fertiliser. When compost is used as a soil improver, nitrogen is organically bounded to the soil and is less susceptible to leaching. Contrary to mineral fertilisers, only 10-20% of the nitrogen content in the compost is able to bind into the soil (Kaiser 2001, Smith 2001, Baldoni 1996). The rest is emitted as fugitive emissions to air and leached through the soil and groundwater. Finally, the potential displaced mineral fertiliser (*PDMF*) is calculated with Equation 5-22.

Equation 5-22 Displaced mineral fertiliser

$$for\ cc = nitrogen:$$

$$PDMF_a = Compost_{a,cc} \cdot FBN^{-1} \cdot \left(\frac{MW_{NBMF} \cdot N_{NBMF}}{MW_N} \right)$$

$$PDMF_a = \sum_w \left[m_{a,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right) \cdot MCC_{w,cc} \cdot \left(DB_{cc} - DOC_w \cdot DOCF_a \cdot BDR_{cc} \right) \right] \cdot A$$

$$A = FBN^{-1} \cdot \left(\frac{MW_{NBMF} \cdot N_{NBMF}}{MW_N} \right)$$

where:

$PDMF_a$	Potential displaced mineral fertiliser; Gg
FBN	Bounded nitrogen fraction, 10%; -
MW_{NBMF}	Molecular weight of the nitrogen based mineral fertiliser; g/gmol
N_{NBMF}	Sum of nitrogen molecular indexes of the nitrogen based mineral fertiliser; -

Another benefit from the use of composted material as substitution of mineral fertilisers is the potential discount of fugitive emissions generated during the production process. Displaced fugitive emissions generated during the production of the mineral fertiliser are calculated with Equation 5-23. This equation makes use of the process-specific coefficients reported in Annex Table 4 for the nitrogen-based fertiliser ammonium nitrate (NH_4NO_3).

Equation 5-23 BTA displaced emissions

$$DFEA_a = PDMF_a \cdot EF_{FEA}$$

6 BIOLOGICAL TREATMENT: ANAEROBIC DIGESTION

6.1 PROCESS DESCRIPTION

Anaerobic digestion is the anaerobic decomposition and biodegradation of biodegradable waste under closed and controlled conditions by the action of microorganisms such as methanogenic bacteria.

Anaerobic biological technologies are classified according to three main parameters, which are moisture content, process temperature and number of stages as shown in Table 6-1. According to (Kranert 2000), in Germany about 80% of all installed digestion plants follow the wet process as co-digestion units. About 75% of this installed capacity has a single stage process and 80% of them run under thermophilic conditions.

Table 6-1 Anaerobic Digestion Process Types

TS%	Temperature	Stages
Wet Process (TS<10%):	Mesophilic (35-37°C):	1-stage
Dry Process (TS>25%):	Thermophilic (55-60°C):	Multi-stage

(Bidlingmaier 2000)

In general, the anaerobic digestion process begins when the waste feedstock is conditioned for impurities removal. Then, it is homogenized and fed into the digester where it remains for a period between two and four weeks. This process generates biogas, which is a mixture of methane, carbon dioxide and trace gases, and as residue a solid, fibrous fraction (digestate) and liquid fraction (liquor). Generated biogas is combusted and converted to heat and power by means biogas fired units such as CHP units. The digestate, which is made of undigested volatile solids and ashes, undergoes further aerobic maturing, known as well as curing, to produce a stable material. The liquor, which is mainly form of dissolved volatile solids and carboxylate salts, is either recycled to the digester to maintain the required moisture level or to the wastewater treatment plant for further treatment.

6.2 BTD SUB-MODEL

The anaerobic biological treatment sub-model (BTD) assesses the life cycle of selected biodegradable municipal solid waste fractions. These fractions or waste categories are shown in Table 6-2 and they are codified according to its entry in the European Waste Catalogue (EWC) adopted with Commission Decision 94/3/EC. Contrary to the aerobic biological treatment, lignin or lignocellulosic material, such as wood, cannot be so easily degraded in anaerobic digestion units. Therefore, this waste category is not considered for treatment in this type of waste management operation.

Table 6-2 Accepted waste categories subject to aerobic biological treatment

EWC	Waste category, w
20 01 01	Separately collected paper and cardboard from MSW
20 01 08	Biowaste: organic biodegradable kitchen waste
20 02 01	Greenwaste: biodegradable waste from gardens, parks and cemeteries
20 03 02	Waste from markets
20 03 03	Street-sweeping waste
20 03 06	Waste from sewage cleaning

As shown in Figure 6-1, the sub-model starts when selected waste categories enters to the waste management facility and ends not only when they are transformed into a valuable end product but also when they are emitted as a fugitive emission to air, water and land. Internal processes include front-end pre-conditioning, biological treatment and final conditioning. Valuable products such as metals and compost are recovered and commercialised in exiting

markets. Secondary wastes such as the oversized fraction are collected for further treatment prior to landfilling as required by the Landfill Directive 1999/31/EC. Acceptable treatments include mechanical-biological and thermal treatment.

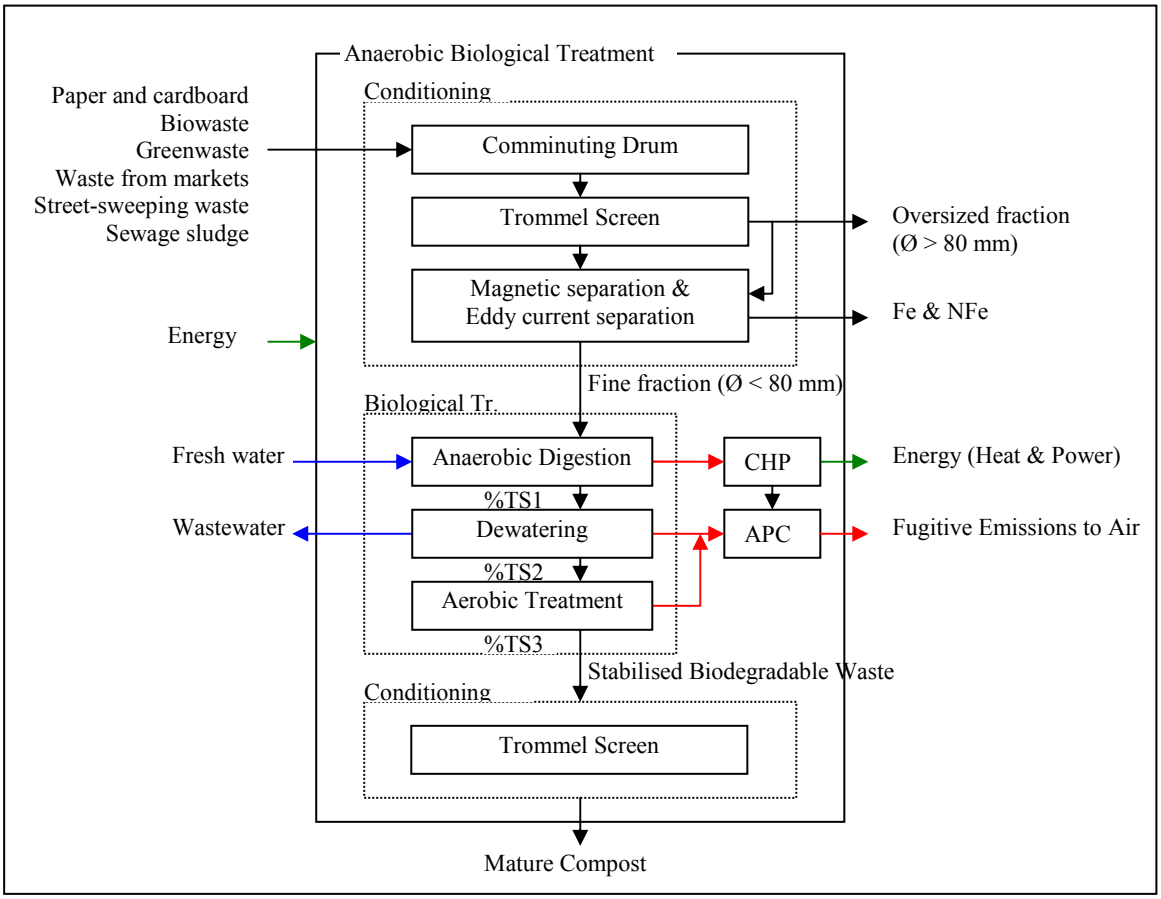


Figure 6-1 Anaerobic Biological Treatment: Anaerobic Digestion

6.2.1 BTD Internal Process

6.2.1.1 Material Input

According to the multi-commodity flow distribution approach, the waste category w generated at the source point j will compete for the scarce and finite network capacity of the anaerobic biological treatment plant d, which is restricted to accept only biodegradable waste category types. Individual material flow distribution is calculated using Equation 6-1. The biodegradable waste flow distribution ($m_{j,d,w}$) is calculated in advance as showed in the subchapter 3.4.1 related to logistic constraints.

Equation 6-1 BTD waste category *w* input acceptance

$$m_{d,w} = \sum_{j} m_{j,d,w}$$

subject to :

$$m_d = \sum_{w} m_{d,w}$$

$$PTC_d > m_d$$

where:

$m_{d,w}$	Total waste category w material flow entering to the aerobic biological treatment unit d ; Gg
$m_{j,d,w}$	Waste category w generated at point j and entering to the aerobic biological treatment unit d; Gg
m_d	Total amount of waste accepted for treatment in aerobic biological treatment d; Gg
PTC_d	Plant treatment capacity, d; Gg

6.2.1.2 Mechanical Treatment: Front-end pre-conditioning

6.2.1.2.1 Comminuting Drum

This device is a rotating drum, in which all-soft organic material break down to smaller particles with a diameter smaller than 80 mm while inert materials such as plastic, textiles and metals do not suffer any size reduction. Any glass material content in the input flow is reduced in size as well. The integer variable (SOM_w) is used to represent which waste category w is subject to comminution. Soft organic material will have a SOM_w value equal to one, otherwise equal to zero.

6.2.1.2.2 Trommel Screen

After the comminution drum, the waste is screened in a trommel screen. The model considers a trommel screen with one opening size of 80 mm. The input waste material is divided in two fractions named fine fraction (Φ<80 mm) and oversized fraction (Φ>80 mm). The fine fraction contains a high percent of organic material, which is suitable for biological treatment. The oversized fraction will consist mainly of impurities such as mixed plastics, textiles, paper and board or similar non-biodegradable materials, which require further treatment prior landfilling. Fine and oversized fraction are calculated with Equation 6-2 and Equation 6-3, respectively.

Equation 6-2 BTD Fine Fraction

$$mFF_{d,w} = m_{d,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w\right)$$

Equation 6-3 BTD Oversized Fraction

$$mOF_{d,w} = m_d \cdot \left(1 - SOM_w\right) \cdot \left(1 - WPD_w\right)$$

where:

$mFF_{d,w}$	Fine Fraction mass flow from anaerobic biological treatment d; Gg
$mOF_{d,w}$	Oversized Fraction mass flow from anaerobic biological treatment d; Gg
$m_{d,w}$	Mass flow of the waste category fraction w which enters to the anaerobic biological treatment d; Gg
SOM_w	Integer variable for the waste category w which is subject to comminution; - For the waste category w, which is soft organic material then, SOM_w is equal to 1, otherwise to 0.
WPD_w	Waste Particle Distribution fraction lower than 80 mm for the waste category w; -

6.2.1.2.3 Metals separation

Ferrous metals are recovered from the waste input by means of a magnet unit while aluminium by means of an eddy-current separator. These recovery units are both suspended above the fine and oversized conveyor belt. It is assumed that the total metal input is separated and recovered from the feedstock stream. The metal flow is calculated with Equation 6-4.

Equation 6-4 Metals separation

for $w = 1..3$;

$$Metal_{d,MET} = m_{d,w}$$

where:

$mMetal_{d,MET}$	Metal mass flow type MET separated and recovered from the anaerobic biological treatment unit d; Gg
MET	Metal type: 1 = metal, 2 = aluminium, 3 = mix; -

6.2.1.3 Anaerobic biological treatment: Anaerobic Digestion

Before the fine fraction enters to the digester, it is homogenized and the moisture content is adjusted according to the process type. For dry and wet processes, the percent of dry solid correspond to 25% and 10%, respectively (%TS1). The total amount of fresh water, which is required to adjust the moisture level in the digester, is calculated with Equation 6-5. This equation is based on the required level of total solids in the digester, the waste moisture input and the recycled liquor.

Equation 6-5 BTD fresh water input used for moisture correction

for $cc = H_2O$

$$m_{H_2O} = \sum_w \left[m_{d,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right) \cdot \left\{ \left(1 - MCC_{w,cc}\right) \cdot \frac{\left(100 - \%TS1_d\right)}{\%TS1_d} - MCC_{w,cc} \right\} \right] - RRL \cdot Liquor_d$$

where:

m_{H2O} Fresh water flow input required to adjust moisture content; Gg
RRL Recycling rate of liquor [0-1]; -

Once the moisture level is adjusted, the anaerobic biological treatment process starts. Similar to the aerobic process, it is possible to calculate the amount of potential degradable material *(PDM)* subject to anaerobic biodegradation based on the chemical composition and on the degradability potential of the fine fraction. This approach follows the default method (Tier 1), which is recommended by the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000). The potential degradable material is calculated with Equation 6-6.

Equation 6-6 BTD Potential Degradable Material, $PDM_{d,cc}$

$$PDM_{d,cc} = \sum_w \left[m_{d,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right) \cdot DOC_w \cdot DOCF_d \cdot MCC_{w,cc} \cdot BDR_{cc} \right]$$

(Rolland 2003) and (AGO 1997) recommend to use Equation 6-7, which was developed by Tabasaran & Rettenber, to calculate the amount of degradable organic carbon dissimilated ($DOCF_d$) under anaerobic conditions. This equation is as a function of the process temperature. Under mesophilic conditions (T=35°C) the value of $DOCF_d$ is 0.77 while for thermophilic ones (T=55°C) is 1.00.

Equation 6-7 Degradable organic carbon dissimilated under anaerobic conditions

$$DOCF_d = \begin{cases} 0.014 \cdot T + 0.28 & if\ T < 51.4°C \\ 1 & if\ T > 51.4°C \end{cases}$$

As the anaerobic digestion progresses, the process generates biogas. This biogas is continuously removed from the digester and either combusted on-site or directed to off-site gas consumers. Additionally to the biogas, a stabilised biodegradable solid residue named digestate is obtained when the process is completed. This sub-product is chemically similar to the compost but with higher moisture content. Due to handling, storage and marketing reasons, the digestate is pumped out of the digester and send to the dewatering unit, where its moisture level is reduced to a value of 60% total solids. Finally, the amount of digestate generated ranges from 100 to 500 kg per Mg of input waste (IPPC 2005). The digestate produced in the anaerobic biological treatment *d* is calculated with Equation 6-8 and Equation 6-9 as dry and wet basis, respectively.

Equation 6-8 BTD Digestate composition, dry basis

$$Digestate_{d,cc} = \sum_w \left[m_{d,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right) \cdot MCC_{w,cc} \cdot \left(MF_{cc} - DOC_w \cdot DOCF_d \cdot BDR_{cc} \right) \right]$$

Equation 6-9 BTD Digestate, wet basis

$$Digestate_d = \frac{100}{\%TS2_d} \cdot \sum_{cc} \sum_w \left[m_{d,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right) \cdot MCC_{w,cc} \cdot \left(MMF_{cc} - DOC_w \cdot DOCF_d \cdot BDR_{cc} \right) \right]$$

From the dewatering units is obtained as well a liquid fraction named liquor. Typical dewatering units include screw press and centrifuges. These units make use of polymer solution, which is added prior the dewatering unit. This is done to flocculate the digestate and facilitate its removal. Most of the liquor is recycled to the homogenisation section, where it is used to adjust the require digester moisture content. Total amount of liquor generated is calculated with Equation 6-10.

Equation 6-10 Water balance at the dewatering unit (1)

$$m_{H_2O,in} = m_{H_2O,out}$$

$$where:$$

$$m_{H_2O,in} = \frac{(100 - \%TS1_d)}{\%TS1_d} \cdot \sum_w \left[m_{d,w} \cdot (SOM_w + (1 - SOM_w) \cdot WPD_w) \cdot (1 - MCC_{w,H_2O}) \right]$$

$$m_{H_2O,out} = \left\{ Liquor_d + \frac{(100 - \%TS2_d)}{\%TS2_d} \cdot \sum_{cc} \sum_w \left[Mdw \cdot MCC_{w,cc} \cdot (MMF_{cc} - DOC_w \cdot DOCF_d \cdot BDR_{cc}) \right] \right.$$

$$Mdw = m_{d,w} \cdot (SOM_w + (1 - SOM_w) \cdot WPD_w)$$

Arranging terms the generated amount of liquor is then calculated with Equation 6-11.

Equation 6-11 BTD Liquor (2)

$$Liquor_d = \left\{ \frac{(100 - \%TS1_d)}{\%TS1_d} \cdot \sum_w \left[Mdw \cdot (1 - MCC_{w,H_2O}) \right] \right\} -$$

$$\left\{ \frac{(100 - \%TS2_d)}{\%TS2_d} \cdot \sum_{cc} \sum_w \left[Mdw \cdot MCC_{w,cc} \cdot (MMF_{cc} - DOC_w \cdot DOCF_d \cdot BDR_{cc}) \right] \right\}$$

$$Mdw = m_{d,w} \cdot (SOM_w + (1 - SOM_w) \cdot WPD_w)$$

$$Liquor_d = \sum_w \left[m_{d,w} \cdot (SOM_w + (1 - SOM_w) \cdot WPD_w) \cdot \left\{ \begin{array}{l} \frac{(100 - \%TS1_d)}{\%TS1_d} \cdot (1 - MCC_{w,H_2O}) - \\ \frac{(100 - \%TS2_d)}{\%TS2_d} \cdot \sum_{cc} MCC_{w,cc} \cdot (MMF_{cc} - DOC_w \cdot DOCF_d \cdot BDR_{cc}) \end{array} \right\} \right]$$

6.2.1.4 Aerobic biological treatment: Curing

The dewatered digestate requires final aerobic curing to ensure complete stabilisation. This is achieved in an enclosed reactor system with a curing time between three and four weeks. Curing piles may be forced-aerated with occasional turning. The potential degradable material (*PDMC*) which is subjected to the aerobic curing process is calculated with Equation 6-12.

Equation 6-12 Potential biodegradable material in the curing process

$$PDMC_{d,cc} = \sum_w \left[m_{d,w} \cdot (SOM_w + (1 - SOM_w) \cdot WPD_w) \cdot (1 - DOC_w \cdot DOCF_d) \cdot DOCFC_d \cdot MCC_{w,cc} \cdot BDR_{cc} \right]$$

Finally, the total amount of compost generated in an anaerobic biological treatment plant is calculated with Equation 6-13 and Equation 6-14 as dry and wet basis, respectively.

Equation 6-13 Compost composition, dry basis

$$Compost_{d,cc} = \sum_w \left[m_{d,w} \cdot (SOM_w + (1 - SOM_w) \cdot WPD_w) \cdot MCC_{w,cc} \cdot \left[\begin{array}{l} BDR_{cc} \cdot (1 - DOC_w \cdot DOCF_d) \cdot (1 - DOCFC_d) \\ + (MF_{cc} - BDR_{cc}) \end{array} \right] \right]$$

Equation 6-14 Compost weight, wet basis @%TS

$$Compost_d = \sum_w \left[m_{d,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w\right) \cdot MCC_{w,cc} \cdot \begin{bmatrix} BDR_{cc} \cdot \left(1 - DOC_w \cdot DOCF_d\right) \cdot \left(1 - DOCFC_d\right) \\ + \left(MMF_{cc} - BDR_{cc}\right) \end{bmatrix} \right]$$

where:

$PDM_{d,cc}$	Mass flow of the chemical compound *cc* which is potentially degradable in the anaerobic biological treatment *d;* Gg
DOC_w	Degradable organic carbon fraction of the waste category fraction *w;* -
$DOCF_d$	Degradable organic carbon dissimilated fraction as a function of the digestion temperature*;* - $DOCF_d = \begin{cases} 0.014 \cdot T + 0.28 & if\ T < 51.4°C \\ 1 & if\ T > 51.4°C \end{cases}$
$DOCFC_d$	Degradable organic carbon dissimilated fraction as a function of the curing residence time*;* - $DOCFC_d = 1 - \exp^{(-0.0577 \cdot CRT_d)}$
$MCC_{w,cc}$	Matrix [waste category fraction *w* vs. chemical compound *cc*] *;* -
BDR_{cc}	Integer variable that represents which chemical compound is subject to biological degradation*;* - For *cc* equal to water, inert material and heavy metals then BDR_{cc} is equal to 0, otherwise equal to 1.
MF_{cc}	Integer variable for setting the equation as moisture free basis*;* - For *cc* equal to water MF_{cc} is equal to 0, otherwise equal to 1.
MMF_{cc}	Integer variable for setting the equation as moisture & heavy metals free basis*;* - For *cc* equal to water and heavy metals, MMF_{cc} is equal to 0, otherwise equal to 1.
%TS	Percent total solids*; %*
MW	Molecular weight; g/gmol

6.2.2 Secondary Waste

The front-end pre-conditioning section segregates the oversized fraction, which consists mainly of inorganic impurities. This rejected fraction requires further treatment before it can finally be disposed of in a landfill. Recommended treatment technologies include mechanical-biological treatment and thermal treatment.

Following the multi-commodity flow distribution approach, the oversized fraction will compete for scarce and finite treatment capacity and it will be restricted to its organic component of dry residue in original substance for its final disposal in landfills as shown in Equation 6-15. In order to keep the balance within the system, it is required to fix two mass balance equations. Therefore, Equation 6-16 is used to balance the decision variables and Equation 6-17 for the balance of the distributed oversized fraction.

Equation 6-15 BTD oversized fraction distribution flow within the system

$$mOF_{d,m} = \sum_w \left[m_d \cdot \left(1 - SOM_w\right) \cdot \left(1 - WPD_w\right) \right] \cdot \delta DM_{d,m}$$

$$mOF_{d,t} = \sum_w \left[m_{d,w} \cdot \left(1 - SOM_w\right) \cdot \left(1 - WPD_w\right) \right] \cdot \delta DT_{d,t}$$

$$mOF_{d,l} = \sum_w \left[m_{d,w} \cdot \left(1 - SOM_w\right) \cdot \left(1 - WPD_w\right) \right] \cdot \delta DL_{d,l} \cdot LFRD_d$$

where:

$$LFRD_d = \begin{cases} 0 & if \sum_w \left[Mdw \cdot MCC_{w,C} \right] > LFC_C \cdot \sum_w \left[Mdw \cdot \left(1 - MCC_{w,H_2O}\right) \right] \\ 1 & if \sum_w \left[Mdw \cdot MCC_{w,C} \right] \le LFC_C \cdot \sum_w \left[Mdw \cdot \left(1 - MCC_{w,H_2O}\right) \right] \end{cases}$$

$$Mdw = m_{d,w} \cdot (1 - SOM_w) \cdot (1 - WPD_w)$$

Equation 6-16 BTD decision variables mass balance

$$1 = \sum_m \delta DM_{d,m} + \sum_t \delta DT_{d,t} + \sum_l \delta DL_{d,l}$$

Equation 6-17 BTD oversized fraction mass balance

$$mOF_d = mOF_{d,m} + mOF_{d,t} + mOF_{d,l}$$

where:

m,t,l	Mechanical-biological unit m, thermal treatment unit t, landfill l; -
$\delta DX_{d,x}$	Decision variable which determinates the fraction of the oversized fraction generated in aerobic biological unit a and transported to units m ,t, l; -
LFR_d	Oversized fraction transportation restriction to landfill generated in unit a; -
LFC_C	Landfill disposal limit criteria for organic component of dry residue; -
$mOF_{d,(m,t,l)}$	Oversized fraction material flow distribution from unit a to unit (m,t,l) ; Gg

6.2.3 Fugitive Emissions to Air, FEA_d

6.2.3.1 FEA_d generation & control: Anaerobic Digestion step

Fugitive emissions to air generated during the anaerobic treatment of waste include the following ones:

- Controlled gaseous emissions of carbon dioxide
- Uncontrolled emissions of trace gases such as ammonia, nitrous oxide, methane and NMVOCs

Under optimal anaerobic conditions, the potential degradable material *(PDM)*, which was calculated with Equation 6-6, will be transformed by facultative anaerobic bacteria into biogas following Reaction 6-1. Theoretically, it is possible to produce 348 Nm^3 methane gas per Mg of degradable organic carbon. Similarly, one Mg of biowaste can generate between 90 and 120 Nm3 of biogas with an average composition of 55-70% methane, 30-45% carbon dioxide and 200-4000 ppm hydrogen sulphide (IPPC 2005, Bidlingmaier 2000). Finally, the biogas composition is calculated with material specific emission model given by Equation 6-18.

Reaction 6-1 Anaerobic biological reaction & physical properties of the digestion biogas (Thomé-Kozmiensky 1989)

$$C_cH_hO_oN_nS_sCl_l + \frac{4c-h-2o+3n+2s+l}{4}H_2O = \frac{4c+h-2o-3n-2s-l}{8}CH_4 + \frac{4c-h+2o+3n+2s+l}{8}CO_2 + nNH_3 + sH_2S + lHCl$$

Equation 6-18 BTD biogas generation

CH_4 $$m_{d,CH_4} = MW_{CH_4} \cdot \left(\frac{4PDM_{d,C}}{MW_C} + \frac{PDM_{d,H}}{MW_H} - \frac{2PDM_{d,O}}{MW_O} - \frac{3PDM_{d,N}}{MW_N} - \frac{2PDM_{d,S}}{MW_S} - \frac{PDM_{d,Cl}}{MW_{Cl}} \right) / 8$$

CO_2 $$m_{d,CO_2} = MW_{CO_2} \cdot \left(\frac{4PDM_{d,C}}{MW_C} - \frac{PDM_{d,H}}{MW_H} + \frac{2PDM_{d,O}}{MW_O} + \frac{3PDM_{d,N}}{MW_N} + \frac{2PDM_{d,S}}{MW_S} + \frac{PDM_{d,Cl}}{MW_{Cl}} \right) / 8$$

NH_3 $$m_{d,NH_3} = PDM_{d,N} \cdot \frac{MW_{NH_3}}{MW_N}$$

H_2S $$m_{d,H_2S} = PDM_{d,S} \cdot \frac{MW_{H_2S}}{MW_S}$$

HCl $$m_{d,HCl} = PDM_{d,Cl} \cdot \frac{MW_{HCl}}{MW_{Cl}}$$

The generated biogas is collected by means of the biogas collection system and burned with digester gas-fired units such as flares, gas turbines or internal combustion engines. The final controlled emission from anaerobic digestion units are a function of the biogas collection efficiency and the removal efficiency from the selected digester gas-fired unit. Biogas collection systems are not 100% efficient. No collected biogas can be emitted to the

atmosphere from emergency vent valves and from poorly sealed water traps (IPPC 2005). The EPA-D (EPA-D 1997) has reported biogas collection efficiencies range between 95% and 98%. In case that there are no site-specific values, it is recommended to take the average value of 96.5%. Final controlled emissions are calculated with Equation 6-19. Removal efficiencies from the selected digester gas-fired unit are given in Table 6-3.

Equation 6-19 BTD fugitive emissions to air

CH_4 $$FEA_{d,1,CH_4} = m_{d,CH_4} \cdot \left[\left(1-\eta_{BGCS}\right)+\eta_{BGCS} \cdot \left(1-\eta_{APC:APC_d,CH_4}\right)\right]$$

CO_2 $$FEA_{d,1,CO_2} = m_{d,CO_2} + m_{d,CH_4} \cdot \eta_{BGCS} \cdot \eta_{APC:APC_d,CH_4} \cdot \frac{MW_{CO_2}}{MW_{CH_4}}$$

NH_3 $$FEA_{d,1,NH_3} = m_{d,NH_3} \cdot \left[\left(1-\eta_{BGCS}\right)+\eta_{BFCS} \cdot \left(1-\eta_{APC:APC_d,NH_3}\right)\right]$$

NOx $$FEA_{d,1,NOx} = m_{d,NH_3} \cdot \eta_{BGCS} \cdot \eta_{APC:APC_d,NH_3} \cdot \frac{MW_{NOx}}{MW_{NH_3}}$$

H_2S $$FEA_{d,1,H_2S} = m_{d,H_2S} \cdot \left[\left(1-\eta_{BGCS}\right)+\eta_{BFCS} \cdot \left(1-\eta_{APC:APC_d,H_2S}\right)\right]$$

SO_2 $$FEA_{d,1,SO_2} = m_{d,H_2S} \cdot \eta_{BGCS} \cdot \eta_{APC:APC_d,H_2S} \cdot \frac{MW_{SO_2}}{MW_{H_2S}}$$

HCl $$FEA_{d,1,HCl} = m_{d,HCl}$$

Table 6-3 Control efficiencies from selected digester gas-fired units (NPI 1999)

	Flare		Gas Turbine		ICE	
	Typical	Range	Typical	Range	Typical	Range
VOCs	99.2	90-99+	94.4	90-99+	97.2	94-99+
Halogenated Species	98	91-99+	99.7	98-99+	93	90-99+
Non-Halogenated	99.7	38-99+	98.2	97-99+	86.1	25-99+

Secondary compounds or trace gases are subsequently controlled in digester gas-fired units. Their mass flow is then calculated with process-specific emission equations and with transfer coefficients. These coefficients are a function of the biogas volume and of the digester gas-fired units located on site. Selected trace gases are calculated with Equation 6-20 and the process-specific coefficients from Table 6-4. Figures for other coefficients than the ones listed in this table have not been identified by this study.

Equation 6-20 BTD controlled fugitive emissions from digester gas-fired units

$$FEA_{d,1,FEA} = V_{BG_d} \cdot EF_{d,FEA}$$

where:

$$V_{BG_d} = \sum_i m_{d,BG_i} \cdot v_{BG_i}$$

where:

V_{BGd}	Volume of biogas generated at the anaerobic plant *d*
BGi	Compounds that form part of the biogas (CH_4, CO_2, NH_3, H_2S and HCl) excluding other trace gases.
$m_{d,BGi}$	Mass flow of the compound *i* content in the biogas
v_{BGi}	Specific volume of compound *i* content in the biogas

6.2.3.2 FEA_d generation & control: Curing

Fugitive emissions to air are generated from the aerobic biological stabilisation of the dewatered digestate. It is assumed a curing time of four weeks in order to achieve complete stabilisation. Fugitive emissions from carbon and nitrogen based-compounds are calculated with Equation 6-21, while other trace gases follow Equation 6-22. Both equations make use of the process-specific coefficients obtained from typical digester biogas-fired units as reported in Table 6-4. Figures from other emissions than the ones listed in that table have not been identified by this study.

Equation 6-21 BTD curing carbon and nitrogen based-compound raw gas

$$mc_{d,FEA} = PDMC_{d,cc} \cdot \frac{MW_{FEA}}{MW_{cc}} \cdot EF_{FEA}$$

Equation 6-22 BTD traces gases in the curing raw gas

$$mc_{d,FEA} = EF_{FEA} \cdot \frac{100}{\%TS2_d} \cdot \sum_{cc} \sum_{w} \left[Mdw \cdot MCC_{w,cc} \cdot \left(MMF_{cc} - DOC_w \cdot DOCF_d \cdot BDR_{cc} \right) \right]$$

$$Mdw = m_{d,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right)$$

Table 6-4 Process-specific coefficients for selected emissions to air from digester gas-fired units

		Biogas	CHP	CHP: Gas Turbine	CHP: Gas Turbine	CHP: ICE
		(IPPC 2005)	LCA-IWM	(Pitschke 2004)	(EPA 2004)	(EPA 2004)
FEA		kg/kg	mg/m^3	mg/m^3	mg/m^3	mg/m^3
Carbon dioxide	CO_2					
Methane	CH_4		15	15		13936.1
Nitrous oxide	N_2O		10	10		
Hydrofluorocarbons	HFCs					
Perfluorocarbons	PFCs					
Sulphur hexafluoride	SF_6					
Sulphur dioxide	SO_2	1.63E-05	56	240	62.49	
Nitrogen dioxide	NO_2	4.12E-05	430	1200	1538.16	18645.6
Ammonia	NH_3					
Hydrogen chloride	HCl		1.5	2		
Hydrogen sulphide	H_2S					
NMVOC	NMVOC	2.30E-09		40	55.76	1153.34
Dioxins & Furans	PCDD/F	2.02E-14	5E-11			0.000
PAH	PAH				4.27	1.288
Carbon monoxide	CO	7.23E-05	610	180	163.43	3392.73
Particulates, < 2.5 µm	PM2.5					369.067
Particulates,	PM					
Particulates, >10 µm	PM10		5	40	115.36	369.067
Cadmium	Cd	9.40E-13	9.00E-04		5.58E-03	
Thallium	Tl					
Mercury	Hg	6.90E-13	4.20E-03		3.27E-02	
Antimony	Sb					
Arsenic	As		4.00E-03		2.21E-02	
Lead	Pb	8.50E-13				
Chromium	Cr	1.10E-13	6.00E-04		1.15E-02	
Cobalt	Co					
Copper	Cu					
Manganese	Mn					
Nickel	Ni		2.00E-04		1.92E-02	
Vanadium	V					

The raw gas generated in the curing process is assumed that is completely collected and controlled by means of a biofilter. The resulting fugitive emission is calculated with Equation 6-23. Additionally, due to the assumption that the raw gas is completely collected the term BTA_a is fix to two, which is the vector of the Matrix related to the biofilter removal efficiency.

Equation 6-23 BTD fugitive emissions to air from the controlled curing raw gas

$$FEA_{d,2,FEA} = mc_{d,FEA} \cdot \left(1 - \eta_{APC:FEA,2}\right)$$

With exception of carbon dioxide and nitrous oxide, the inventory data of fugitive emissions to air from controlled curing raw gas are calculated as well with Equation 6-23, which uses the APC removal efficiency values given in Table 5-4. Figures for other removal efficiencies

than the ones listed in this table have not been identified by this study. Final carbon dioxide and nitrous oxide emissions are calculated with Equation 6-24.

Equation 6-24 BTD fugitive emissions to air from the controlled curing raw gas, CO_2

CO_2 $$FEA_{d,2,CO_2} = mc_{d,2,CO_2} + mc_{d,2,CH_4} \cdot \eta_{APC:CH_4,2} \cdot \frac{MW_{CO_2}}{MW_{CH_4}} + mc_{d,2,CO} \cdot \eta_{APC:CO,2} \cdot \frac{MW_{CO_2}}{MW_{CO}}$$

N_2O $$FEA_{d,2,N_2O} = m_{a,2,N_2O} + m_{a,2,NH3} \cdot 0.22 \cdot \frac{MW_{N_2O}}{MW_{NH_3}}$$

NO_2 $$FEA_{a,2,NO_2} = m_{a,2,NO_2} + m_{a,2,NH3} \cdot 0.38 \cdot \frac{MW_{NO_2}}{MW_{NH_3}}$$

6.2.3.3 BTD total fugitive emissions to air

Finally, the total amounts of fugitive emissions generated in an anaerobic biological treatment are equal to the addition of those generated during the anaerobic and curing steps. BTD total fugitive emissions to air are then calculated with Equation 6-25.

Equation 6-25 BTD Total fugitive emissions to air

$$FEA_{d,FEA} = \sum_i FEA_{d,i,FEA}$$

$where$:

$$i = \begin{Bmatrix} 1 & \text{if i = Biogas} \\ 2 & \text{if i = curing raw gas} \end{Bmatrix}$$

6.2.4 Fugitive Emissions to Water, FEW_d

The amount of wastewater generated from anaerobic biological plants depends on the extent of biodegradation, the moisture content of input waste and on the amount of liquor, which was not recycled to the system. Site studies state typical wastewater generation rates between 100 and 500 kg of wastewater per Mg of waste (wet weight) (Hogg 2002, IPPC 2005). Similarly, (Bidlingmaier 2000) reports 444 kg/Mg and 327kg/Mg of wastewater for dry and wet processes, respectively. This elementary flow needs to be conditioned in a wastewater treatment plant before final discharge. The amount of wastewater generated in the anaerobic biological treatment unit *d* can be calculated with Equation 6-26. This equation provides similar results to the ones shown in Table 6-5.

Equation 6-26 BTD wastewater generation, Gg

$$V_{WW:d} = (1 - RRL_d) \cdot Liquor_d$$

$$V_{WW,d} : \begin{Bmatrix} 0.375 & if\ Q_d < 5.5 \\ 0.004Q_d + 0.3561 & if\ 5.5 < Q_d < 22.5;\ R^2 = 0.986 \\ 0.445 & if\ Q_d > 22.5 \end{Bmatrix}$$

Table 6-5 Average wastewater discharged from anaerobic digestion units, Gg/Gg

	min-max	average	min-max	average	min-max	average
Plant treatment capacity, Gg	**5-6**	**5.5**	**10-12**	**11**	**20-25**	**22.5**
Wastewater discharge, fraction input	0.30-0.45	0.375	0.34-0.47	0.405	0.34-0.55	0.445

Selected fugitive emissions to water are calculated using Equation 6-27 and the process-specific coefficients from Table 6-6.

Equation 6-27 BTD fugitive emissions to water, Gg

$$FEW_{d,FEW} = V_{WW,d} \cdot EF_{d,FEW}$$

Table 6-6 Average values from selected compounds founded in leachate from anaerobic digestion units, g/l

		(Pitschke 2004)	(RIS 2002)	(Bidling maier 2000)	(IPPC 2005),	(Hogg 2002)		In this study, $EF_{d,FEW}$	
	FEW	min-max	Average	min-max	Average	Dry	Wet	Dry	Wet
Biological Oxygen Demand	BOD_5	-	2.3	0.5-1.5	1	5 - 10	2.5 - 5	7.5	3.75
Chemical Oxygen Demand	COD	-	10.9	3-7	5	20 - 40	6 - 24	30	15
Total Nitrogen	N-tot	-	0.614	0.4-1.6	0.6	2 - 4	0.8 – 1.2	3	1
Total Phosphorous	P-tot	-	0.116	0.04-0.3	0.1			0.1	0.1
Mercury	Hg	-	-	-	-			-	-

6.2.5 Energy consumption

Energy consumed by anaerobic biological treatment units depend on the choice of technology. In general, it can be calculated using Equation 6-28 and the process-specific coefficients given in Table 6-7. Required electricity can be produced on-site by the combustion of biogas in recovery units such as combined heat and power plants.

Equation 6-28 BTD Energy consumption

$$EU_{d,ES} = EF_{BTD_d,ES} \cdot \sum_{w} m_{d,w}$$

subject to :

$$BTD_d = \begin{Bmatrix} 1 & \text{if d = Dry process} \\ 2 & \text{if d = Wet process} \end{Bmatrix}$$

where:

$EU_{d,ES}$ Total energy type *ES* consumed by aerobic biological treatment unit *a*
$EF_{BTDd,ES}$ Emission factor of energy type *ES* consumed by aerobic biological treatment type *BTAa*
ES Energy source

Table 6-7 Energy requirements from selected anaerobic digestion systems

	(Bidlingmaier 2000)		(Pitschke 2004)			(IPPC 2005)	In this study	
Anaerobic Digestion Technology	Dry	Wet	PTC: 5-6 Gg	PTC: 10-12 Gg	PTC: 20-25 Gg	-	Dry	Wet
Electricity medium voltage, kWh/Mg	60	100	100-160	100-200	100-160	55	60	100
Heat: Total, MJ/Mg	256	60					256	60
Diesel, l	-	-	-	-	-	-	-	-

6.2.6 Costs

6.2.6.1 Treatment Cost

Anaerobic biological treatment costs are affected by diverse parameters such as:

- Source segregation efficiency
- Choice of technology
- Scale
- Plant capital costs (cost of land acquisition, planning costs and construction/plant development costs)

- Plant operation costs (plant utilisation rate)
- Revenues for sale of energy (energy recovery efficiency, legislation related to the electricity production from renewable energy sources)
- Revenues for sale of recovered material

Similarly to aerobic biological treatment, when one accounts for choice of technology and scale there is a degree of convergence in the costs as shown in Table 6-8 (Pitschke 2004, Crowe 2002, Hogg 2002, Hogg 2001, Smith 2001, Steinfeld 2002, Rösch 1996, Auksutat 1998). Anaerobic biological treatment costs are calculated as a function of the specific plant treatment capacity as given by Equation 6-29.

Table 6-8 Anaerobic biological treatment cost, €/Mg

Source	Min	Max	Aver	Comments
(LCA-IWM 2005)	45	301	-	General treatment cost as a function of the plant treatment capacity (PCT): €/Mg = 16771 $PCT^{-0.5153}$ Range 2,500 - 100,000 Mg/a
(Crowe 2002)	89	109	-	Dry Method as a function of the plant treatment capacity (*PTC*): (*) € / Mg = 379.48 $PTC^{-0.1457}$; $R^2 = 0.9985$ Scale: 5-20 Gg
(Crowe 2002)	20	36	-	Wet Method as a function of the plant treatment capacity (*PTC*): (*) € / Mg = 8E-09 $PTC^2 - 0.0012PTC + 56.144$; $R^2=1$ Scale: 20-100 Gg
(Hogg 2001)	80	100	-	Dry method. Scale not referred
(Hogg 2002)				
(Kern 1999)	72	113	93	Include the cost of residue disposal and income from sales.
(Rösch 1996)	72	191	115	Include the cost of residue disposal and income from sales.
(Smith 2001)	-	-	65	n.a.
(Steinfeld 2002)	65	75	70	Include the cost of residue disposal and income from sales.

* Treatment costs are fee gates and exclude energy conversion gas engine, costs of transport, residue disposal, staff costs, income form sales of residue/by products and income from net sales of energy.

Equation 6-29 Anaerobic biological treatment costs

a. Dry Method

$$TC_d = \begin{cases} 109.71 & if\ PTC_d < 5{,}000 \\ 379.48 \cdot PTC_d^{-0.1457} & if\ 5{,}000 < PTC_d < 20{,}000 \\ 89.65 & if\ PTC_d > 20{,}000 \end{cases}$$

b. Wet Method

$$TC_d = \begin{cases} 35.34 & if\ PTC_d < 20{,}000 \\ 8E-09 \cdot PTC_d^2 - 0.0012 \cdot PTC_d + 56.144 & if\ 20{,}000 < PTC_d < 100{,}000 \\ 16.14 & if\ PTC_d > 100{,}000 \end{cases}$$

6.2.7 Benefits

6.2.7.1 Recovered Material

Recovered material consists mainly of stabilised organic material and less proportion can be as well the recovery of metals.

Compost generated from anaerobic biological treatments has the same chemical composition as the one from aerobic units. Similarly to the aerobic compost, price drivers such as source of raw materials, compost quality criteria, type of application, local marketing strategies for composted products and existing legislation will determinate the final price, use and market shares of compost. Additionally, drivers such as local cropping conditions and existing animal husbandry will influence as well the final use of compost.

Compost from anaerobic units should fulfil the quality criteria of mature compost. Therefore, in this study will be used the price range between 0 and 50 €/Mg, with an average value of 17.5 €/Mg given by (MUNLV 1999). With this value, the economical benefit from the sales of compost is calculated with Equation 6-30.

Equation 6-30 Benefits from the sale of compost

$$BCom_d = Compost_d \cdot P_{compost} \cdot CF_{tpa-ktpa}$$

subject to :

$$P_{compost} = \{17.5\ €/\text{ton} \quad \text{for mature compost}\}$$

where:

$BCom_a$	Total benefit from the sale of compost, €/ Gg
$P_{compost}$	Compost price as a function of its quality, €/ Mg
CF_{tpa-Gg}	Conversion factor from Mg to Gg. CF = 1000, -

Additionally, these waste management units can obtain as well revenues from the segregation and commercialisation of recovered metal. Metal prices drivers vary considerable from region to region. Therefore, in order to have a point of reference, the metal prices are trade values given by the Global Recycling Network (GRN). Finally, the total benefit from the recovery of metals is calculated with Equation 6-31.

Equation 6-31 BTA revenues from recovered metals

$$BMET_d = Metal_{d,MET} \cdot P_{MET}$$

where :

$$P_{MET} = \begin{Bmatrix} 126\ €/\text{ton} & \text{if MET} = 1 \\ 493\ €/\text{ton} & \text{if MET} = 2 \\ 126\ €/\text{ton} & \text{if MET} = 3 \end{Bmatrix}$$

6.2.7.2 Recovered Energy

Energy can be recovered from the combustion of the recovered biogas in biogas-fired units. Mathematically it is calculated with Equation 6-32. This equation is restricted to the operation temperature of the digester, the biogas collection efficiency and the conversion efficiency of the biogas-fired unit. In this equation, it is assumed that the biogas collection system operates with an efficiency of 95%. The power conversion efficiency is fixed to the biogas gas-fired unit type. Gas turbines have overall power recovery efficiencies between 22 and 36 %, with an average value of 29%. Similarly, internal combustion engines have overall power recovery efficiencies between 22 and 40%, with an average value of 31% (GE 2000a, EPA 2002c). In this model is not considered the recovery of heat. Finally, the economical revenue from the sale of the recovered energy is integrated in Equation 3-21.

Equation 6-32 Total recovered energy in BTD units

for $k = 4$:

$$RE_k = \sum_d m_{d,1,CH_4} \cdot v_{CH_4} \cdot HHV_{CH_4} \cdot \eta_{BGCS} \cdot \eta_{CHP} \cdot CF_{kJ-kWh}$$

where:

RE_k	Recovered energy in the waste management operation *k(x)*, [kWh]
$m_{d,CH4}$	Methane mass flow in the biogas, kg/year
v_{CH4}	Methane specific volume: 1.5796 m^3/ kg (Mesophilic) ; 1.7335 m^3/ kg (Thermophilic)
η_{BGCS}	Biogas collection system efficiency
η_{CHP}	Combined heat and power conversion efficiency
HHV_{CH4}	Higher heating value of methane: 33,810 kJ/m^3
CF_{kJ-kWh}	Conversion factor kJ to kWh: 1kWh=3.6x10^3 kJ
	Electricity price: 0.1 € per kWh [EC 2003]
P_{kWh}	Bonus a: when is produced from plants (phytomass), manure or a combination of both = 0.06€/kWh
	Bonus c: when electricity is generated within a Combined Heat and Power unit = 0.02 €/kWh

6.2.7.3 Displaced resources and emissions

Mature compost produced from source separated biodegradable waste can be used as a sustainable substitute of mineral fertilisers. Mineral fertilisers are chemical compounds that provide essential nutrients for plant growth and are categorised according to its nutrient content (nitrogen, phosphorous and potassium).

Based on the compost quality is possible to determinate the potential amount and type of substituted mineral fertiliser. In this study is assumed that the mineral fertiliser being displaced is the nitrogen-based fertiliser ammonium nitrate (NH_4NO_3). It is assumed as well that the compost's nitrogen content displaces an equal quantity of bounded nitrogen to soil from the substituted mineral fertiliser. According to (Kaiser 2001), when compost is used as a soil improver, nitrogen is organically bounded to the soil and is less susceptible to leaching. Contrary to mineral fertilisers, where only 10-20% of the nitrogen content is able to bind into the soil (Kaiser 2001, Smith 2001, Baldoni 1996). The rest is emitted as fugitive emissions to air and leached through the soil and groundwater. Finally, the potential displaced mineral fertiliser (*PDMF*) is calculated with Equation 6-33.

Equation 6-33 Displaced mineral fertiliser

$$for\ cc = nitrogen:$$

$$PDMF_d = Compost_{d,cc} \cdot FBN^{-1} \cdot \left(\frac{MW_{NBMF} \cdot N_{NBMF}}{MW_N} \right)$$

and :

$$Compost_{d,cc} = \sum_w \left[Mdw \cdot (1 - DOC_w \cdot DOCF_d) \cdot (1 - DOCFC_d) \cdot MCC_{w,cc} \cdot (MF_{cc} - BDR_{cc}) \right]$$

$$Mdw = m_{d,w} \cdot (SOM_w + (1 - SOM_w) \cdot WPD_w)$$

where:

$PDMF_d$	Potential displaced mineral fertiliser, Gg
FBN	Bounded nitrogen fraction from mineral fertilisers = 0.10 (10%), -
MW_{NBMF}	Molecular weight of the nitrogen based mineral fertiliser, g/gmol
N_{NBMF}	Sum of nitrogen molecular indexes of the nitrogen based mineral fertiliser, -

Another benefit from the use of composted material as substitution of mineral fertilisers is the potential discount of fugitive emission to air and water generated during the production process. Fugitive emissions to air and water generated during the production of the mineral fertiliser are calculated with Equation 6-34 with the process-specific coefficients reported in Annex Table 4 for the nitrogen-based fertiliser ammonium nitrate (NH_4NO_3).

Equation 6-34 BTD displaced emissions to air

$$DFEA_d = PDMF_d \cdot EF_{FEA}$$

7 MECHANICAL-BIOLOGICAL TREATMENT: MBT

7.1 PROCESS DESCRIPTION

Mechanical-biological treatment (MBT) is defined by AbfAblV as the "*processing or conversion of waste from human settlements ... with biologically degradable organic components, via a combination of mechanical and other physical processes (for example, cutting or crushing, sorting) with biological processes (rotting, fermentation)*". The aim of this waste management operation is not only to reduce the fermentability and volume of the waste, but also to separate to certain extend the amount of hazardous waste and to recover valuable material, such as compost-like products, biogas, refuse-derived fuel (RDF) and solid recovered fuel (SRF). Thus, MBT units are the waste management alternative to enhance landfill diversion and recovery and recycling targets.

The configuration of MBT units is extensive and it depends on the material they want to produce. Following the hierarchy of waste, these configurations may have the following purposes (Archer 2005, LCA IWM 2005, MUNLV 1998):

- Material and energy recovery. This configuration considers the generation of valuable products such as compost-like products (e.g. lower grade soil improver) and biogas. In the one hand, generated compost-like products should not been confused with compost. Compost is generated from source-separated material. Additionally, MBT compost-like materials are normally rejected by the market because they do not fulfil existing compost quality criteria due to their high level of visual and chemical contamination. On the other hand, lower grade soil improvers have a limited demand with a low or negative value of the product. This waste fraction can be used as a top dressing, as a top covering cap in landfills and as landscaping material for road construction.
- Integrate the MBT with a co-incineration plant. This configuration considers the generation of tertiary waste fractions named refuse-derived fuel (RDF) and solid recovered fuel (SRF). These waste fractions can be used in co-incineration plants such as cement and powers plants for the recovery of energy and materials. However, there is a lack of enthusiasm from the power sector to use this material due to concerns about technical problems such as corrosion in the co-combustion boiler.
- Integrate the MBT with an incineration plant. The MBT is configured only as a pre-treatment waste management operation that is designed to reduce the volume and biodegradability of the input waste. Additionally, it reduces the scale of the incineration plant. This configuration is as well used for the acceptance of MBT secondary waste that do not have a market and to those that do not fulfil the landfill waste acceptance criteria.
- Integrate the MBT with a landfill. The MBT is configured only as a pre-treatment waste management operation that is designed to reduce the volume and biodegradability of the input waste. This configuration generates a stabilised biodegradable waste fraction. This waste fraction does not have a market and fulfils the landfill acceptance criteria. Therefore, it can be used both as a daily cover and as final cap for landfill restorations or simply it is landfilled. This configuration aims to minimise the generation of landfill gas and leachate in the landfill.
- A combination of the previous configurations.

In a typical MBT unit, municipal solid waste is received and storage in a close building that operates at negative pressure. Subsequently, municipal solid waste is sorted and conditioned in the mechanical treatment section. The purpose of this section is to maximise resource

recovery, to condition the waste for the biological section and to refine outputs. The range of treatment sequences is extensive because they are used to suit end-use requirements. However, a typical mechanical treatment sequence consists of a combination of sorting, separation, size reduction and sieving technologies. Typically, the mechanical treatment starts with the size reduction of the input waste. Shredding units such as crushers, mills, shears and grinders are used to archive this goal. Once reduced, the conditioned waste undergoes size classification in a sieve or trommel drum. Two fractions are generated in this step named fine fraction and oversized fraction. Fine fraction is sent to the biological section, while the oversized fraction undergoes further mechanical conditioning in a separation unit. Separation units such as air classifiers, ballistic separators or pneumatic tables are used to split the oversized fraction in two fractions named lightweight and heavy fraction. In the one hand, the lightweight fraction is a valuable product stream with a high calorific value (>11000 kJ/kg). This fraction is known as refuse derived fuel (RDF) or solid recovered fuel (SRF). RDF/SRF is used in co-incineration plants for further recovery of energy. On the other hand, the heavy weight fraction consists of dense plastics, composite material and other undefined large items. This waste fraction has a typical calorific value lower than 11,000 kJ/kg. Thus, it is not suitable to be used as a RDF/SRF but to be disposed in a thermal treatment. Finally, ferrous and non-ferrous metals are segregated as well from the input waste in the mechanical treatment section.

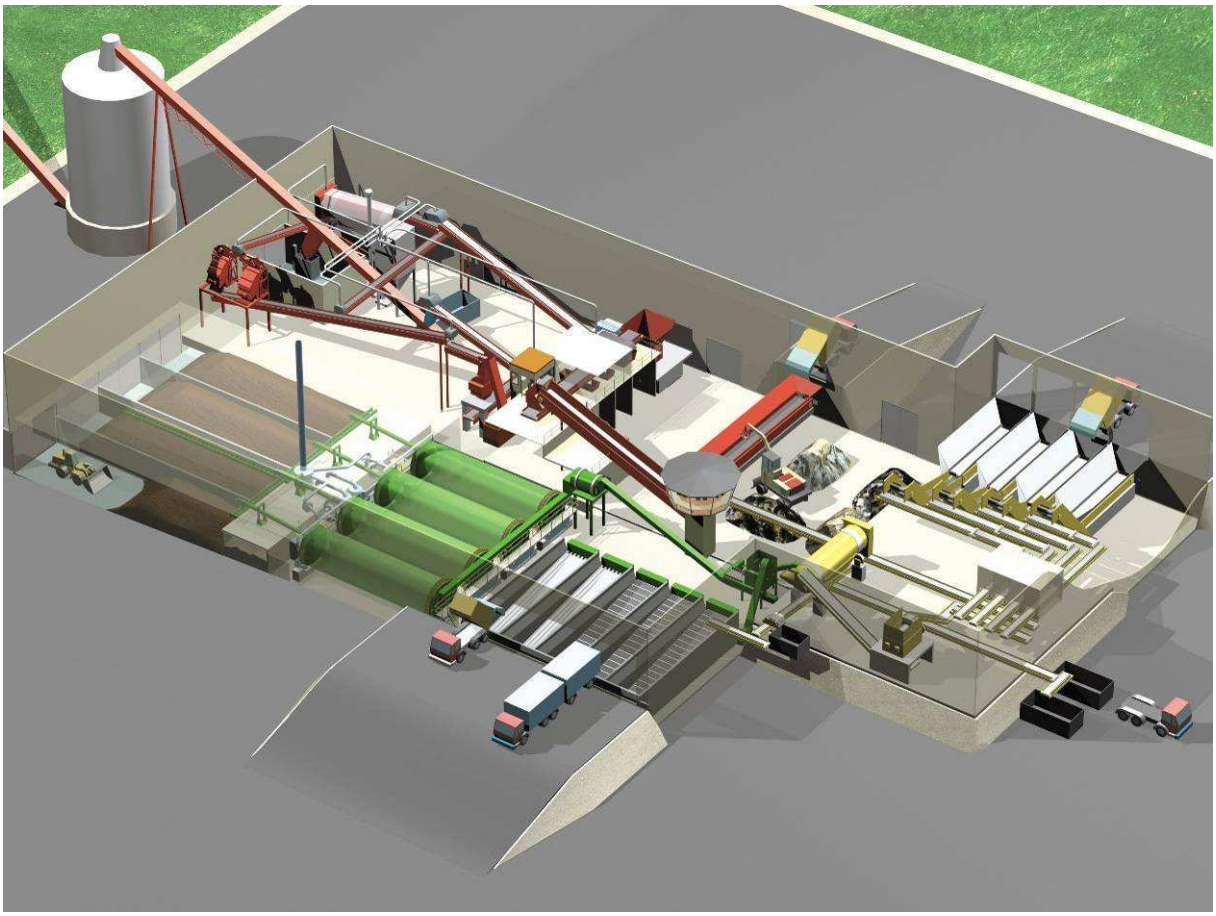


Figure 7-1 Typical scheme for a MBT plant (MBT Rumen Oy of Lahti, Finland)

The generated fine fraction in the mechanical treatment section undergoes further treatment in the biological section. The purpose of this section is to generate either a compost-like product or a stabilised biodegradable waste, whose composition determinates its use. Biological treatment is achieved in either aerobic or anaerobic treatment units, where aerobic treatment is

the most used technology. The final product of the biological treatment is a stabilised material such as a compost-like product or a stabilised biodegradable material. The final use of this material depends on its chemical composition. In one hand, it can be recovered and used as a substitute of virgin soil for non-food land applications. On the other hand, this stabilised material can be disposed of if it fulfils the landfill allocation criteria; otherwise, it is finally treated in an incineration plant.

In Europe, MBT units are regulated by the IPPC Directive and the Waste Framework Directive. The former directive recommends the use of Best Available Techniques (BAT) to ensure the minimum environmental impact from this type of waste management operation. These recommendations are given in the BAT reference (BREF) for Waste Treatment. Additionally, the output of MBT units will be regulated by EU policy framework on both solid fuels (CEN/TC 343) and land application (Soil Strategy).

7.2 MBT SUB-MODEL

The mechanical-biological sub-model (MBT) assesses the life cycle of municipal solid waste in mechanical-biological treatment waste management operation. As shown in Figure 7-2, the sub-model starts when the municipal solid waste fractions and the secondary waste generated in other waste management operations enter to the mechanical-biological treatment facility. The product system ends not only when the input waste is emitted as a fugitive emission to air, water and land but also when it is transformed into a valuable product such as recovered energy and materials.

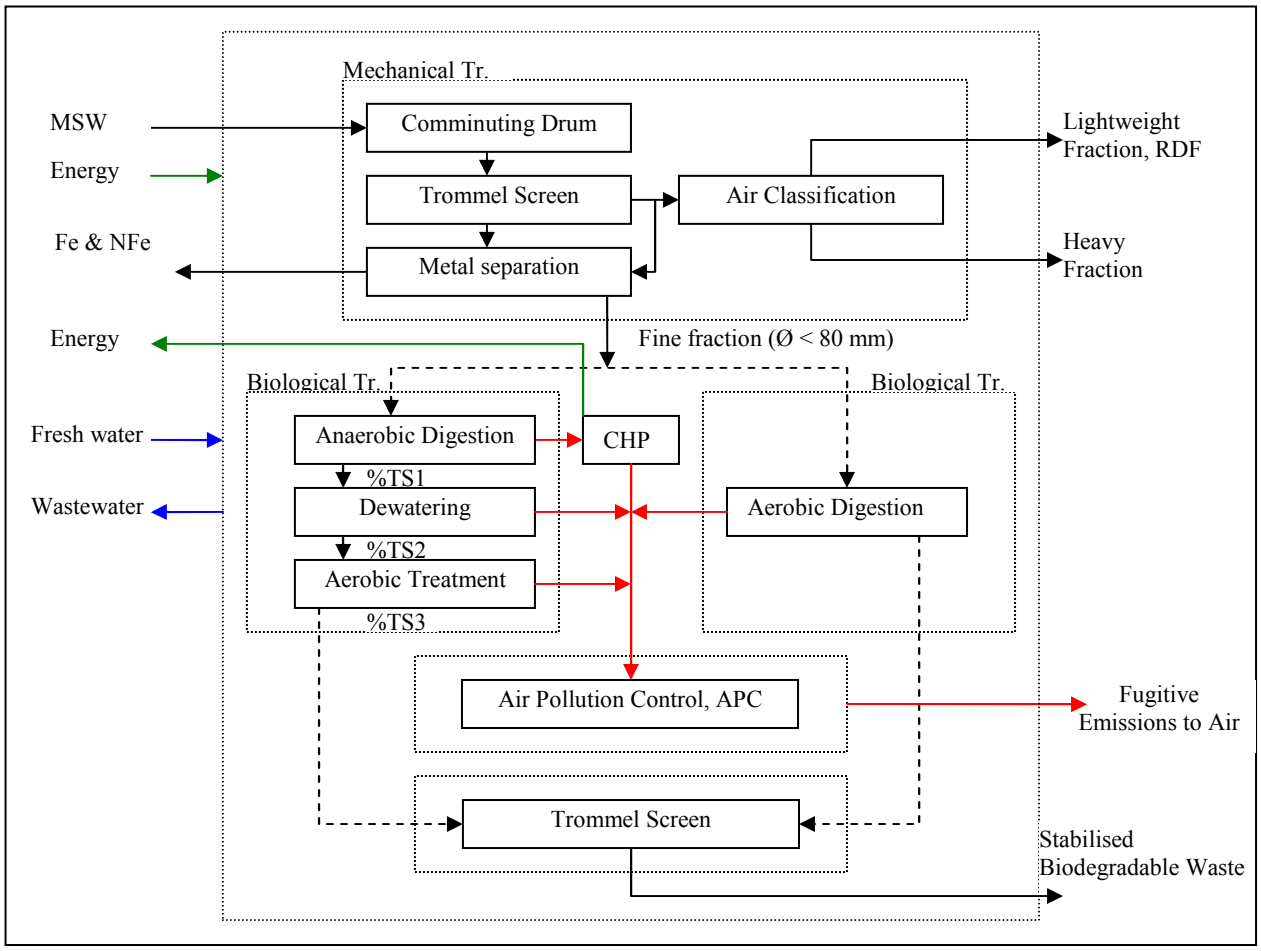


Figure 7-2 System boundaries of the mechanical-biological treatment sub-model

Material flows are calculated based on waste-specific and process-specific models. Waste-specific models depend on the composition of the input waste and on the choice of technology installed on site. On the other hand, process-specific models depend exclusively on the choice of technology and they are constant for every waste composition.

7.2.1 MBT Internal Process

7.2.1.1 Material Input

According to the multi-commodity flow distribution approach, the waste category *w* generated at the source point *j* and at the waste management facility *x* will compete for the scarce and finite capacity of the MBT *m*. The material flow distribution for every MBT unit is calculated with Equation 7-1. The input variables of this equation are previously calculated as shown in subchapter 3.4.1 related to logistic constraints.

Equation 7-1 MBT waste category *w* input acceptance

$$mmw_{m,w} = \left[\sum_{j} mjtw_{j,t,w} + \sum_{s} \left(mfst_{s,t,w} + most_{s,t,w} \right) + \sum_{c} \left(mfct_{c,t,w} + mhct_{c,t,w} \right) + \sum_{a} \left(moat_{a,t,w} \right) + \sum_{d} \left(m\,odt_{d,t,w} \right) \right]$$

subject to :

$$m_m = \sum_{w} mmw_{m,w}$$

$$PTC_m > m_m$$

where:

$mmw_{t,w}$	Total waste category *w* entering to the mechanical-biological plant *m*; [Gg]
$mjmw_{j,m,w}$	Total waste category *w* entering to the mechanical-biological plant *m* coming from the generation point *j*; [Gg]
$mzxm_{x,m,w}$	Total waste category *w* entering to the mechanical-biological plant *m* coming from the waste management facility *x* and fraction type *z*; [Gg]
m_m	Total amount of waste received in the mechanical-biological plant *m*; [Gg]
PTC_m	Plant treatment capacity for the mechanical-biological plant *m*; [Gg]

7.2.1.2 Mechanical treatment

The mechanical treatment section is used to maximise resource recovery, to remove impurities, to condition the waste that undergoes biological treatment and to refine the physical composition of generated secondary and tertiary waste. Mechanical treatment considers a combination of sorting, separation, size reduction and sieving technologies.

7.2.1.2.1 Comminuting Drum

This device is a rotating drum, where soft organic material break down to smaller particles with a diameter smaller than 80 mm while inert materials such as plastic, textiles and metals do not suffer any size reduction. Any glass material content in the input flow is reduced in size as well. The integer variable (SOM_w) is used to represent which waste category *w* is subject to comminution. Soft organic material will have a SOM_w value equal to one, otherwise equal to zero.

7.2.1.2.2 Trommel Screen

After the comminution drum, the waste is segregated in a trommel screen as a function of its grain size. The model considers a trommel screen with one opening size of 80 mm. The input waste material is divided in two fractions named fine fraction (Φ<80 mm) and oversized fraction (Φ>80 mm). The fine fraction contains a high percent of organic material, which is suitable for biological treatment. The oversized fraction consists mainly of impurities such as mixed plastics, textiles, paper and cardboard or similar non-biodegradable materials. Fine and oversized fraction are calculated with Equation 7-2 and Equation 7-3, respectively.

Equation 7-2 MBT Fine Fraction

$$mFF_{m,w} = m_{m,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w\right)$$

Equation 7-3 MBT Oversized Fraction

$$mOF_{m,w} = m_m \cdot \left(1 - SOM_w\right) \cdot \left(1 - WPD_w\right)$$

7.2.1.2.3 Density separator

The oversized fraction is conveyed to a density separator for further segregation. In this unit, the oversized fraction is divided in two fractions named lightweight fraction and heavy weigh fraction. The lightweight fraction consists of waste fractions such as paper, cardboard, plastic material (films) and composites with high calorific values. This lightweight fraction is suitable for the production of RDF/SRF only if it fulfils quality standards. Good quality RDF/SRF products can be used for energy recovery in co-incineration plants. On the other hand, the heavy weight fraction consists of dense plastics (i.e. plastic bottles, other dense plastic composite packaging material), larger metal containers and composite materials. The heavy weight fraction is suitable for mechanical or feedstock recycling.

Density separator units are commonly based on air separation technologies, which can be divided *inter alia* in the crosswise air classification, foils suction in combination with infrared plastic detection and the air knife classifier (Rotter 2004). The crosswise air classification units segregate the input material by means of their grain size and density. Lightweight particles are separated with a crosswise air stream. Thus, the grain size distribution is limited in previous steps to optimise the sorting effect. Similarly, the foils suction in combination with infrared plastic detection is based on the automatic segregation of lightweight particles. Automated sorting systems employing NIR (Near-Infra-Red) technology identify lightweight fractions based on material properties and they provide a signal to a blower, which segregates these fractions from the material conveyor. Finally, the air knife classifier segregated hard from soft materials based on their impact behaviour. This segregation process is supported by an air classifier.

In this model, it is assumed that existing MBT units have a crosswise air classification density separator. Therefore, the potential amount of lightweight material that can be recovered from the oversized fraction is calculated with Equation 7-4, while the potential heavyweight fraction is calculated with Equation 7-5. These equations make use of the LFD_w variable, which indicates the efficiency of an air separation type zick-zack related to individual waste categories (Fricke 2002, Bilitewski 1991). Typical air separation efficiencies are given in the Annex Table 2, under $MPP_{w,3}$.

Equation 7-4 MBT lightweight fraction

$$mLF_{m,w} = m_m \cdot \left(1 - SOM_w\right) \cdot \left(1 - WPD_w\right) \cdot LFD_w$$

Equation 7-5 MBT heavy weight fraction

$$mHF_{m,w} = m_m \cdot \left(1 - SOM_w\right) \cdot \left(1 - WPD_w\right) \cdot \left(1 - LFD_w\right)$$

where:

$m_{m,w}$	Mass flow of the waste category fraction w which enters to the mechanical-biological treatment m; [Gg]
$mFF_{m,w}$	Fine Fraction mass flow from mechanical-biological treatment m; [Gg]
$mOF_{m,w}$	Oversized Fraction mass flow from mechanical-biological treatment m; [Gg]
$mLF_{m,w}$	Lightweight fraction mass flow from mechanical-biological treatment m; [Gg]
$mHF_{m,w}$	Heavy weight fraction mass flow from mechanical-biological treatment m; [Gg]
SOM_w	Integer variable for the waste category w which is subject to comminution; [-] For the waste category w, that is soft organic material then SOM_w is equal to 1, otherwise to 0.
WPD_w	Waste Particle Distribution fraction lower than 80 mm for the waste category w; [-]
LFD_w	Lightweight fraction distribution for the waste category w; [-]

7.2.1.2.4 Metals separation

Ferrous metals are recovered from the waste input by means of a magnet unit while aluminium by means of an eddy-current separator. These recovery units are both suspended above the fine and oversized conveyor belt. It is assumed that the total metal input is separated and recovered from the feedstock stream. Therefore, the recovery metal flow is calculated with Equation 7-6.

Equation 7-6 MBT metals separation

for $w = 1..3$;

$$Metal_{m,MET} = m_{m,w}$$

where:

$Metal_{m,MET}$	Metal mass flow type *MET* separated and recovered from mechanical-biological treatment unit *m*;[Gg]
MET	Metal type: 1 = metal, 2 = aluminium, 3 = mix; -

7.2.1.3 Biological treatment

The fine fraction that was segregated in the mechanical treatment undergoes further conditioning in the biological treatment section. Biological treatment is carried out in either aerobic or anaerobic treatment units, whose purpose is to reduce the fermentability and volume of the waste. The choice of biological treatment technology and residence time is related to the desired output from the MBT. The output of the biological treatment section could be stabilised biodegradable waste, a compost-like product and/or biogas. In the one hand, in aerobic treatment units, biodegradable waste fractions are biodegraded and stabilised. Similarly, anaerobic digestion units produce not only a stabilised product but also biogas. On the other hand, short-term maturation periods are given for biological drying purposes, while long-term maturation periods are given for a controlled degradation of the biodegradable waste.

Aerobic digestion is the most common choice of technology employed in MBT units. Contrary, anaerobic digestion units are not widely used in Europe. The methodology used to calculate the material flow in aerobic and anaerobic biological treatment units is the same as the one applied in chapter 5 and chapter 6, respectively. Therefore, in this section are given only the main waste-specific equations for the determination of potential degradable material and stabilised biodegradable waste in the biological section of the MBT unit.

In both aerobic and anaerobic treatment sections, the potential degradable material *(PDM)* subject to biological degradation is based on both the chemical composition and on the degradability potential of the fine fraction. This approach follows the default method (Tier 1), which is recommended by the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000). The potential degradable material entering to the biological section is calculated with Equation 7-7. This equation is restricted to the integer variable $BDR_{cc,}$ which fixes the input of water, inert material and heavy metals into the substrate. Additionally, the BREF for Waste Treatment recommends that thermophilic digestion conditions should be used and the production of biogas should be maximised in the anaerobic biological section.

Equation 7-7 MBT Potential Degradable Material, $PDM_{m,cc}$

$$PDM_{m,cc} = \sum_{w} \left[m_{m,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right) \cdot DOC_w \cdot DOCF_{m,BT_m} \cdot MCC_{w,cc} \cdot BDR_{cc} \right]$$

and

$$DOCF_{m,BT} = \begin{cases} 1 - \exp^{(-0.0577 \cdot CRT_m)} & \text{if } BT_m = 1; \text{Aerobic Treatment} \\ 0.014 \cdot T_m + 0.28 & \text{if } BT_m = 2; \text{Anaerobic Treatment} \end{cases}$$

In aerobic treatment units, the amount of stabilised biodegradable waste is directly calculated with Equation 7-8.

Equation 7-8 MBT Aerobic stabilised biodegradable material, $SBWA_{m,cc}$

$$SBWA_{m,cc} = \sum_{w} \left[m_{m,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right) \cdot MCC_{w,cc} \cdot \left(MF_{cc} - DOC_w \cdot DOCF_{m,BT_m} \cdot BDR_{cc} \right) \right]$$

On the other hand, the anaerobic biological treatment is a two-step process. Firstly, the fine fraction is anaerobically degraded. During the anaerobic process, the potential amount of degradable material is calculated with Equation 7-7. In this step, three products named biogas, liquor, and digestate are generated. The biogas is collected for energy recovery. The liquor is recycled to the digester to balance the moisture, while the digestate undergoes further aerobic conditioning in the curing section.

Equation 7-9 MBT Potential Degradable Material (Anaerobic Treatment, Curing section), $PDMC_{m,cc}$

$$PDMD_{m,cc} = \sum_{w} \left[m_{m,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right) \cdot (1 - DOC_w \cdot DOCF_{m,BT_m}) \cdot DOCFC_m \cdot MCC_{w,cc} \cdot BDR_{cc} \right]$$

and

$$DOCF_{m,BT} = \begin{Bmatrix} 1 - \exp^{(-0.0577 \cdot CRT_m)} & \text{if } BT_m = 1; \text{Aerobic Treatment} \\ 0.014 \cdot T_m + 0.28 & \text{if } BT_m = 2; \text{Anaerobic Treatment} \end{Bmatrix}$$

$$DOCFC_m = 1 - \exp^{(-0.0577 \cdot CRT_m)}$$

The potential amount of stabilised biodegradable waste generated in the curing section is calculated with Equation 7-10. In this equation are considered both the anaerobic and aerobic biological treatment of the fine input fraction.

Equation 7-10 MBT Anaerobic stabilised biodegradable material, $SBWD_{m,cc}$

$$SBWD_{m,cc} = \sum_{w} \left[m_{m,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right) \cdot MCC_{w,cc} \cdot \begin{bmatrix} BDR_{cc} \cdot \left(1 - DOC_w \cdot DOCF_{m,BT_m}\right) \cdot \left(1 - DOCFC_m\right) \\ + \left(MF_{cc} - BDR_{cc}\right) \end{bmatrix} \right]$$

Finally, the potential amount and composition of the stabilised biodegradable waste generated by the MBT unit are calculated with Equation 7-11 and Equation 7-12, respectively. These equations are a function of the type of biological treatment installed on site.

Equation 7-11 Generation of stabilised biodegradable waste, $SBW_{m,w}$

$$mSBWA_{m,w} = \begin{Bmatrix} Mmw \cdot \left(1 - MCC_{w,H_2O}\right) \cdot \left(1 - DOC_w \cdot DOCF_{m,BT_m}\right) & \text{if } BT_m = 1 \\ Mmw \cdot \left(1 - MCC_{w,H_2O}\right) \cdot \left(1 - DOC_w \cdot DOCF_{m,BT_m}\right) \cdot \left(1 - DOCFC_m\right) & \text{if } BT_m = 2 \end{Bmatrix}$$

and

$$Mmw = m_{m,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w \right)$$

Equation 7-12 Stabilised biodegradable waste composition, $SBW_{m,cc}$

$$SBW_{m,cc} = \begin{Bmatrix} SBWA_{m,cc} & \text{if } BT_m = 1; \text{Aerobic Treatment} \\ SBWD_{m,cc} & \text{if } BT_m = 2; \text{Anaerobic Treatment} \end{Bmatrix}$$

7.2.2 Secondary Waste

According to the market situation, MBT outputs can be considered as secondary or tertiary waste. Under unfavourable market conditions, MBT outputs that are considered as secondary waste include the oversize fraction and the stabilised biodegradable waste fraction. The lightweight fraction can be considered as well as secondary waste only if it does not fulfil exiting RDF/SRF quality criteria.

Following the multi-commodity flow distribution approach, the secondary waste fractions generated in the mechanical-biological treatment unit *m* will compete for scarce treatment and disposal capacity in the thermal treatment *t* and in the landfill *l*. The material flow distribution of these waste fractions depends on its composition. Waste fractions that fulfil the provisions given by the Council Decision 2003/33/EC on waste acceptance criteria at landfill could be disposed of. The material flow distribution of secondary waste to landfill *l* is subject to the integer variable $LFRM_m$. Both the heavy weight fraction and the stabilised biodegradable waste flow distribution are calculated with Equation 7-13 and Equation 7-14, respectively. Both equations consider the flow distribution of each secondary waste subject to the decision variable $\delta MX_{m,x}$, where *X* and *x* are substituted with the specific waste management operation index (*T,L*) and (*t,l*), respectively. Subsequently, both the decision variables and secondary flows are balance to ensure the equilibrium of the system.

Equation 7-13 MBT heavy weight fraction flow distribution

$$mHMT_{m,t} = \sum_{w} \left[m_m \cdot (1 - SOM_w) \cdot (1 - WPD_w) \cdot (1 - LFD_w) \right] \cdot \delta MT_{m,t}$$

$$mHML_{m,l} = \sum_{w} \left[m_m \cdot (1 - SOM_w) \cdot (1 - WPD_w) \cdot (1 - LFD_w) \right] \cdot \delta ML_{m,l} \cdot LFRM_m$$

and :

$$1 = \sum_{t} \delta MT_{m,t} + \sum_{t} \delta ML_{m,l}$$

$$\sum_{w} mHF_{m,w} = \sum_{t} mHMT_{m,t} + \sum_{l} mHML_{m,l}$$

$$HM_w = m_m \cdot (1 - SOM_w) \cdot (1 - WPD_w) \cdot (1 - LFD_w)$$

$$LFRM_m = \begin{Bmatrix} 0 & \text{if } \sum_{w} \left[HM_w \cdot MCC_{w,C} \right] > LFC_C \cdot \sum_{w} \left[HM_w \cdot (1 - MCC_{w,C}) \right] \\ 1 & \text{if } \sum_{w} \left[HM_w \cdot MCC_{w,C} \right] \leq LFC_C \cdot \sum_{w} \left[HM_w \cdot (1 - MCC_{w,C}) \right] \end{Bmatrix}$$

Equation 7-14 MBT stabilised biodegradable waste flow distribution

$$mFMT_{m,t} = \sum_{w} \left[mSBW_{m,w} \right] \cdot \delta MT_{m,t}$$

$$mFML_{m,l} = \sum_{w} \left[mSBW_{m,w} \right] \cdot \delta ML_{m,l} \cdot LFRM_m$$

and :

$$1 = \sum_{t} \delta MT_{m,t} + \sum_{t} \delta ML_{m,l}$$

$$\sum_{w} mSBW_{m,w} = \sum_{t} mFMT_{m,t} + \sum_{l} mFML_{m,l}$$

$$LFRM_m = \begin{Bmatrix} 0 & \text{if } \sum_{w} \left[mSBW_{m,w} \cdot MCC_{w,C} \right] > LFC_C \cdot \sum_{w} \left[mSBW_{m,w} \cdot (1 - MCC_{w,C}) \right] \\ 1 & \text{if } \sum_{w} \left[mSBW_{m,w} \cdot MCC_{w,C} \right] \leq LFC_C \cdot \sum_{w} \left[mSBW_{m,w} \cdot (1 - MCC_{w,C}) \right] \end{Bmatrix}$$

where:

t,l	thermal treatment unit t, landfill l; -
$\delta MX_{m,x}$	Decision variable which determinates the fraction of secondary waste generated in MBT unit m and transported to units x:(t,l);[-]
$LFRM_m$	Transportation restriction to landfill from the secondary waste generated in unit m; [-]
LFC_C	Landfill disposal limit criteria for organic component of dry residue; [-]
$mZMX_{m,x}$	Secondary waste Z flow distribution from unit m to unit x:(t,l) ; Gg

7.2.3 Fugitive Emissions to Air, FEA_m

Generation fugitive emissions are generated in two sources. In the one hand, there is the exhaust gas from the mechanical treatment, which is lightly intermittent load. On the other hand, there is the exhaust gas from the biological treatment units, which is a high continuous load. Generated fugitive emissions to air from MBT units are regulated by the IPPC directive. This directive recommends the use of Best Available Techniques (BAT) to ensure the minimum environmental impact from this type of waste management operation. These recommendations are given in the BAT reference (BREF) for Waste Treatment.

Fugitive emission such as CO_2, CH_4, CO, N_2O, NH_3,SO_2 and HCl, are calculated with waste-specific models. On the other hand, trace gases such as NMVOC, PAH, PCDD/F and particular matter are calculated with process-specific models. The last ones are derived from background sources such as (IPPC 2005), (Soyez 2002), (BASF 2004), (Angerer 1999), (Häusler 1998) and (Häusler 1999). Process-specific transfer coefficients are given in Table 7-1.

7.2.3.1 FEA_m Generation

Fugitive emissions to air are generated in both mechanical and biological treatment sections. Emissions from the mechanical treatment section include particular matter (dust), bio-aerosols and odours; while fugitive emissions to air generated in the biological treatment section depend on the installed choice of technology. Aerobic biological treatment technologies produce a raw gas, which mainly consists of carbon dioxide (CO_2) and water. In less magnitude, trace gases such as ammonia (NH_3), organic compounds (NMVOCs), bioaerosols and particular matter are as well generated. Fugitive emissions generated in the aerobic treatment section are calculated as indicated in chapter 5.2.3.1. In contrast, anaerobic biological treatment technologies generated mainly biogas (CH_4 and CO_2) and trace gases. The generation of fugitive emissions in the anaerobic treatment section is calculated as indicated in chapter 6.2.3.1 and 6.2.3.2. Therefore, the methodology use to estimate the generation of fugitive emissions will not be explained in detail in this section. The lecturer is invited to read the mentioned chapter for further considerations.

In the one hand, fugitive emissions generated in the aerobic biological treatment section are calculated based on the stoichiometric coefficient of Reaction 5-1. The right-hand compounds of this reaction are calculated with a waste-specific emission model, while traces gases are calculated with a process-specific emission model. Both waste-specific and process-specific emission models are shown in Equation 7-15.

Table 7-1 MBT raw flue gas

	Source	(IPPC 2005)	(Soyez 2002)	(BASF 2004)	(Greenpeace 2003)	(Angerer 1999)	(Häusler 1998)	(Häusler 1999)	min	max	aver
FEA	kg/kg										
Carbon dioxide	CO_2				1.220E-1				1.220E-1	1.220E-1	1.220E-1
Methane	CH_4	1.206E-3	1.000E-4	1.606E-5	5.340E-5				1.606E-5	1.206E-3	3.437E-4
Nitrous oxide	N_2O	6.050E-5		1.077E-5					1.077E-5	6.050E-5	3.564E-5
	HFC-23								-	-	
	CF4								-	-	
Sulphur hexafluoride	SF_6								-	-	
Sulphur dioxide	SO_2			2.324E-6	8.770E-14				8.770E-14	2.324E-6	1.162E-6
Nitrogen dioxide	NO_2	1.000E-4			2.070E-10				2.070E-10	1.000E-4	5.000E-5
Ammonia	NH_3	1.853E-3	5.000E-4	2.493E-5	6.540E-5	5.059E-4	1.360E-5		1.360E-5	1.853E-3	4.937E-4
Hydrogen chloride	HCl			1.901E-6					1.901E-6	1.901E-6	1.901E-6
Hydrogen sulphide	H_2S								-	-	
NMVOC or TOC	NMVOC	3.004E-4	6.000E-4	1.014E-4		4.900E-4	4.100E-4		1.014E-4	6.000E-4	3.804E-4
Dioxins & Furans	PCDD/F	1.625E-12			1.350E-14		3.000E-17		3.000E-17	1.625E-12	5.462E-13
PAH	PAH								-	-	
Carbon monoxide	CO				5.670E-11				5.670E-11	5.670E-11	5.670E-11
Particulates, < 2.5 µm	PM2.5								-	-	
Particulates,	PM				4.720E-6				4.720E-6	4.720E-6	4.720E-6
Particulates, >10 µm	PM10	1.745E-4							1.745E-4	1.745E-4	1.745E-4
Cadmium	Cd			2.028E-7		6.000E-11	2.500E-11	6.000E-11	2.500E-11	2.028E-7	5.074E-8
Thallium	Tl								-	-	
Mercury	Hg			4.225E-9	2.500E-9	2.145E-8	1.800E-9	4.150E-9	1.800E-9	2.145E-8	6.825E-9
Antimony	Sb								-	-	
Arsenic	As						1.000E-11		1.000E-11	1.000E-11	1.000E-11
Lead	Pb					1.300E-9	1.000E-10	3.500E-10	1.000E-10	1.300E-9	5.833E-10
Chromium	Cr								-	-	
Cobalt	Co								-	-	
Copper	Cu					6.050E-10	1.000E-10	1.000E-9	1.000E-10	1.000E-9	5.683E-10
Manganese	Mn					1.745E-9	1.000E-10	1.350E-9	1.000E-10	1.745E-9	1.065E-9
Nickel	Ni						1.500E-10	1.750E-9	1.500E-10	1.750E-9	9.500E-10
Vanadium	V										

Equation 7-15 MBT raw gas generation (Aerobic biological treatment)

for $fea = CO_2, NH_3, H_2S, HCl, CO, CH_4$ and N_2O :

$$gFEAMA_{m,fea} = \sum_{w}\left[m_{m,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w\right) \cdot DOC_w \cdot DOCF_{m,BT_m} \cdot MCC_{w,cc} \cdot \frac{MW_{fea}}{MW_{cc}} \cdot x_{cc-fea} \right]$$

otherwise :

$$gFEAMA_{m,fea} = EFA_{fea} \cdot \sum_{w}\left[m_{m,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w\right)\right]$$

On the other hand, in the anaerobic biological treatment section is generated biogas based on the stoichiometric coefficient of Reaction 6-1. The right-hand compounds of this reaction are calculated with a waste-specific emission model, while traces gases are calculated with a process-specific emission model. Both waste-specific and process-specific emission models are shown in Equation 7-16.

Equation 7-16 MBT biogas generation (Anaerobic biological treatment)

for $fea = CH_4, CO_2, NH_3, H_2S$ and HCl :

$$gFEAMD_{m,CH_4} = MW_{CH_4} \cdot \left(\frac{4PDM_{m,C}}{MW_C} + \frac{PDM_{m,H}}{MW_H} - \frac{2PDM_{m,O}}{MW_O} - \frac{3PDM_{m,N}}{MW_N} - \frac{2PDM_{m,S}}{MW_S} - \frac{PDM_{m,Cl}}{MW_{Cl}} \right) / 8$$

$$gFEAMD_{m,CO_2} = MW_{CO_2} \cdot \left(\frac{4PDM_{m,C}}{MW_C} - \frac{PDM_{m,H}}{MW_H} + \frac{2PDM_{m,O}}{MW_O} + \frac{3PDM_{m,N}}{MW_N} + \frac{2PDM_{m,S}}{MW_S} + \frac{PDM_{m,Cl}}{MW_{Cl}} \right) / 8$$

$$gFEAMD_{m,NH_3} = PDM_{m,N} \cdot \frac{MW_{NH_3}}{MW_N}$$

$$gFEAMD_{m,H_2S} = PDM_{m,S} \cdot \frac{MW_{H_2S}}{MW_S}$$

$$gFEAMD_{m,HCl} = PDM_{m,Cl} \cdot \frac{MW_{HCl}}{MW_{Cl}}$$

and

$$PDM_{m,cc} = \sum_{w}\left[m_{m,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w\right) \cdot DOC_w \cdot DOCF_{m,BT_m} \cdot MCC_{w,cc} \right]$$

otherwise :

$$gFEAMD_{m,fea} = EFD_{fea} \cdot \sum_{w}\left[m_{m,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w\right)\right]$$

After stabilisation of the fine fraction in the anaerobic digester, the produced substrate known as digestate undergoes further aerobic biological treatment. This curing process generates as well raw gas based on the stoichiometric coefficient of Reaction 5-1. The right-hand compounds of this reaction are calculated with a waste-specific emission model, while traces gases are calculated with a process-specific emission model. Both waste-specific and process-specific emission models are shown in Equation 7-17.

Equation 7-17 MBT raw gas generation (Aerobic biological treatment: Curing)

for $fea = CO_2, NH_3, H_2S, HCl, CO, CH_4$ and N_2O :

$$gFEAMC_{m,fea} = \sum_{w}\left[Mmw \cdot \left(1 - DOC_w \cdot DOCF_{m,BT_m}\right) \cdot DOCFC_m \cdot MCC_{w,cc} \cdot \frac{MW_{fea}}{MW_{cc}} \cdot x_{cc-fea} \right]$$

$$Mmw = m_{m,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w\right)$$

otherwise :

$$gFEAMA_{m,fea} = EFA_{fea} \cdot \sum_{w}\left[m_{m,w} \cdot \left(SOM_w + \left(1 - SOM_w\right) \cdot WPD_w\right) \cdot \left(1 - MCC_{w,H_2O}\right) \cdot \left(1 - DOC_w \cdot DOCF_{m,BT_m}\right)\right]$$

Finally, the total amount of raw gas generated in the biological treatment section of the mechanical-biological treatment unit *m* is the one of its choice of technology. Equation 7-18 provides the amount of raw gas and biogas generated in every treatment unit.

Equation 7-18 MBT raw gas generation at MBT_m

$$gFEAM_{m,fea} = \begin{cases} gFEAMA_{m,fea} & \text{if } BT_m = 1 \\ gFEAMD_{m,fea} + gFEAMC_{m,fea} & \text{if } BT_m = 2 \end{cases}$$

7.2.3.2 FEA_m Control

Both the raw gas and the biogas generated in the biological treatment section are collected for further control. In the one hand, the raw gas is treated in an APC unit previous its emissions to the atmosphere. The BREF Waste Treatment states that air emissions from MBT process should be abated by the application of regenerative thermal oxidation or catalytic oxidation. Currently, most of the existing MBT units have installed APC unit such as biofilters. With this assumption, the controlled emissions of fugitive emissions to air from the aerobic biological treatment section are calculated with Equation 7-19. The efficiency of the biofilter unit is given by the variable vector used in the matrix $\eta_{APC:FEA,BTAa}$. The term BTA_a is fixed to two having in consideration that the biological treatment choice of technology is an enclosed or in-vessel reactor system.

On the other hand, the biogas generated in the anaerobic biological treatment section is collected by means of the biogas collection system and burned with biogas-fired units. Typical biogas-fired units include flares, gas turbines and internal combustion engines. The final controlled emission from anaerobic digestion units are a function of the biogas collection efficiency and the removal efficiency from the selected digester gas-fired unit. Biogas collection systems are not 100% efficient. No collected biogas can be emitted to the atmosphere from emergency vent valves and from poorly sealed water traps (IPPC 2005). The EPA-D (EPA-D 1997) has reported biogas collection efficiencies range between 95% and 98%. In case that there are no site-specific values, it is recommended to take the average value of 96.5%. Final controlled emissions are calculated with Equation 7-20.

Equation 7-19 MBT controlled fugitive emissions to air from the aerobic biological treatment raw gas

for $fea = CO_2, N_2O \text{ and } NO_2$:

$$FEAMA_{m,CO_2} = gFEAMA_{m,CO_2} + gFEAMA_{m,CH_4} \cdot \eta_{APC:CH_4,BTA_a} \cdot \frac{MW_{CO_2}}{MW_{CH_4}} + gFEAMA_{m,CO} \cdot \eta_{APC:CO,BTA_a} \cdot \frac{MW_{CO_2}}{MW_{CO}}$$

$$FEAMA_{m,N_2O} = gFEAMA_{m,N_2O} + gFEAMA_{m,NH_3} \cdot x_{NH_3-N_2O} \cdot \frac{MW_{N_2O}}{MW_{NH_3}}$$

$$FEAMA_{m,NO_2} = gFEAMA_{m,NO_2} + gFEAMA_{m,NH_3} \cdot x_{NH_3-NO_2} \cdot \frac{MW_{NO_2}}{MW_{NH_3}}$$

otherwise :

$$FEAMA_{m,fea} = gFEAMA_{m,fea} \cdot \eta_{APC:fea,BTA_a}$$

Equation 7-20 MBT controlled fugitive emissions to air from the combustion of gas in the biogas-fired unit

for $fea = CO_2, SO_2, NO_2$ and HCl; then :

$$FEAMD_{m,CO_2} = gFEAMD_{m,CO_2} + gFEAMD_{m,CH_4} \cdot \eta_{BGCS} \cdot \eta_{APC:APC_m,CH_4} \cdot \frac{MW_{CO_2}}{MW_{CH_4}}$$

$$FEAMD_{m,SO_2} = gFEAMD_{m,H_2S} \cdot \eta_{BGCS} \cdot \eta_{APC:APC_m,H_2S} \cdot \frac{MW_{SO_2}}{MW_{H_2S}}$$

$$FEAMD_{m,NO_2} = gFEAMD_{m,NH_3} \cdot \eta_{BGCS} \cdot \eta_{APC:APC_m,NH_3} \cdot \frac{MW_{NO_2}}{MW_{NH_3}}$$

$$FEAMD_{m,HCl} = gFEAMD_{m,HCl}$$

for $fea = CH_4, H_2S$ and NH_3; then :

$$FEAMD_{m,fea} = gFEAMD_{m,fea} \cdot \left[(1 - \eta_{BGCS}) + \eta_{BGCS} \cdot (1 - \eta_{APC:APC_m,fea})\right]$$

otherwise :

$$FEAMA_{m,fea} = gFEAMA_{m,fea} \cdot \eta_{APC:fea,BTA_a}$$

Raw gas generated in the curing section is as well collected and controlled in a biofilter unit. The controlled fugitive emissions of the biofilter are calculated with Equation 7-21 as a function of the raw gas composition and the biogas removal efficiency.

Equation 7-21 MBT controlled fugitive emissions to air from the aerobic biological treatment raw gas (curing)

for $fea = CO_2, N_2O$ and NO_2 :

$$FEAMC_{m,CO_2} = gFEAMC_{m,CO_2} + gFEAMC_{m,CH_4} \cdot \eta_{APC:CH_4,BTA_a} \cdot \frac{MW_{CO_2}}{MW_{CH_4}} + gFEAMC_{m,CO} \cdot \eta_{APC:CO,BTA_a} \cdot \frac{MW_{CO_2}}{MW_{CO}}$$

$$FEAMC_{m,N_2O} = gFEAMC_{m,N_2O} + gFEAMC_{m,NH_3} \cdot x_{NH_3-N_2O} \cdot \frac{MW_{N_2O}}{MW_{NH_3}}$$

$$FEAMC_{m,NO_2} = gFEAMC_{m,NO_2} + gFEAMC_{m,NH_3} \cdot x_{NH_3-NO_2} \cdot \frac{MW_{NO_2}}{MW_{NH_3}}$$

otherwise :

$$FEAMC_{m,fea} = gFEAMC_{m,fea} \cdot \eta_{APC:fea,BTA_a}$$

Finally, the total amount of fugitive emissions to air generated in the biological treatment section of the MBT unit *m* is calculated with Equation 7-22. This emission depends on the installed choice of technology.

Equation 7-22 MBT fugitive emissions to air

$$FEAM_{m,fea} = \begin{cases} FEAMA_{m,fea} & \text{if } BT_m = 1 \\ FEAMD_{m,fea} + FEAMC_{m,fea} & \text{if } BT_m = 2 \end{cases}$$

7.2.4 Fugitive Emissions to Water, FEW_m

In mechanical-biological treatments units, wastewater is mainly generated in the biological section. Other sources include as well the leachate generated in the waste reception hall and the condensates from the biofilter. Generated wastewater is collected and recycled to the biological section to correct its moisture level. As a result, mechanical-biological treatment units can operate without the generation and discharge of wastewater (Greenpeace 2003, LCA IWM 2005, Fricke 2002). In this model, fugitive emissions to water are calculated with a

process-specific model (Equation 7-23) based on the background sources, as given in Table 7-2.

Equation 7-23 MBT fugitive emissions to water, Gg

$$FEW_{m,few} = PEF_{few} \cdot \sum_{w} m_{m,w}$$

Table 7-2 MBT fugitive emissions to water

FEW		(IPPC 2005c)	(Pitschke 2004)
		mg/kg	
Waste water volume	m^3/Mg		0.180
Biological oxygen demand	BOD	(20, 25, 22.5)	
Chemical oxygen demand	COD	(120, 200, 160)	
Nitrogen Total	N-tot	70	
Phosphorous Total	P-tot	(1, 3, 2)	
Mercury	Hg	-	

7.2.5 Energy consumption

Energy consumption in MBT units depends mainly on the choice of the biological technology installed on site. In this model, energy consumption is calculated with the process-specific model represented by Equation 7-24, which is based the background information given in Table 7-3. It is assumed that MBT units with an aerobic biological section such as non-reactor system will consume only diesel for heating operations (15 MJ/Mg). Similarly, enclosed reactor systems have an average energy consumption of 50 kWh/Mg electricity and 5 MJ/Mg diesel. On the other hand, MBT units with an anaerobic biological section have an average energy consumption of 55kWh/Mg electricity and 19.2MJ/Mg diesel.

Equation 7-24 MBT energy consumption

$$EU_{m,ES} = PEF_{BT_m,ES} \cdot \sum_{w} m_{m,w}$$

Table 7-3 MBT energy consumption

Source	(IPPC 2005): Aerobic - NRS	(IPPC 2005): Aerobic - ERS	(Pitschke 2004)	(LCA IWM 2005) Aerobic	(LCA IWM 2005) Anaerobic
Electricity medium voltage, kWh/Mg	0	(27, 65, 50)	46	(40, 70, 55)	55
Heat: Total, MJ/Mg	-	-			
Diesel, MJ/Mg	15	5	15.36	19.2	19.2

(Min, Max, Aver)
Diesel (38.4 MJ/L, 48MJ/kg); Heavy fuel oil (42 MJ/kg); Natural gas (52 MJ/kg)

7.2.6 Costs

7.2.6.1 Treatment Cost

Treatment costs in MBT depend on diverse parameters such as:

- Installed choice of mechanical treatment technology
- Installed choice of biological treatment technology
- Scale
- Plant capital costs (costs of acquisition, planning costs and construction/plant development costs)
- Plant operation costs (plant utilisation rate)
- Revenues from recovered material and energy
- Disposal costs of secondary waste in incineration plants and landfills

The variety of mechanical-biological treatment costs is extensive. However, when one accounts for the choice of technology and scale there is a degree of convergence as shown in Table 7-4. From this background information, the capital and operational costs estimated by (LCA-IWM 2005) provide the most representative values. Therefore, in this model the thermal treatment cost is calculated with Equation 8-13, which is based on the plant treatment capacity and on the installed biological treatment type. It is assumed that the mechanical-treatment plant operates at full utilisation rate.

Equation 7-25 MBT treatment costs

$$TC_m = \begin{Bmatrix} 3173.3 \cdot PTC_m^{-0.3535} & if\ BT_m = 1\ \text{(aerobic)} \\ 3800 \cdot PTC_m^{-0.3425} & if\ BT_m = 2\ \text{(anaerobic)} \end{Bmatrix}$$

Table 7-4 MBT treatment costs, €/Mg

Source	Min	Max	Aver	Comments
(Archer 2005)	45	100	-	Treatment costs including operational and amortised capital costs and debt servicing, but excluding profit margin and revenues.
(Heyer 2000)	36	90	-	General treatment cost as a function of the plant treatment capacity (PCT): €/Mg = 1521.7 $PCT^{-0.306}$ Range 10,000 – 200,000 Mg/a
(LCA-IWM 2005)	43	123	-	General treatment cost for a MBT unit with an aerobic digestion units as a function of the plant treatment capacity (PCT): €/Mg = 3173.3 $PCT^{-0.3535}$ Range 10,000 – 200,000 Mg/a
(LCA-IWM 2005)	58	163	-	General treatment cost for a MBT unit with an anaerobic digestion units as a function of the plant treatment capacity (PCT): €/Mg = 3800 $PCT^{-0.3425}$ Range 10,000 - 200,000 Mg/a
(Smith 2001)	60	87	75	Fee gate including landfill and/or incineration fees
(DSD 2003)			50	Modern MBT facility with a capacity of 100,000 Mg/a
(Pitschke 2004)	32	87	58	General treatment cost based on Bilitewski & Heilmann 1998.

7.2.7 Benefits

7.2.7.1 Recovered Energy

Mechanical-biological treatment units configured with an anaerobic biological treatment section are suitable to recover energy from the combustion of the recovered biogas in biogas-fired units. Mathematically this is calculated with Equation 7-26. This equation is restricted to the operation temperature of the digester, the biogas collection efficiency and the conversion efficiency of the biogas-fired unit. In this equation, it is assumed that the biogas collection system operates with an efficiency of 95%. The power conversion efficiency is fixed to the biogas gas-fired unit type. Gas turbines have overall power recovery efficiencies between 22 and 36 %, with an average value of 29%. Similarly, internal combustion engines have overall power recovery efficiencies between 22 and 40%, with an average value of 31% (GE 2000a, EPA 2002c). In this model is not considered the recovery of heat. Finally, the economical revenue from the sale of the recovered energy is integrated in Equation 3-21.

Equation 7-26 Total recovered energy in MBT units

for $k = 5$:

$$RE_k = \begin{Bmatrix} 0 & \text{if } BT_m = 1 \\ \sum_m m_{m,1,CH_4} \cdot \nu_{CH_4} \cdot HHV_{CH_4} \cdot \eta_{BGCS} \cdot \eta_{CHP} \cdot CF_{kJ-kWh} & \text{if } BT_m = 2 \end{Bmatrix}$$

where:

RE_k	Recovered energy in the waste management operation *k(x)*, [kWh]
$m_{m,CH4}$	Methane mass flow in the biogas, kg/year
v_{CH4}	Methane specific volume: 1.5796 m^3/ kg (Mesophilic) ; 1.7335 m^3/ kg (Thermophilic)
η_{BGCS}	Biogas collection system efficiency
η_{CHP}	Combined heat and power conversion efficiency
HHV_{CH4}	Higher heating value of methane: 33,810 kJ/m^3
$CF_{kJ\text{-}kWh}$	Conversion factor kJ to kWh: 1kWh=3.6x10^3 kJ
	Electricity price: 0.1 € per kWh [EC 2003]
P_{kWh}	Bonus a: when is produced from plants (phytomass), manure or a combination of both = 0.06€/kWh
	Bonus c: when electricity is generated within a Combined Heat and Power unit = 0.02 €/kWh

7.2.7.2 Recovered Material

The type of recovered material in MBT units depends on the choice of technology installed. They are designed to produce solid fuel, compost-like product, stabilised biodegradable waste and/or biogas. Aluminium and tinplate are as well recovered in these units.

Solid fuel could be used as refuse-derived fuel in co-incineration plants only if it fulfils the selected quality criteria for it use. In Europe, the quality criteria for RDF material are not regulated by European law. They are normally imposed by the cement industry and power stations. In future time, this will be standardised through the CEN/TC 343 standard. Currently, the BREF Waste Treatment provides quality parameters based on the implementation of best available techniques. Similarly, there are voluntary quality criteria systems for RDF such as the RAL-GZ 724, SFS 5875 and the EURITS criteria. On the other hand, RDF and SRF solid fuels have low or negative revenue. RDF is accepted by co-incineration plants by paying a fee gate between 0 and 40 €/Mg. SRF may have a fee gate between -30€/Mg and 35€/Mg (LCA IWM 2005).

It is not expected that generated compost-like product could be commercialised under current market conditions. The market rejects this material because it does not fulfil existing compost quality criteria due to their high level of visual and chemical contamination. However, this material is accounted as a benefit only if it fulfils existing voluntary quality assurance systems for compost such as the RAL-GZ 251.

7.2.7.3 Displaced resources and emissions

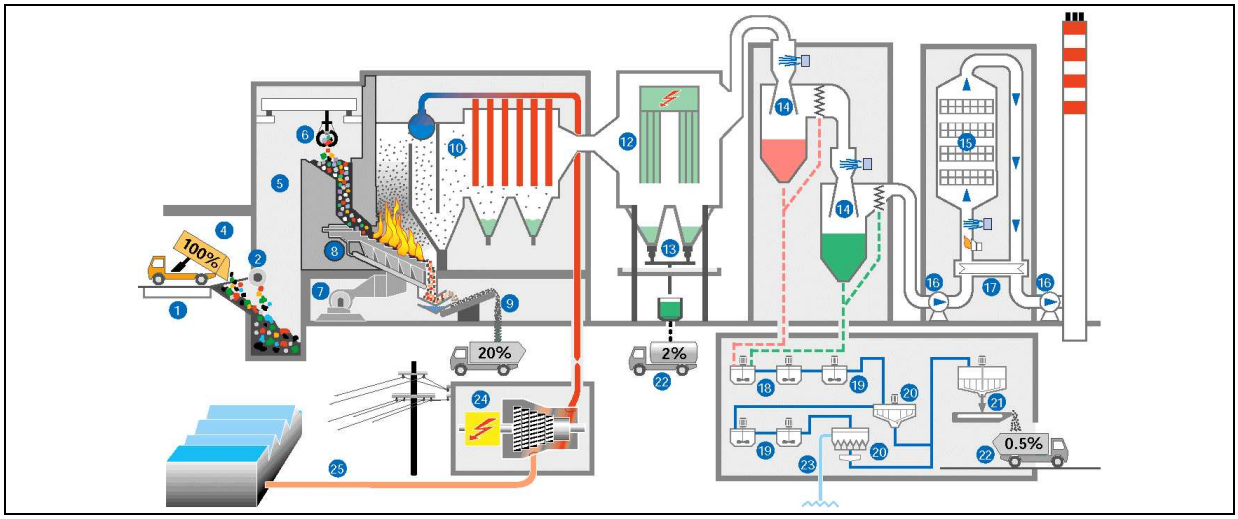
Displaced resources and emissions derive from the potential recovery of energy from RDF/SRF and biogas. Both RDF/SRF and biogas are used in energy recovery processes. Therefore, displaced resources and emission derived from the use of these materials are related to the amount of energy they can substitute. The potential amount of energy that can be substituted from them is a function of their calorific value. In the one hand, the calorific value of the RDF/SRF is calculated as a function of its macro-chemical composition with the ultimate analysis equation derived by Dulong (Kathiravale 2003). On the other hand, the biogas calorific value is calculated as a function of its methane concentration. In both cases, recovered energy will be proportional to the amount of displaced fugitive emissions associated to the country-specific power plant technology and the fuel source that is used to generate the same amount of energy.

8 THERMAL TREATMENT: THT

8.1 PROCESS DESCRIPTION

Incineration is defined by the EU Waste Statistics Regulation[51] as the thermal treatment of waste in an incineration plant as defined in Article 3(4) or in a co-incineration plant as defined in Article 3(5) of Directive 2000/76/EC on the incineration of waste. This directive will be further referred as WID. The main difference between these incineration units is that an incineration plant is dedicated to the thermal treatment of waste with or without heat generated by combustion, while a co-incineration plant has the main purpose to generate energy or the production of material products using waste as a regular or additional fuel. In both plant types, the incineration process is achieved by the thermal oxidation of combustible materials contained in waste in an excess of air.

A typical municipal solid waste incineration (MSWI) is shown in Figure 8-1. In these waste management operations, accepted waste is stored in the bunker. Subsequently, the waste is transferred to the furnace chamber by means of a crane. In the furnace chamber, the waste is thermally treated at temperature above 1000°C, while in the post-combustion chamber exhaust gases are required to have a minimum temperature of 850°C. The combustion products are the bottom ashes and the raw flue gas. Bottom ashes are cooled down and transported to the slag bunker, while the raw gas flows to the heat recovery steam generator (HRSG) or boiler. The raw flue gas enters the HRSG with a temperature between 850°C and 1100°C, and leaves it around 200°C. The HRSG recovers heat in the form of steam, which subsequently is expanded in a steam turbine in order to generate electricity. The generated raw flue gas enters to the flue gas treatment system, where the concentration of pollutants is reduced below to the permitted maximum emission limits. Typical flue gas treatment units consist of particular matter, acid gases and trace gases removal units. These flue gas treatment units produce secondary waste such as fly ash, scrubber sludge and wastewater, which require further treatment or disposal. Finally, the cleaned flue gas is released into the atmosphere through a stack as an exhaust gas.



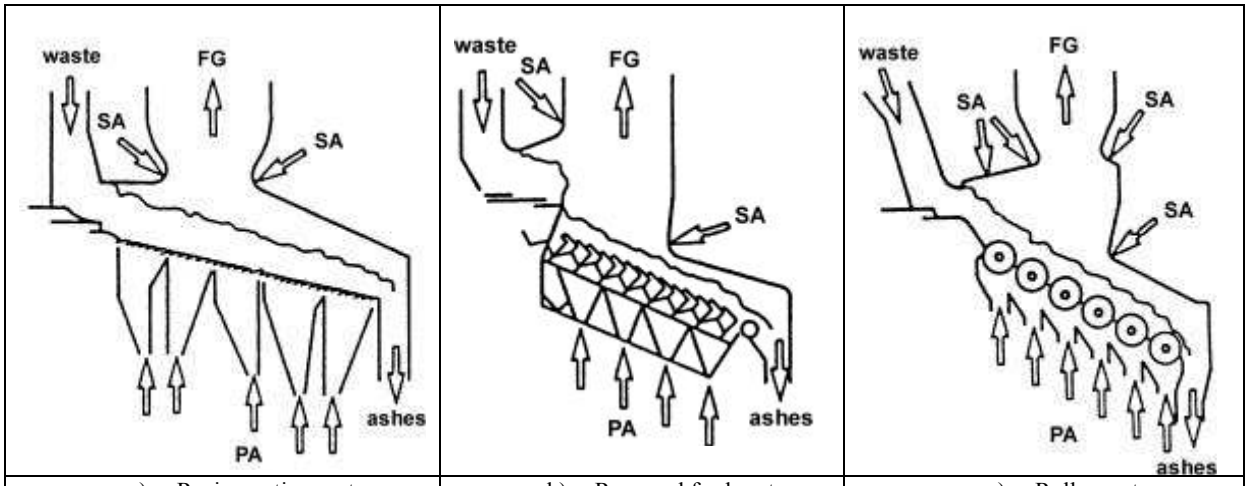
Source (Doka 2003)

Figure 8-1 Typical scheme of a incineration plant (Buchs AG, Switzerland)

[51] Regulation (EC) No. 2150/2002 of the European Parliament and of the Council of 25 November 2002 on Waste Statistics Art 2(i).

Incineration plants are classified by the manner in which waste is moved through the furnace chamber. Furnace chamber are classified in grate firing system, rotary kiln and the fluidised bed system. From those is the grate firing system the most common technology on use in Europe for the treatment of municipal solid waste. Therefore, this model is focus exclusively in this furnace technology.

In general, grate firing systems can handle large volumes of waste, they can achieve high operating temperatures and they are very flexible on waste composition. Grate firing systems support the waste over the grates, which are inclined at an angle so that the waste can tumble under the action of gravity and through the movement of the grates. According to the type of grate installed, they are classified in roller grates, reciprocating grates reversed feed grates and counter reciprocating grates as shown in Figure 8-2. Independently of the grate classification, in this furnace technology it is possible to detect four main zones, which are function of the grate temperature. These zones are drying (100-200°C), degassing (200-500°C), gasification (500-1200°C) and combustion (1000-100°C). In every zone are carried particular and interrelated reactions that are required to achieve combustion. Additionally, the solid waste flows through the grates with a maximum residence time of 60 minutes (IPPC 2005c). This ensures complete thermal destruction of the input waste.

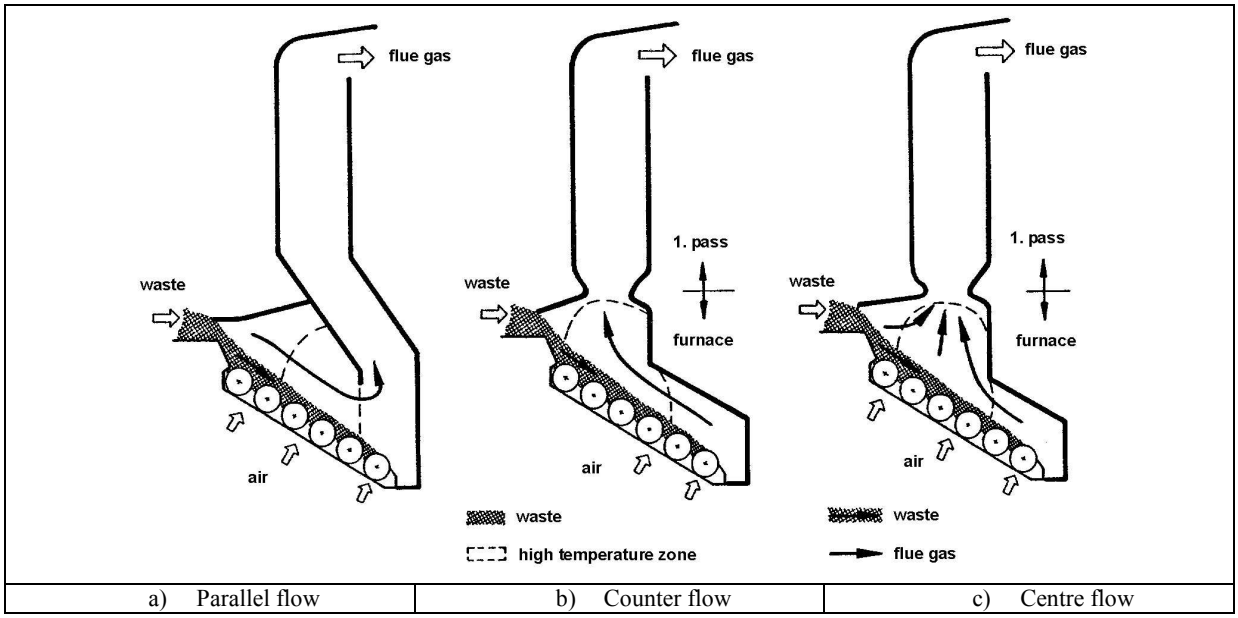


a) Reciprocating grate | b) Reversed feed grate | c) Roller grate

Where: PA – primary air, SA – secondary air, FG – flue gas

Figure 8-2 Grate technologies for municipal waste incineration plants (Görner 2002)

Every grate system has a particular furnace geometry and a primary/secondary combustion air system. In one hand, the furnace geometry is defined by the direction of the flue gas flow in comparison with the movement of the waste on the grate. There are three basic furnace geometries, which are parallel flow, counter flow and centre flow. These typical furnace geometries are shown in Figure 8-3. On the other hand, incineration plants supply combustion air in the form of primary and secondary air to achieve complete combustion. Typical air ratios (λ) are between 1.2 and 2.5 times the stoichiometric air value (IPPC 2005c, Niessen 2002). In new incineration plants, the relation between primary a secondary air is 40/60, while in old plants is 80/20. Primary air provides the required oxygen to support the reactions that take place in the different zones of the grate (drying, gasification, and volatilisation). As well it is used to cool the grates and consequently to prevent slag and corrosion. Secondary air is used to ensure post combustion of organic material and as a mixing device for the flue gas.



a) Parallel flow	b) Counter flow	c) Centre flow

Figure 8-3 Furnace geometries for municipal waste incineration plants (Görner 2002)

Modelled waste incineration units are subject to the provisions imposed by the WID and to the requirements of the IPPC Directive. This legal framework provides minimum requirements for permissible emissions, monitoring and certain operational conditions. As well, it demands that from the 28 December 2005 existing and new waste incineration plants are obligated to adopt the provisions of the WID. This directive provides limit values for incineration plant emissions to the atmosphere in Annex V to the WID. Considered emissions are *inter alia* total dust, total organic carbon, hydrogen chloride, sulphur dioxide, nitrogen monoxide, nitrogen dioxide, carbon monoxide and heavy metals. Similarly, Annex IV provides emission limit values for discharges of wastewater from the cleaning of exhaust gas mainly heavy metals, total suspended solids, dioxins and furans.

8.2 THT SUB-MODEL

The thermal treatment sub-model (THT) assesses the life cycle of the treatment of municipal solid waste in a grate firing incineration plant. As shown in Figure 8-4, the sub-model starts when the municipal solid waste fractions and the secondary waste generated in other waste management operations enter to the thermal treatment facility. The product system ends not only when the input waste is emitted as a fugitive emission to air, water and land but also when it is transformed into a valuable product such as recovered energy and materials.

Material flows are calculated based on waste-specific and process-specific models. Waste-specific models depend on the composition of the input waste and on the choice of technology installed on site. On the other hand, process-specific models depend exclusively on the choice of technology and they are constant for every waste composition.

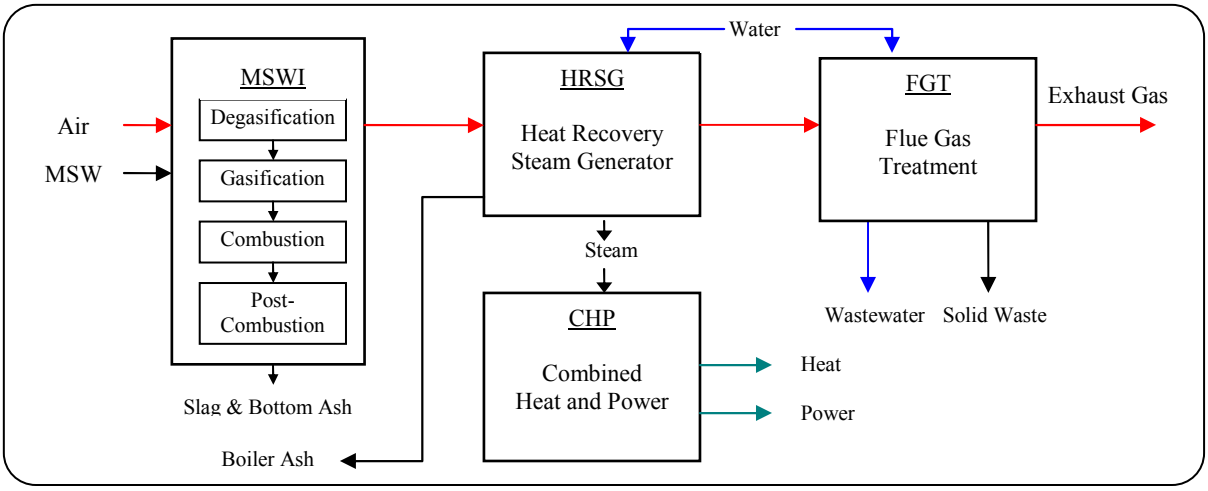


Figure 8-4 System boundaries of the thermal treatment sub-model

8.2.1 THT Internal Process

8.2.1.1 Material Input

According to the multi-commodity flow distribution approach, the waste category *w* generated at the source point *j* and at the waste management facility *x* will compete for the scarce and finite capacity of the MSWI *t*. The material flow distribution for every incinerator is calculated with Equation 8-1. The input variables of this equation are previously calculated as shown in subchapter 3.4.1 related to logistic constraints.

Equation 8-1 THT waste category *w* input acceptance

$$mtw_{t,w} = \left[\sum_{j} mjtw_{j,t,w} + \sum_{s} \left(mfst_{s,t,w} + most_{s,t,w} \right) + \sum_{c} \left(mfct_{c,t,w} + mhct_{c,t,w} \right) + \sum_{a} \left(moat_{a,t,w} \right) + \sum_{d} \left(m\,odt_{d,t,w} \right) + \sum_{m} mhmt_{m,t,w} \right]$$

subject to :

$$m_t = \sum_{w} mtw_{t,w}$$

$$PTC_t > m_t$$

where:

$mtw_{t,w}$	Total waste category *w* entering to the incinerator *t*; [Gg]
$mjtw_{j,t,w}$	Total waste category *w* entering to the incinerator *t* coming from the generation point *j*; [Gg]
$mzxt_{x,t,w}$	Total waste category *w* entering to the incinerator *t* coming from the waste management facility *x* and fraction type *z*; [Gg]
m_t	Total amount of waste received in the incinerator *t*; [Gg]
PTC_t	Plant treatment capacity for the incinerator *t*; [Gg]

8.2.2 Fugitive Emissions to Air, FEA_t

Fugitive emissions to air generated in an incineration plant consist mainly of the following compounds:

- Particular matter (e.g. $PM_{2.5}$, PM_{10})
- Acid gases (e.g. HCl, SO_2, NOx, NH_3)
- Heavy metals (e.g. Cd, Tl, Hg, Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V),
- Carbon compounds (e.g. CO_2, CO, NMVOCs, PCDD/F, PAH)

These compounds are generated during the oxidation process in the combustion chamber, minimised in the flue-gas treatment section and finally emitted to the atmosphere as exhaust gas. These process steps are assessed as follows.

8.2.2.1 Raw flue gas generation

The thermal treatment of municipal solid waste in incinerations plants generates raw flue gas. The raw flue gas composition is mainly influenced by the composition of the input waste and the design and operational conditions at the furnace chamber. Under optimal operational conditions, the raw flue gas is a mixture of species such as CO_2, HCl, SO_2, NOx, N_2 and O_2. Additionally, the raw flue gas is composed of trace gases compounds such as CO, VOCs, N_2O, NH_3, PCDD/F, particular matter and heavy metals.

The concentration of carbon dioxide, acid gases and particular matter depend mainly on the composition of the input waste. Under optimal combustion conditions, most of the carbon content in the burnable input waste is oxidised to carbon dioxide. A minor fraction is converted to carbon monoxide. Under chemical equilibrium conditions at a temperature of 1000°C, the conversion ratio of carbon-to-carbon monoxide (x_{CO}) is equal to 8.8651E-04%. The remainder 99.9991% corresponds to carbon dioxide.

Nitrogen oxides are originated from the conversion of the nitrogen contained in the waste (fuel NOx), from the direct oxidation of elemental nitrogen in the combustion air (thermal NOx) and from the indirect oxidation of nitrogen present in the combustion air with free hydrocarbons radicals (prompt NOx). From these three sources, fuel NOx is the main generation source in MSWI. Both thermal NOx and prompt NOx play a marginal role n the incineration process. In one hand, thermal NOx is only representative at temperatures above 1200°C and the generation of prompt NOx is so minimal that is neglected in this model. It has been observed that about 10 to 20% of the nitrogen contained in the waste is transformed to fuel NOx (IPPC 2005c). The remainder fuel nitrogen is emitted as nitrogen gas. Therefore, it is assumed that the fuel NOx conversion ration (x_F) is equal to the maximum expected value of 20%. The proportion of NO/NO_2 in the exhaust gas is usually 95% NO and 5% NO_2. However, both nitrogen monoxide and nitrogen dioxide are expressed as nitrogen dioxide according to WID.

The concentration of heavy metals in the raw flue gas is mainly related to the heavy metal degree of volatilisation. Metal volatilisation is a complex function and it depends on the initial speciation and concentration of the heavy metals, the treatment temperature and duration, the airflow rate, the heavy metal vapour pressure and the presence of other species such as chorine, sulphur and combustible substances (Abanades 2001, Morf 2000). Heavy metals with high vapour pressure volatilise easier. Additionally, the presence of chlorine enhances metal vaporisation because metal chlorides have a higher vapour pressure than their corresponding oxides. However, the presence of sulphur enhances the formation of condensed phases, which are trapped in the ash or captured in the flue gas treatment units (Mkilaha 2002, Watanabe 2000, Spiegel 1997). Under typical conditions, heavy metals such as Pb, Cr, Co, Cu, Mn, Ni and V with low vapour pressure have low degree of volatilisation and they remain trapped in the bottom ash. On the other hand, heavy metals such as Cd and Hg undergo volatilisation and remain in the raw flue gas at the post-combustion chamber (IPPC 2005, Belevi 2005, Doka 2003, Hellweg 2001 and Angened 1990).

Under abnormal operational conditions, the concentration of species such as CO, C_xH_y, NO and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) is considerably increased. PCDD/F generation is enhanced in the presence of chlorine and metals. Its generation follows two mechanisms named de novo synthesis and synthesis from precursors. They are formed in both the gas phase at temperatures above 600°C and on the surface of dust and ashes in the temperature range between 225 and 400°C (Yasuhara 2003, Stanmore 2002). Thus, the emission of PCDD/F is related to the emission of particular matter.

Abnormal conditions are influenced by a deficit of the oxygen concentration, residence time, temperature and mixing conditions. The last three parameters are known as the 3T-rule: time-temperature-turbulence. Therefore, the WID demands a minimum operational temperature of 850°C and at least two seconds residence time of the combustion gases at the furnace chamber. Additionally, if the input waste contains hazardous waste with a content of more than 1% halogenated organic substances, the temperature has to be raised to 1100°C for at least 2 seconds.

In this model, the composition of the raw flue gas is calculated using both waste-specific and process-specific emission equations. Main raw gas species such as CO_2, SO_2, HCl, NO_2, particular matter and heavy metals are calculated with waste-specific emission equations; while selected trace gases are calculated with process-specific emission equations.
The implementation of the waste-specific emission equations requires some assumptions for consideration. These assumptions are:

- the combustion follows the ideal combustion reaction (Reaction 8-1),
- only burnable waste fractions can be oxidised,
- only volatilised material is thermally oxidised,
- all raw flue gas species behave as an ideal gas,
- the conversion ratio of carbon to carbon dioxide is 1-x_{CO}
- only nitrogen in the waste is oxidised to nitrogen dioxide at a conversion ratio of x_F
- all volatilised sulphur is converted to sulphur dioxide
- the moisture content in the combustion air is negligible
- air is 79% nitrogen and 21% oxygen

Reaction 8-1 Ideal reaction of combustion

$$C_c H_h O_o N_n S_s Cl_l + \alpha\left(O_2 + 3.7619 N_2\right) + wH_2O \rightarrow \qquad cCO_2 + w'H_2O + n'N_2 + o'O_2 + n''NO_2 + sSO_2 + lHCl$$

On the other hand, the process-specific emission equations make use of process-specific coefficients. These process-specific coefficients are given in Table 8-1. They represent the use of the best available technology (BAT) from some European MSWI plants as demanded by the IPPC Directive. Figures for other species than the ones listed in this table have not been identified by this study. The implementation of the waste-specific emission equations are based on the following sequence. Firstly, it is calculated the chemical composition of the input waste in a molar basis as shown in Equation 8-2. This equation makes a distinction between burnable and non-burnable fractions because only burnable ones are subject to combustion. This property is represented by the integer variable BF_w. Waste fractions that are subject to combustion have a BF_w equal to one, otherwise to zero. As well, this equation considers the fraction of the chemical compound *cc* that is transferred to the gaseous phase (volatilisation) and subsequently oxidised.

Equation 8-2 Raw flue gases subject to oxidation, molar basis

$$ntc_{t,cc} = \sum_{w} \frac{mtw_{t,w} \cdot MCC_{w,cc} \cdot BF_w \cdot VF_{cc}}{MW_{cc}}$$

where:

$mtc_{t,cc}$	Total mass flow of waste category *w* entering to the incinerator *t*; [Gg]
$ntc_{t,cc}$	Total molar flow of waste category *w* entering to the incinerator *t*; [Gmol]
BF_w	Burnable waste category *w*. If w is burnable then BF_w is equal to one otherwise to zero. Integer variable [1,0]
VF_{cc}	Volatilisation factor of the chemical compound *cc*

Table 8-1 Fugitive emission inventory for incineration plants

		UBA-2000	Gemis	IWM-2	IPPC 2005	IPPC 2000	Asdonkshof 2005	LUA-NRW 2001	Pitschke 2004	LCIWM	Ecoinvent	min	max	aver
CO2	kg/kg	9.26E-01	7.41E-01		1.20E+00	9.50E-01	2.60E+00				1.22E+00	7.41E-01	2.60E+00	1.27E+00
CH4	kg/kg	1.71E-06	1.71E-06		-	-	-	-			4.76E-05	-	4.76E-05	7.29E-06
N2O	kg/kg	6.57E-07	6.57E-07		9.00E-06	9.00E-06			1.20E-05	6.12E-06		6.57E-07	1.20E-05	6.24E-06
HFC-23	kg/kg										1.24E-15	1.24E-15	1.24E-15	1.24E-15
CF4	kg/kg											-	-	-
SF6	kg/kg										1.21E-09	1.21E-09	1.21E-09	1.21E-09
SO2	kg/kg	1.25E-05	1.25E-05	1.38E-04	1.52E-04		2.94E-06	2.40E-03	3.72E-05		5.02E-05	2.94E-06	2.40E-03	3.51E-04
NOx	kg/kg	3.80E-04	3.80E-04	1.67E-03	6.90E-04	2.40E-03	5.26E-04	2.10E-03	5.65E-04	6.66E-04	5.20E-04	3.80E-04	2.40E-03	9.90E-04
NH3	kg/kg	3.91E-08	3.91E-08		9.30E-06	2.40E-05			1.50E-06	3.00E-06	1.10E-05	3.91E-08	2.40E-05	6.99E-06
HCl	kg/kg	1.02E-05	1.02E-05	9.00E-05				4.80E-03	1.18E-05		6.29E-07	6.29E-07	4.80E-03	8.20E-04
H2S	kg/kg										8.31E-08	8.31E-08	8.31E-08	8.31E-08
NMVOC	kg/kg	9.27E-06	8.50E-06		3.03E-05	3.00E-05				1.00E-06	8.18E-05	1.00E-06	8.18E-05	2.68E-05
PCDD/F	kg/kg		2.25E-14	2.70E-11					7.20E-14	5.00E-15	1.55E-11	5.00E-15	2.70E-11	8.52E-12
PAH	kg/kg	1.89E-11	1.89E-11								3.07E-09	1.89E-11	3.07E-09	1.04E-09
CO	kg/kg	2.41E-04	2.41E-04	1.98E-04	6.00E-05	6.00E-05		1.20E-04	6.00E-05	1.00E-05	2.85E-04	1.00E-05	2.85E-04	1.42E-04
PM2.5	kg/kg										2.27E-05	2.27E-05	2.27E-05	2.27E-05
PM	kg/kg	3.27E-06	3.27E-06	2.40E-11	4.52E-05		3.66E-06	1.20E-02	6.60E-06	6.90E-06	7.24E-05	2.40E-11	1.20E-02	1.35E-03
PM10	kg/kg										8.58E-05	8.58E-05	8.58E-05	8.58E-05
Cd	mg/kg	8.67E-03	8.67E-03		9.90E-03			6.00E-03			1.50E-03	1.50E-03	9.90E-03	6.95E-03
Tl	mg/kg							6.00E-04			7.77E-05	7.77E-05	6.00E-04	3.39E-04
Hg	mg/kg	4.00E-03	4.00E-03		1.52E-01		1.20E-03	2.40E-03	3.60E-02		5.31E-03	1.20E-03	1.52E-01	2.92E-02
Sb	mg/kg										1.80E-04	1.80E-04	1.80E-04	1.80E-04
As	mg/kg	1.89E-03	1.89E-03		3.30E-03			6.00E-04			1.58E-03	6.00E-04	3.30E-03	1.85E-03
Pb	mg/kg	1.57E-01	1.57E-01		1.38E-01			1.20E-02			2.74E-02	1.20E-02	1.57E-01	9.83E-02
Cr	mg/kg	1.65E-04	1.65E-04		7.20E-03						3.32E-02	1.65E-04	3.32E-02	1.02E-02
Co	mg/kg				1.20E-02						1.61E-03	1.61E-03	1.20E-02	6.80E-03
Cu	mg/kg	3.24E-02	3.24E-02								1.45E-02	1.45E-02	3.24E-02	2.64E-02
Mn	mg/kg										2.08E-03	2.08E-03	2.08E-03	2.08E-03
Ni	mg/kg	4.61E-09	4.61E-09		6.90E-03						1.41E-02	4.61E-09	1.41E-02	5.25E-03
V	mg/kg										3.76E-02	3.76E-02	3.76E-02	3.76E-02

Additionally, the stoichiometric amount of oxygen required to sustain the combustion reaction is calculated with Equation 8-3. This equation is a function of the molar composition of the burnable input waste. The stoichiometric coefficients are taken from Reaction 8-1.

Equation 8-3 Stoichiometric oxygen, molar basis

$$\alpha_{t,EST} = c + 0.25h + n'' + s - 0.25l - 0.5o \rightarrow ntc_{t,C} + 0.25ntc_{t,H} + x_F \cdot ntc_{t,N} + ntc_{t,S} - 0.25ntc_{t,Cl} - 0.5ntc_{t,O}$$

Subsequently, the stoichiometric amount of oxygen is adjusted with the excess air ratio (λ), which is site specific and can range from 1.2 to 2.5. For further calculations, it is assumed an excess ratio of 1.5. The required amount of oxygen is calculated with Equation 8-4.

Equation 8-4 Total oxygen input, molar basis

$$\alpha_t = \alpha_{t,EST} \cdot \lambda_t$$

The composition of the main raw flue gas species is calculated with Equation 8-5. This equation is a function of both the molar composition of the input burnable waste and the total input air.

Equation 8-5 Molar flow of the raw flue gas generated in the MSWI

CO_2 $\quad FG_{t,CO_2} = c = ntc_{t,C}$

H_2O $\quad FG_{t,H_2O} = w + 0.5h - 0.5l = ntc_{t,H_20} + 0.5ntc_{t,H} - 0.5ntc_{t,Cl}$

NOx $\quad FG_{t,NO_2} = n'' = x_F \cdot n = x_F \cdot ntc_{t,N}$

SO_2 $\quad FG_{t,SO_2} = s = ntc_{t,S}$

HCl $\quad FG_{t,HCl} = l = ntc_{t,Cl}$

O_2 $\quad FG_{t,O_2} = o' = 0.5o + \alpha - c - 0.25h - n'' + 0.25l - s$
$= 0.5ntc_{t,O} + \alpha_t - ntc_{t,C} - 0.25ntc_{t,H} - x_F \cdot ntc_{t,N} + 0.25ntc_{t,Cl} - ntc_{t,S}$

N_2 $\quad FG_{t,N_2} = n' = 3.7619\alpha_t + 0.5 \cdot (1 - x_F) \cdot n = 3.7619\alpha_t + 0.5 \cdot (1 - x_F) \cdot ntc_{t,N}$

Finally, the dry volume of the raw flue gas is calculated with Equation 8-6. This equation assumes that the raw flue gas behaves as an ideal gas, an operation pressure of one atm and a flue gas temperature of 1000°C.

Equation 8-6 Volume of flue gas produced

$$V_{t,FG} = \frac{n_{t,FG} \cdot R \cdot T}{P}$$

where:

$$n_{t,FG} = c + o' + n' + n'' + s + l$$

and:

$$o' = 0.5o + \alpha - c - 0.25h - n'' + 0.25l - s$$

$$n' = 3.7619\alpha + 0.5n \cdot (1 - x_F)$$

$$n'' = n \cdot x_F$$

$\therefore$

$$n_{t,FG} = 0.5o + 4.7619\alpha - 0.25h + 0.5n(1 - x_F) + 1.25l$$

where:

$V_{t,FG}$	Dry flue gases produced at STPN, [m^3]
$n_{t,FG}$	Dry flue gases produced at STPN, [Gmol]
R	Gas Law Constant, 0.0820575 atm m^3 $Gmol^{-1}$ K^{-1}
T	Combustion temperature, [K]
P	Operation pressure, [atm]
x_F	Fuel NOx conversion rate, [-]

Equation 8-7 Volume and emission concentration at the standard percentage oxygen concentration

$$E_S = \frac{21 - O_S}{21 - O_M} \cdot E_M$$

where:

E_S	Standard emission concentration at the standard percentage oxygen concentration
E_M	Calculated emission concentration
O_S	Standard oxygen concentration
O_M	Calculated oxygen concentration

8.2.2.2 Flue gas treatment

The WID Art 7(1) requires that all incinerators to be designed and operated, as a minimum, to meet the emission limit values (ELVs) set out in Annex V of the Directive. Table 3-5 summarise the ELVs that must be achieved by every incineration plant. The substances partition depends mainly on the chemical properties of the input waste and on the design and operation of the incineration plant. The chemical composition of the flue gas is calculated with Equation 8-8, which uses the process-specific parameters reported in Table 8-2 and Table 8-3.

Equation 8-8 Chemical composition of the treated flue gas as a function of existing FGT

$$TFG_{t,cc} = \sum_{w} \left[mtw_{t,w} \cdot MCC_{w,cc} \cdot BF_w \cdot VF_{cc} \cdot BoF_{cc} \cdot \prod_{FGT} \left(1 - MFGT_{cc,FGT} \cdot IFGT_{t,FGT}\right) \right]$$

where:

$TFGt,cc$	Treated flue gas at thermal treatment unit *t* with chemical composition *cc*, [Gg]
$MCC_{w,cc}$	Matrix (waste category fraction *w* vs. chemical compound *cc*); [-]
BF_w	Burnable waste category *w*. If w is burnable then BF_w is equal to one otherwise to zero. Integer variable [1,0]
VF_{cc}	Volatilisation fraction of the chemical compound *cc*
BoF_{cc}	Chemical compound *cc* flow distribution through the boiler
$MFGT_{cc,FGT}$	Flue gas treatment removal efficiency Matrix (chemical composition *cc* vs. flue gas treatment type *FGT*)
$IFGT_{t,FGT}$	Presence of flue gas treatment integer variable. If the waste category *w* is burnable then BF_w is equal to one otherwise zero.

Table 8-2 Average volatilisation factor in furnace and boiler of a incineration plant

	VF_{cc}	BoF_{cc}
Cc	Furnace	Boiler
C	0.9850	1.0000
H	1.0000	1.0000
O	1.0000	0.9978
N	1.0000	1.0000
S	0.5300	1.0000
Cl	0.8900	1.0000
Inert	0.0500	0.5000
H_2O	1.0000	1.0000
Cd	0.9100	1.0000
Tl	0.1460	1.0000
Hg	0.9500	0.9979
Sb	0.7500	0.9815
As	0.3100	0.9333
Pb	0.2800	1.0000
Cr	0.0800	0.9415
Co	0.1000	0.9333
Cu	0.0600	1.0000
Mn	0.0600	0.9286
Ni	0.0200	0.6410
V	0.1100	0.9092

Adapted from:
(IPPC 2005c), (Belevi 2005), (EPA 2002d), (Achternbosch 2002), AP-42:2.1, (Hellweg 2002)

Table 8-3 Removal efficiency of flue gas treatment units

	Particular Matter							Acid Gases		NOx	
Cc	FF	CFB	ESP	DSI/ ESP	SD/ ESP	DSI/FF	SD/FF	ClS	SS	SCR	SNCR
C			0.0010								
H			0.0000								
O			0.0108								
N			0.0000							0.7000	0.5500
S	0.4420	0.4420	0.3635	0.7249	0.8110	0.5867	0.8399	0.1000	0.9850	0.0000	0.0000
Cl	0.1220	0.1220	0.1553	0.9566	0.6275	0.9042	0.9604	0.8820	0.9780	0.0000	0.0000
Inert	0.9995	0.9995	0.9950								
H_2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
Cd	0.9900	0.9900	0.9720	0.9919	0.9993	0.9979	0.9975	0.7080	0.9070		
Tl											
Hg	0.9000	0.9000	0.0320	0.2929	0.4179	0.6071	0.6071	0.8350	0.3290		
Sb			0.8489	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
As			0.9949	0.0000	0.9968	0.9976	0.9901	0.0000	0.0000		
Pb	0.9770	0.9770	0.9770	0.9864	0.9957	0.9986	0.9992	0.8730	0.4770		
Cr			0.9874	0.9965	0.9710	0.9777	0.9967				
Co			0.8571								
Cu			0.8311								
Mn			0.9231								
Ni			0.9858	0.5903	0.9656	0.9818	0.9934				
V			0.9000								

FF: fabric filter, ESP: electrostatic precipitator, ClS: HCl wet scrubber, SS: SO_2 wet scrubber, SD: spray dryer, DSI: duct sorbent injection, SCR: selective catalytic reduction, SNCR: selective noncatalytic reduction, CFB: catalytic filter bag.
Source: Adapted from (IPPC 2005c), (Belevi 2005), (EPA 2002d), (Achternbosch 2002), AP-42:2.1, (Hellweg 2002)

8.2.2.3 Exhaust gas emissions

Finally, the amount and composition of the exhaust gas is calculated with both waste-specific and process-specific models. These models are defined by Equation 8-9. In the one hand, the emissions of CO_2, SO_2, NO_2, HCl, CO, PM and heavy metals are calculated based on the oxidation of the input material. On the other hand, the emissions of N_2O, NH_3, NMVOCs, PCDD/F and CO are calculated based on the flue gas volume. The average concentration of this compounds are derived from background and foreground sources such as IPPC (IPPC 2005), Ecoinvent (Doka 2004), AP-42, NPi and from installed MSWI in Germany. These values are shown in Table 8-1.

Equation 8-9 Fugitive emissions to air from a MSWI

FEA		**Waste-specific emission modelling**	**Process-specific emission modelling, kg/kg***
Carbon dioxide	CO_2	$FEA_{t,CO_2} = TFG_{t,C} \cdot (1 - x_{CO}) \cdot \frac{MW_{CO_2}}{MW_C}$	-
Methane	CH_4	-	1.71E-06
Nitrous oxide	N_2O	-	8.25E-06
Sulphur hexafluoride	SF_6	-	-
Sulphur dioxide	SO_2	$FEA_{t,SO_2} = TFG_{t,S} \cdot \frac{MW_{SO_2}}{MW_S}$	-
Nitrogen dioxide	NO_2	$FEA_{t,NO_2} = TFG_{t,N} \cdot x_{NOx} \cdot \frac{MW_{NO_2}}{MW_N}$	-
Ammonia	NH_3	-	9.3E-06
Hydrogen chloride	HCl	$FEA_{t,HCl} = TFG_{t,Cl} \cdot \frac{MW_{HCl}}{MW_{Cl}}$	-
Hydrogen sulphide	H_2S	-	8.31E-08
NMVOC or TOC	NMVOC	-	2.68E-05
Dioxins & Furans	PCDD/F	-	8.52E-12
PAH	PAH	-	1.89E-11

Carbon monoxide	CO	$FEA_{t,CO_2} = TFG_{t,C} \cdot x_{CO} \cdot \frac{MW_{CO_2}}{MW_C}$	5.5E-05
Particulates, < 2.5 μm	PM2.5	$FEA_{t,PM} = TFG_{t,Inert}\ 0.95$	-
Particulates,	PM	$FEA_{t,PM} = TFG_{t,Inert}\ 0.05$	-
Particulates, >10 μm	PM10	-	-
Heavy Metals: Cd, Tl, Hg, Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V	HM	$FEA_{t,HM} = TFG_{t,HM}$	-

*Process-specific emission coefficients adapted from Gemis, Wisard, IWM2, (IPPC 2005), (LCIWM 2005), (Pitschke 2004), (Doka 2004), (UBA 2000) and (LUA-NRW 2000).

8.2.3 Fugitive Emissions to Water, FEW_t

Incineration plants generate wastewater from the cleaning of the raw flue gas in the flue-gas treatment units. Other sources of wastewater include as well boiler water, cooling water and discharges of the waste water treatment plant. Generated wastewater discharges are limited in accordance with the emission limit values set in Annex IV of the WID. The amount of wastewater generated in an incineration plants depends on its choice of technology and the amount of waste treated. Dry flue gas treatment technologies generate the least water and wet technologies the most. Typical values for a wet technology are between 150 and 250 kg/Mg of waste treated (IPPC 2005c), as shown in Table 8-4.

Table 8-4 Typical concentration of pollutants in water from wet flue gas treatment facilities

FEW		(IPPC 2005c)	(Doka 2003)	(UBA 2000)
		mg/l	kg/kg	
Waste water volume	m^3/Mg	0.15-0.25		0.98
Biological oxygen demand	BOD		6.0320E-03	
Chemical oxygen demand	COD	(140, 390, 260)	1.8295E-02	
Nitrogen Total	N-tot		2.1732E-07	
Phosphorous Total	P-tot		6.3385E-09	
Mercury	Hg	(1030,19025,6167) μg/l		

(Min, Max, Aver)
A WWT of two stages, with milk lime for a MSW incinerator of 250 Gg/yr

8.2.4 Secondary Waste

Secondary waste is generated in different stages of the process and they are named as follows:

- Bottom ash or slag - inert non-burnable fraction of the input waste such as ashes, metals and glass, that is cooled and collected at the end of the grate.
- Boiler ash – settled ash that is removed from the boiler tubes.
- Fly ash – fine ash that is collected and removed by flue gas treatment options such as cyclone, fabric filter or electrostatic precipitator control units.
- FGT residues – solid waste generated due to the physical-chemical treatment of the raw flue gas in the FGT units

Secondary waste generation depends mainly on the composition of the input waste and on the design and operation of both the furnace chamber and the flue gas treatment units. Secondary waste generation rates are calculated with Equation 8-10. This equation is a waste-specific model and it based not only on the composition ($mtw_{t,w}$)and burnability factor of the input waste (BF_w) but also on the volatilisation factor (VF_{cc}) and efficiency removal of the flue gas treatment units ($MFGT_{cc,FGT}$).

Equation 8-10 Secondary waste generation rates

Bottom Ash $$SW_{t,1} = \sum_{w} \sum_{cc \neq HM} \left[mtw_{t,w} \cdot MCC_{w,cc} \cdot BF_w \cdot \left(1 - VF_{cc}\right) \right]$$

Boiler Ash $$SW_{t,2} = \sum_{w} \sum_{cc \neq HM} \left[mtw_{t,w} \cdot MCC_{w,cc} \cdot BF_w \cdot VF_{cc} \cdot \left(1 - BoF_{cc}\right) \right]$$

Fly Ash $$SW_{t,3} = \sum_{w} \sum_{cc \neq HM} \left[mtw_{t,w} \cdot MCC_{w,cc} \cdot BF_w \cdot VF_{cc} \cdot BoF_{cc} \cdot \prod_{FGT=PM} \left(MFGT_{cc,FGT} \cdot IFGT_{t,FGT} \right) \right]$$

FGT waste $$SW_{t,4} = \sum_{w} \sum_{cc \neq HM} \left[mtw_{t,w} \cdot MCC_{w,cc} \cdot BF_w \cdot VF_{cc} \cdot BoF_{cc} \cdot \prod_{FGT} \left(MFGT_{cc,FGT} \cdot IFGT_{t,FGT} \right) \right]$$

where:

$SW_{t,sw}$	Secondary waste type *sw* generated in the incineration plant *t*, [Gg] sw=1: bottom ash; sw=2: boiler ash; sw=3: fly ash; sw=4: FGT waste
$MCC_{w,cc}$	Matrix (waste category fraction *w* vs. chemical compound *cc*); [-]
BF_w	Burnable waste category *w*. If w is burnable then BF_w is equal to one otherwise to zero. Integer variable [1,0]
VF_{cc}	Volatilisation fraction of the chemical compound *cc*
BoF_{cc}	Chemical compound *cc* flow distribution through the boiler
$MFGT_{cc,FGT}$	Flue gas treatment removal efficiency Matrix (chemical composition *cc* vs. flue gas treatment type *FGT*)
$IFGT_{t,FGT}$	Presence of flue gas treatment integer variable. If the waste category *w* is burnable then BF_w is equal to one otherwise zero.

The only acceptable disposal route for secondary waste coming from MSWI is landfill. In some countries, bottom ashes are used as construction material. However, in this model it is assumed that this waste fraction is suitable only for landfill previous recovery of valuable products. Following the multi-commodity flow distribution approach, the secondary waste *sw* generated in the MSWI *t* will compete for a scarce and finite disposal capacity at the landfill *l*. The secondary waste flow distribution is calculated with Equation 8-11. In this equation, it is assumed that the metal content in the bottom ash is segregated on site. As well, it considers that only waste fractions that fulfil the waste acceptance criteria at landfills as defined by the Council decision 2003/33/EC are suitable for landfill. Finally, the decision variable $\delta TL_{t,l,sw}$. determinates the amount of secondary waste that flows from the thermal treatment *t* to the landfill *l*. This variable is fixed with a mass balance restriction in order to keep balanced the system.

Equation 8-11THT secondary waste distribution flow

for $w = \text{inert}$:

$$matl_{t,l,w} = \sum_{t} SW_{t,sw} \cdot \delta TL_{t,l,sw} \cdot LFRT_{t,sw}$$

where :

$$LFRT_{t,sw} = \begin{Bmatrix} 0 & \text{if } SW_{t,sw,C} > LFC_C \cdot SW_{t,sw} \\ 1 & \text{if } SW_{t,sw,C} \leq LFC_C \cdot SW_{t,sw} \end{Bmatrix}$$

for sw, l :

$$1 = \sum_{t} \delta TL_{t,l,sw}$$

8.2.5 Energy consumption

Energy consumption in MSWI depends mainly on the calorific value of the input waste and on the design of the installations. The calorific value of the input waste will determinate the amount of support fuel required to sustain the optimal combustion temperature. The higher the calorific value the lower the energy consumption. Installations such as mechanical preparation systems, preparation, incineration pre-heating and flue-gas treatment units are sources of energy consumption. In most of the cases, this energy demand is satisfy with the energy that is recovered from the incineration of waste. In this model, the energy consumed in incineration plants is calculated with Equation 8-12. Energy consumption is assigned due to the amount of input waste. The data of average energy consumption derive from background sources, as shown in Table 8-5.

Equation 8-12 THT energy consumption

$$EU_{t,ES} = EF_{ES} \cdot \sum_{w} mtw_{t,w}$$

Table 8-5 Energy consumption in MSW Incinerators

Source	(IPPC 2005c)	(Doka 2003)	(Pitschke 2004)	(UBA 2000)
Electricity medium voltage, kWh/Mg	(62, 257, 142)	144		
Heat: Total, MJ/Mg	(75.6, 3366, 1558.8)	839	86	97.44
Diesel, l/Mg				

(Min, Max, Aver)

8.2.6 Costs

8.2.6.1 Treatment Cost

Treatment costs in MSWI are affected by diverse parameters such as:

- Scale
- Plant utilisation rate
- Plant capital costs (cost of land acquisition, planning costs and constriction/plant development costs)
- Plant operation costs
- Choice of incineration technology
- Choice of flue gas treatment technology
- Treatment and disposal of secondary wastes
- Energy and material recovery efficiency
- Taxes and subsidies

The variety of thermal treatment costs is extensive. However, when one accounts for the scale there is a degree of convergence as shown in Table 8-6. From this background information, the capital and operational costs estimated by (Crowe 2002) is the most representative. Therefore, in this model the thermal treatment cost is calculated with Equation 8-13, which is based on the plant treatment capacity of waste management operation. It is assumed that the thermal treatment plant operates at full utilisation rate.

Equation 8-13 THT treatment cost

$$TC_t = \begin{cases} 218.87 & if\ PTC_t \le 50{,}000 \\ 69792 \cdot PTC_t^{\,-0.5328} & if\ 50{,}000 < PTC_t < 500{,}000 \\ 64.18 & if\ PTC_t \ge 500{,}000 \end{cases}$$

Table 8-6 THT treatment costs, €/Mg

Source	Min	Max	Aver	Comments
(Auksutat 1998)	56	245	150	Include the disposal cost of secondary waste and revenues
(Baum 2002)	86	305	170	Include the disposal cost of secondary waste and revenues
(Crowe 2002)	65	230	-	Treatment costs as a function of the plant treatment capacity (PTC_t): €/Mg=69792 $PTC_t^{-0.5328}$; R^2=0.9907 Range: 50,000-500,000 Mg/a
(EUWID 2000)	67	357	212	Include the disposal cost of secondary waste and revenues
(LCA-IWM 2005)	47.87	81.47	-	Treatment costs as a function of the plant treatment capacity (PTC_t): €/Mg=991.04 $PTC_t^{-0.231}$; R^2=1 Range: 50,000-500,000 Mg/a
(Reimann 2001)	89	330	155	
(IPPC 2005c)	20	350	-	Gate fees for European incineration plants

8.2.7 Benefits

Incineration plants can recover energy and material from the input waste fractions. Energy is recovered in the form of power and heat, which can be sold to the grid system. Similarly, recovered material such as bottom ashes can be conditioned and segregated in construction material, while ferrous and non-ferrous scrap materials can be used in the metal industry.

8.2.7.1 Recovered Energy

The WID Art 6(6) establishes that any heat generated by the incineration plant should be recovered as far as practicable e.g. through combined heat and power, the generating of process steam or district heating.

The amount of recovered energy is directly linked with the heating value of the input waste. The heating value from municipal solid waste can be calculated with models based on ultimate analysis, on proximate analysis and on physical composition Ultimate analysis models are based on the macro-chemical composition of MSW, while proximate analysis models are based on the weight percentage of volatile matter and fixed carbon in the MSW. Only physical composition models are based on the percentage of waste fractions such as paper, textiles, plastics, greenwaste, biowaste, food, rubber, leather and other combustibles. Following the scope of this study and structure of available data, in this model the heating value is calculated with the ultimate analysis equation derived by Dulong (Kathiravale 2003). Dulong's model is represented with Equation 8-14.

Equation 8-14 Dulong ultimate analysis model, higher heating value

$$HHV = 4.184 \cdot \left[78.31C + 359.32\left(H - \frac{O}{8}\right) + 22.12S + 11.87O + 5.78N\right]$$

where:

HHV	Higher heating value, [kJ/kg]
C,H,O,N,S	Weight percentage of C,H,O,N, dry basis, [%]

The modified ultimate analysis model of Dulong is then corrected with the specific water content of the input waste. This will provide the lower heating of waste, which is the minimum amount of heat that can be recovered from it. The lower heating value is calculated with Equation 8-15.

Equation 8-15 Lower heating value

$$LHV_t = HHV_t - \lambda v_{H2O} \cdot W$$

where:

LHV	Lower heating value, [kJ/kg]
λv_{H2O}	Specific heat of vaporisation. λv_{H2O} =2441J/g=43938J/mol according to DIN 51900 T2

The potential amount of energy recovery in one MSWI can be then calculated with Equation 8-16.

Equation 8-16 Total energy recovery in THT units

$$for\ k = 6$$

$$REk = \sum_t \sum_w mtw_{t,w} \cdot LHV_t \cdot \eta_{HRSG} \cdot \eta_{ST}$$

In the previous equation the following assumption where taken. Typical heat recovery steam generators (HRSG) or boilers have average heat recovery efficiency (η_{HRSG}) between 75% and 85%, with an average value of 80% (IPPC 2005c). In this model, it is considered the average value of 80% as default coefficient. On the other hand, recovered heat is obtained in the form of high-pressure steam. This steam is then expanded in a steam turbine, where electricity can be recovered. The properties of the steam will determinate efficiency of electricity generation

in the steam turbine (η_{ST}). For example, from high-pressure steam with parameters of 60 bars and 420°C is possible to recover from it about 25% of the energy in the form of power (electricity). Similarly, for a high-pressure steam with parameters of 80 bars and 500°C the electrical efficiency recovery can be increased to 30% (IPPC 2005c, IPCC 2000). For conservative reasons, in this model is considered a power conversion efficiency of 25% in the steam turbine. These assumptions provide potential energy recovery values between 400 and 700 kWh of electricity per tonne of municipal solid waste treated in an incineration plant.

8.2.7.2 Recovered Material

Some secondary waste streams can be use as an important source for material recovery material if treated. Specifically, segregated bottom ashes can be conditioned and from them it is possible recover valuable materials such as construction materials, ferrous and non-ferrous scraps. The potential amounts of ferrous and non-ferrous metals that can be recovered from the bottom ash are calculated with Equation 8-17 . The recovered material depends on the metal recovery efficiency of the mechanical conditioning treatment, which is estimated on 40% (LCA-IWM 2005). This tertiary waste are separated from the bottom ash in order to generate a valuable product and consequently to reduce the disposal cost of bottom ash.

Equation 8-17 Potential recovery of metals from bottom ash

$$forw = 1...3:$$

$$Metal_{t,MET} = \sum_{w} mtw_{t,w} \cdot \eta_{MR}$$

8.2.7.3 Displaced resources and emissions

Displaced resources and emissions from thermal treatment of waste in MSWI are related to the amount of energy and materials recovered on site. Recovered energy will be proportional to the amount of displace fugitive emissions associated to the country-specific power plant technology and the fuel source that is used to generate the same amount of energy. Similarly, recovered material will be proportional to the amount of displaced fugitive emissions associated to the production of iron. Displaced environmental costs from landfills are calculated with Equation 3-20.

9 LANDFILL: LFS

9.1 Process Description

The term landfill is defined by the Council Directive 1999/31/EC on landfill of waste as the "*waste disposal site for the deposit of the waste onto or into (i.e. underground), including: internal waste disposal sites and permanent sites which are used for temporary storage of waste, but excluding facilities where waste is unloaded in order to permit its preparation for further transport for recovery, treatment or disposal elsewhere, and storage of waste prior to recovery or treatment for a period less than three years as a general rule, or storage of waste prior to disposal for a period less than one year*" .

This Council Directive classified landfills in three major classes of landfill according to the type of waste that they are allowed to receive. This classification includes:

- Landfill for inert waste
- Landfill for non-hazardous waste
- Landfill for hazardous waste

Every landfill class is restricted to the acceptance procedure laid down in this Directive, which imposes that:

- Only pre-treated waste can be landfilled,
- Landfills for hazardous waste must be used only for hazardous waste fractions as defined in Article 2(c) and covered by Article 1(4) of Council Directive 91/689/EEC on hazardous waste,
- Landfills for non-hazardous waste must be used exclusively for municipal waste and for non-hazardous waste not covered by Article 2(c),
- Landfills for inert waste must be used only for inert waste as defined in Article 2(e)

Additionally, the Council Directive 1999/31/EC defines as treatment options the use of chemical, physical, thermal or biological process as acceptable technologies prior landfilling. Treated waste must follow the criteria and procedures for the acceptance of waste at landfills as imposed by the Council Decision 2003/33/EC pursuant to Article 16 of and Annex II to Directive 1999/31/EC. Only the waste fractions that fulfil these provisions could be disposed of.

9.2 LFS Sub-Model

The landfill sub-model (LFS) assesses the life cycle of the product system named landfill as shown in Figure 9-1. The sub-model starts when the waste category *w* generated at the source point *j* and at the waste management facility *x* enters to the landfill *l*. It ends when it is either transformed into a valuable end product (landfill gas, energy) and/or emitted as a fugitive emission to air ($FEA_{l,FEA}$) and to water ($FEW_{l,FEW}$). Even though fugitive emissions from landfills are generated over a long period of time and reaching a pseudo steady state after 100 years, in this model it is considered that all emissions to air and water are accounted and allocated to the year in which waste was disposed of. This assumption follows the recommendation of the IPPC Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000). Generated fugitive emissions are assessed considering the input waste composition, the landfill class type and the regional weather conditions. Considered landfills include only landfill class type LCI and LCII because the model assesses exclusively non-hazardous waste fractions.

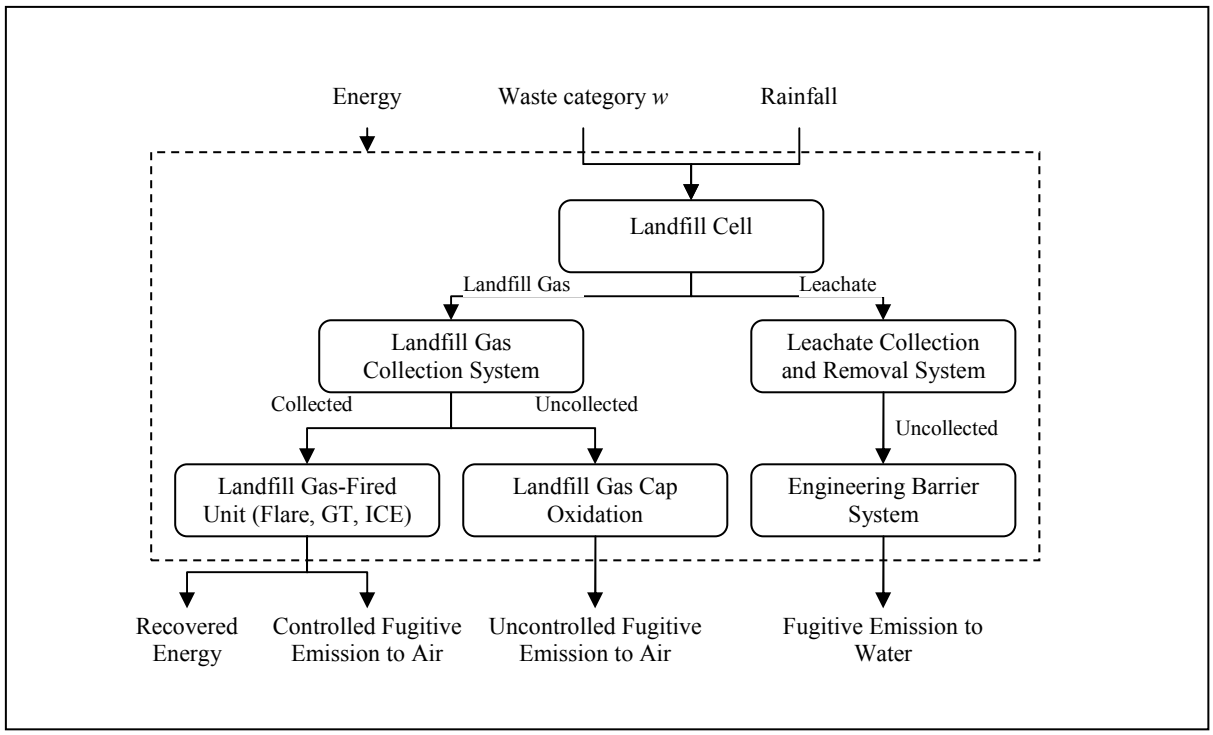


Figure 9-1 Boundaries of the landfill sub-model

Existing landfills are classified in managed and unmanaged ones. Managed landfills are well design landfills, with defined controls on the composition and amount of the input waste. Disposed waste is monitored, compacted and covered in a daily basis. Moreover, these landfills have installed adequate engineering barrier systems, landfill gas and leachate collection and removal systems, landfill gas-fired units and leachate control units for the minimisation of emissions to the environment. On the other hand, unmanaged landfills are poorly designed landfills with minimal control on the composition or amount of the input waste. Additionally, this landfill type has a negligible management of the generated landfill gas and leachate.

9.2.1 LFS Internal Process

9.2.1.1 Material Input

According to the multi-commodity flow distribution approach, the waste category *w* generated at the source point *j* and at the waste management facility *x* will compete for the scarce and finite capacity of the landfill *l*. The material flow distribution for every landfill is then calculated with Equation 9-1. The input variables of this equation are previously calculated as shown in subchapter 3.4.1 related to logistic constraints.

Equation 9-1 LFS waste category *w* input acceptance

$$mlw_{l,w} = \left[\begin{array}{l} \sum_{j} mjlw_{j,l,w} + \sum_{s} \left(mfsl_{s,l,w} + mosl_{s,l,w} \right) + \sum_{c} \left(mfcl_{c,l,w} + mhcl_{c,l,w} \right) + \sum_{a} \left(moal_{a,l,w} \right) + \sum_{d} \left(m\,odl_{d,l,w} \right) \\ + \sum_{m} mhml_{m,l,w} + \sum_{t} matl_{t,l,w} \end{array} \right]$$

subject to :

$$m_l = \sum_{w} mlw_{l,w}$$

$$PTC_l > m_l$$

where:

$mlw_{l,w}$ Total waste category *w* entering to the landfill *l*; [Gg]

$mjlw_{j,l,w}$ Total waste category *w* entering to the landfill *l* coming from the generation point *j*; [Gg]

$mzxl_{x,l,w}$ Total waste category w entering to the landfill l coming from the waste management facility x and fraction type z; [Gg]
m_l Total amount of waste received in the landfill l; [Gg]
PTC_l Annual tipping capacity for the landfill l; [Gg]

The definition of this statement considers the provisions given by the Council Directive 1999/31/EC on landfill of waste and the European waste acceptance criteria at landfills as defined by the Council Decision 2003/33/EC. The acceptance criterion in landfills is reported in Table 3-6, which is represented by the matrix LFC_C. The acceptance and material flow distribution of every secondary waste generated by existing waste management operations in the product system is restricted to the integer variable $LFRX_{k(x)}$. If the composition of the secondary waste fulfils these acceptance criteria then $LFRX_{k(x)}$ is equal to one and thus considered to be landfilled. Otherwise, it is zero and further treatment is required. Variable $LFRX_{k(x)}$ is used in the multi-commodity flow distribution equations from every waste management operation.

9.2.2 Secondary Waste

There is no secondary waste produced in landfills.

9.2.3 Fugitive Emissions to Air, FEA_l

Fugitive emissions to air generated from landfills come from uncontrolled emissions of landfill gas and controlled emissions from landfill-gas fired units. Emissions from uncontrolled sources consist mainly of methane (CH_4), carbon dioxide (CO_2) and trace gases such as ammonia (NH_3), nitrous oxide (N_2O), hydrogen sulphide (H_2S) and non-methane volatile organic compounds (NMVOCs). Then, total fugitive emissions to air from landfills depend mainly on:

- Landfill gas generation rates
- Landfill gas collection efficiency
- Landfill gas control efficiency

In this model, it is assumed that considered landfills spread a covering material over the deposited waste at the end of every working day in order to minimise infiltration of water into the landfill cell and to maximise run-off. Therefore, the initial aerobic phase that occurs as waste is placed in the landfill is not reflected in the modelling methodology. This assumption is based on the knowledge that aerobic waste decomposition takes place in a minor part of the landfill lifetime and it less significant than anaerobic decomposition (Zacharof 2004)

9.2.3.1 Landfill gas generation

The landfill gas generation rate varies considerably through the life of the landfill. This rate depends of several factors such as the waste or substrate composition, initial waste moisture content, degree of compaction, landfill pH, temperature and landfill phase. Several studies have tried to determinate a default landfill gas generation rate, but as expected, it varies considerably. It has been found in literature ranges between 90 and 300 m^3/Mg with an average value of 180 m^3/Mg. Table 9-1 shows reported landfill gas generation values.

Table 9-1 Landfill gas potential

Author	Landfill Gas Potential m^3/Mg	Author	Landfill Gas Potential m^3/Mg
AP-42	100		
Stegmann & Dernbach	105-140	Hoins	229-280
Bingemer & Crutzen	255	Orlich	218
Poller	120	Selzer & Zittel	200-300
Augstein & Pacey	80-160	Ehring	100-180
Grassi	150-200	ATV	150-250

Similarly, the composition of the landfill gas is not constant. It varies significantly during the different biological phases that take place inside the landfill. Once the generation of landfill gas reaches a steady state condition (phase IV), its composition is approximately 40% carbon dioxide, 55% methane, 5% nitrogen and trace gases (NPi 1999). Graphically, this can be observed in Figure 9-2.

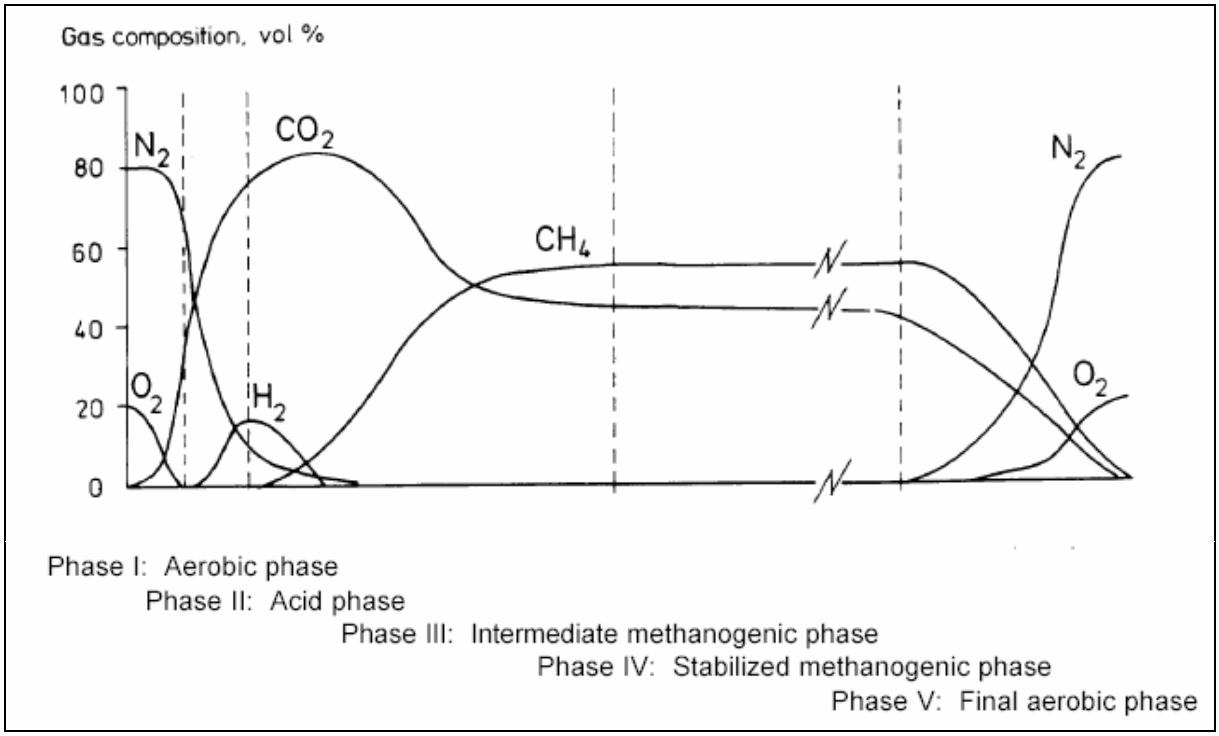


Figure 9-2 Development of the landfill gas generation

The emission modelling approach follows the default method (Tier 1) recommended by the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000). This approach is based on the assumption that landfill gas is generated in the year the waste was disposed of and that the composition and amount of disposed waste do not varied significantly over a period of several decades. With this assumption, the theoretical potential degradable material ($TPDM_{l,cc}$) can be calculated as a function of the amount, composition and degradability potential of the disposed waste. The degradability of the specific waste category *w* refers to the first 100 years after its placement in the landfill. The waste degradability is assumed homogeneous. Biochemically degraded material is divided in two fractions, dissimilated and assimilated. The dissimilated fraction is the portion of the substrate that is converted into landfill gas, while the assimilated fraction is the remainder substrate that is not biochemically degraded. Finally, the potential degradable material, which is biochemically transformed to landfill gas, needs to be adjusted with a correction factor (MCF_l) that relates how waste is managed on site. Well-managed and unmanaged landfills will have a correction factor equal to one and 0.6, respectively (IPCC 2000). As a result, the theoretical potential degradable material is calculated with Equation 9-2.

Equation 9-2 LFS Theoretical Potential Degradable Material, PDM $_1$

$$TPDM_{l,cc} = \sum_{w} \left[mlw_{l,w} \cdot MCC_{w,cc} \cdot DOC_{w} \cdot DOCF_{w} \cdot MCF_{l} \right]$$

where:

$TPDM_{l,cc}$ Theoretical mass flow of the chemical compound *cc* which is potentially degradable in the landfill *l*; [Gg]
$PDM_{l,cc,}$ Adjusted mass flow of the chemical compound *cc* which is potentially degradable in the landfill *l*; [Gg]

$mlw_{l,w}$ Waste category fraction *w* entering to the landfill *l*; [Gg]
$MCC_{w,cc}$ Matrix (waste category fraction *w* vs. chemical compound *cc*); [-]
$DOCF_w$ Degradable organic carbon dissimilated fraction of the waste category fraction *w*; [-]
MCF_l Methane correction fraction; [-]
$TCL_{cc,x}$ Process-specific coefficient of the potential degradable material flow distribution; [-]

Studies carried out by (Doka 2003) and (Belevi 1989) have found that in the methane phase the theoretical potential degradable material ($TPDM_{l,cc}$) is not completely transformed to landfill gas but washed out and precipitated into the leachate. This phenomenon is considered and the theoretical potential degradable material is adjusted with the fraction of the chemical compound *cc* that is emitted as landfill gas and the one that is washed into leachate during the methane phase. Finally, the adjusted potential degradable material ($PDM_{l,cc}$) is calculated with Equation 9-3, which uses the process-specific coefficient (TCL_{cc}) given in Table 9-2.

Equation 9-3 Potential degradable material in landfill gas

$$PDM_{l,cc} = TPDM_{l,cc} \cdot TCL_{cc}$$

Table 9-2 Fraction of the degradable chemical compound cc that is emitted in landfill gas and leachate

TCL_{cc}	Biogas fraction	Leachate fraction	TCL_{cc}	Biogas fraction	Leachate fraction
C	0.9709	0.029126	Cd	0.0066	0.993377
H	0.9709	0.029126	Tl	0.0002	0.99975
O	0.9709	0.029126	Hg	0.2857	0.714286
N	0.0644	0.935616	Sb	0.0002	0.99975
S	0.1491	0.850906	As	0.0138	0.986175
Cl	0.0138	0.986175	Pb	0.0003	0.999667
Inert	0.0000	1	Cr	0.0002	0.99975
H2O	0.0000	1	Co	0.0002	0.99975
			Cu	0.0003	0.999714
			Mn	0.0002	0.99975

Source: Adapted from (Doka 2003) and (Belevi 1989)

Under optimal anaerobic conditions, the potential degradable material *($PDM_{l,cc}$)* will be transformed by facultative anaerobic bacteria into landfill gas following the stoichiometric Reaction 9-1. This reaction assumes that degradable material is completely transformed to methane, carbon dioxide, ammonia, hydrogen sulphide and hydrogen chlorine.

Reaction 9-1 Anaerobic biological degradation

$$C_cH_hO_oN_nS_sCl_l + \frac{4c-h-2o+3n+2s+l}{4}H_2O \rightarrow \begin{cases} \frac{4c+h-2o-3n-2s-l}{8}CH_4 + \frac{4c-h+2o+3n+2s+l}{8}CO_2 \\ +nNH_3 + sH_2S + lHCl \end{cases}$$

The landfill gas generation potential depends mainly on the macro-chemical composition of the input waste fractions. Site-specific landfill gas mass flows are calculated with Equation 9-4, which is based on the potential degradable material of the input material. This is a waste-specific emission equation and it applies only to the main landfill gas components.

Equation 9-4 Landfill gas generation

CH_4 $$LG_{l,CH_4} = MW_{CH_4} \cdot \left(\frac{4PDM_{l,C}}{MW_C} + \frac{PDM_{l,H}}{MW_H} - \frac{2PDM_{l,O}}{MW_O} - \frac{3PDM_{l,N}}{MW_N} - \frac{2PDM_{l,S}}{MW_S} - \frac{PDM_{l,Cl}}{MW_{Cl}} \right) / 8$$

CO_2 $$LG_{l,CO_2} = MW_{CO_2} \cdot \left(\frac{4PDM_{l,C}}{MW_C} - \frac{PDM_{l,H}}{MW_H} + \frac{2PDM_{l,O}}{MW_O} + \frac{3PDM_{l,N}}{MW_N} + \frac{2PDM_{l,S}}{MW_S} + \frac{PDM_{l,Cl}}{MW_{Cl}} \right) / 8$$

NH_3 $$LG_{l,NH_3} = PDM_{l,N} \cdot \frac{MW_{NH_3}}{MW_N}$$

H_2S $$LG_{l,H_2S} = PDM_{l,S} \cdot \frac{MW_{H_2S}}{MW_S}$$

HCl $$LG_{l,HCl} = PDM_{l,Cl} \cdot \frac{MW_{HCl}}{MW_{Cl}}$$

where:

$LG_{l,LG}$	Total mass flow of the landfill gas compound *LG* generated in the landfill *l*; [Gg]
MW_{cc}	Molecular weight of the chemical compound *cc*; [g/gmol]
$PDM_{l,cc}$	Potential degradable material *cc* in the landfill *l*; [Gg]

On the other hand, trace gases are assessed separately with a process-specific emission equation based on process-specific coefficients values and on the landfill gas volume. Thus, it is assumed that the volume of trace gases emitted will be in constant proportion to the volume of total landfill gas generated. This assumption follows the recommendations of the Environmental Protection Agency (AP-42, NPi 1999) and on the reference documents in best available techniques (IPPC 2005a). However, in order to do so, it is required to convert the landfill gas mass flows into volume flows. This is done by multiplying the landfill gas mass flow ($LG_{l,LG}$) times its specific volume (v_{LG}), as shown in Equation 9-5.

Equation 9-5 Landfill gas volume flow

$$VLG_l = 1E06 \cdot \sum_{LG} \left(LG_{l,LG} \cdot v_{LG} \right)$$

where:

VLG_l	Total volume flow of landfill gas generated in the landfill *l*; [m^3]
$LG_{l,LG,1}$	Total mass flow of the landfill gas compound *LG* generated in the landfill *l*; [Gg]
v_{LG}	Specific volume of the landfill gas compound *LG*; [m^3/kg]

The practitioner needs to define the landfill reaction temperature (mesophilic or thermophilic) for the best selection of the landfill gas specific volume. In case the practitioner does not count with this information a default value of 35°C is used considering mesophilic conditions as recommended by (NPi 1999). The specific volume for the main landfill gas components are given in Table 9-3.

Table 9-3 Specific volume of landfill gas components

			CH_4	CO_2	NH_3	H_2S	HCl
Molecular weight	MW_{LG}	g/gmol	16	44	17	34	36.455
Specific Volume (Mesophilic)	v_{LG}	m^3/kg	1.5796	0.5744	1.4867	0.7433	0.6933
Specific Volume (Thermophilic)	v_{LG}	m^3/kg	1.7335	0.6304	1.6315	0.8157	0.7608

Subsequently, the trace gases volume flow ($VFEA_{l,FEA}$) is calculated using Equation 9-6 and the process-specific coefficients given in Table 9-4. Figures for other emissions than the ones listed in this table have not been identified by this study.

Equation 9-6 Volume flow of landfill gas including selected trace gases

$$VFEA_{l,FEA} = VLG_l \cdot TC_{FEA}$$

where:

$VFEA_{l,FEA}$	Volume flow of the compound *FEA* generated at the landfill *l*; [m^3]
VLG_l	Total volume flow of landfill gas generated in the landfill *l*; [m^3]
TC_{FEA}	Process-specific coefficient for landfill gas compound *FEA*; [ppm_v]

Table 9-4 Process-specific coefficients of air pollutants in the landfill gas

fea		NPi, AP-42, ppmv	(UBA 2000)	*fea*		NPi, AP-42, ppmv	(UBA 2000)
CO_2	kg/kg		4.9980E-1	$PM_{2.5}$	kg/kg		
CH_4	kg/kg		9.0648E-2	PM	kg/kg		
N_2O	kg/kg		2.3100E-7	PM_{10}	kg/kg		
HFCs	kg/kg			Cd	mg/kg		7.1400E-5
PFCs	kg/kg			Tl	mg/kg		
SF_6	kg/kg			Hg	mg/kg	2.92E-04	6.9800E-11
SO_2	kg/kg		1.2700E-4	Sb	mg/kg		
NO_2	kg/kg		3.1000E-4	As	mg/kg		9.8200E-5
NH_3	kg/kg		3.2100E-6	Pb	mg/kg		1.6500E-10
HCl	kg/kg	43.18	1.5400E-5	Cr	mg/kg		1.6200E-4
H_2S	kg/kg	35.5	2.7300E-5	Co	mg/kg		
NMVOC	kg/kg	595[2]	1.1310E-5	Cu	mg/kg		1.5500E-11
PCDD/F	kg/kg		6.9100E-15	Mn	mg/kg		
PAH	kg/kg		1.4318E-8	Ni	mg/kg		3.3200E-3
CO	kg/kg	141	5.1400E-4	V	mg/kg		

[1] Non-methane volatile organic compounds are given as hexane.
[2] It is suggested a value of 595 ppmv for no or unknown co-disposal of waste and 2420 ppmv for the co-disposal of waste in landfills.

Finally, the volume flow is converted into a mass flow with Equation 9-7. This equation assumes that the operation pressure of the landfill is one atmosphere, while the operation temperature is either mesophilic (35°C) or thermophilic (55°C). Once again, if the practitioner does not count with this information, a default value of 35°C is used considering mesophilic conditions as recommended by (NPi 1999).

Equation 9-7 Mass flow of landfill gas including selected trace gases

$$gFEA_{l,FEA} = VFEA_{l,FEA} \cdot \left(\frac{MW_{FEA} \cdot P}{R \cdot 1E+06 \cdot (273 + T_l)} \right)$$

where:

$gFEA_{l,FEA}$ Mass flow of the compound *FEA* generated at the landfill *l*; [Gg]
$VFEA_{l,FEA}$ Volume flow of the compound *FEA* generated at the landfill *l*; [m^3]
MW_{FEA} Molecular weight of the compound *FEA*; [g/gmol]
P Operation pressure; [atm]
R Ideal gas constant: 8.205E-02 m^3 atm / kg K
T_l Landfill operation temperature; [°C]

9.2.3.2 Landfill gas collection

Recovery of landfill gas is an important factor in reducing uncontrolled fugitive emissions from landfills. Moreover, landfill gas is a valuable source of renewable energy. Generated landfill gas is collected by means of the landfill gas collection system. These systems are not 100% efficient. Additionally, not all landfills count with this infrastructure. Landfills with well-designed landfill gas collection systems achieve collection efficiencies (η_{LGCS}) between 60 to 90%, with an average of 75% (NPi 1999, AP-42, Hogg 2002, Smith 2001). In this model is assumed that if the landfill site has installed a landfill gas collection system, then its collection efficiency is equal to 75%, otherwise to cero.

9.2.3.3 Landfill gas uncontrolled emission

Uncollected landfill gas will be emitted to the atmosphere as a fugitive emission through the landfill surface sealing system and through lateral migration from the sides of the landfill. It has been observed that a minor fraction of the uncollected gas is oxidised in the soil or covering material of the landfill surface sealing system. The percent of the uncontrolled landfill gas that is oxidised in the landfill cap is represented by the variable *OX*. Specifically, methane and hydrogen sulphide are partly oxidised in this top layer to carbon dioxide and sulphur dioxide, respectively. The amount of oxidation that occurs in the sealing cap however

is uncertain and depends of several factors such as latitude (temperature) and the soil oxidising capacity, among others (Cooper 1992, EPA 1999, Burroughs 2003). When the landfill is well managed, the IPCC Guidelines (IPCC 2000) establish a default value of zero for the biological methane oxidation; otherwise, it is equal to one. Similarly, (EPA 1999) and (IPCC 2000) give typical oxidation factors for managed landfills with ranges between 0.1 and 0.46. (IPPC 2000) recommends a default value of 0.1. In the case of hydrogen sulphide, it is assumed an oxidation rate equal to one because hydrogen sulphide, which was not oxidised in the landfill surface sealing system, is quickly oxidised to sulphur dioxide in the atmosphere.

Finally, the mass flow of landfill gas components that are uncontrolled emitted to the atmosphere are calculated with Equation 9-8. This equation is restricted to the compounds that are not oxidised in the landfill surface sealing system and the efficiency of the landfill gas collection system. As well, it assumes that all the landfill gas that was not collected by the landfill gas collection system (LGCS) is emitted to the atmosphere. Components that are oxidised in the landfill surface sealing and the ones that are produced during this oxidation process are separately calculated with Equation 9-9. This equation considers the amount of landfill gas that is suitable to biological oxidation in the cap.

Equation 9-8 Uncontrolled emission of landfill gas

$$for\ FEA \neq CH_4, CO_2, H_2S \text{ and } SO_2:$$
$$uFEA_{l,FEA} = gFEA_{l,FEA} \cdot (1 - \eta_{LGCS:l})$$

Equation 9-9 Uncontrolled emission of methane gas

CH_4 $$uFEA_{l,CH_4} = gFEA_{l,CH_4} \cdot (1 - \eta_{LGCS:l}) \cdot (1 - OX)$$

CO_2 $$uFEA_{l,CO_2} = gFEA_{l,CO_2} \cdot (1 - \eta_{LGCS:l}) + gFEA_{l,CH_4} \cdot (1 - \eta_{LGCS:l}) \cdot OX \cdot \frac{MW_{CO_2}}{MW_{CH_4}}$$

H_2S $$uFEA_{l,H_2S} = 0$$

SO_2 $$uFEA_{l,SO_2} = gFEA_{l,H_2S} \cdot (1 - \eta_{LGCS:l}) \cdot \frac{MW_{SO_2}}{MW_{H_2S}}$$

9.2.3.4 Landfill gas controlled emission

Collected landfill gas is treated by means of landfill gas-fired units such as flares, gas turbines or internal combustion engines. The final controlled emission depends on the removal efficiency of the installed landfill gas-fired unit. Typical removal efficiencies are given in Table 9-5. Therefore, controlled fugitive emissions to air are calculated with Equation 9-10. Some compounds such as methane, ammonia and hydrogen sulphide are oxidised into carbon dioxide, nitrogen dioxide and sulphur dioxide, respectively. The final emission of these gases is separately calculated with Equation 9-11. Both equations follow the waste-specific emission modelling approach.

Table 9-5 Landfill gas-fired units control efficiencies

	Flare		Gas Turbine		Internal Combustion Engine	
	Typical	Range	Typical	Range	Typical	Range
VOC	99.2	90-99+	94.4	90-99+	97.2	94-99+
Halogenated species	98.0	91-99+	99.7	98-99+	93.0	90-99+
Non-halogenated	99.7	38-99+	98.2	97-99+	86.1	25-99+

Source: Adapted from (NPi 1999, AP-42)

Equation 9-10 Controlled fugitive emissions to air from landfill gas-fired units

$$for\ FEA \neq CO_2, NO_2\ and\ SO_2:$$
$$cFEA_{l,FEA} = gFEA_{l,FEA} \cdot \eta_{LGCS:l} \cdot \eta_{APC:FEA,APC}$$

Equation 9-11 Selected fugitive emissions to air from landfill gas-fired units

CO_2
$$cFEA_{l,CO_2} = \begin{cases} gFEA_{l,CO_2} \cdot \eta_{LGCS:l} \cdot \eta_{APC:CO_2,APC} \\ + gFEA_{l,CH_4} \cdot \eta_{LGCS:l} \cdot \left(1 - \eta_{APC:CH_4,APC}\right) \cdot \dfrac{MW_{CO_2}}{MW_{CH_4}} \\ + gFEA_{l,NMVOC} \cdot \eta_{LGCS:l} \cdot \left(1 - \eta_{APC:NMVOC,APC}\right) \cdot \dfrac{MW_{CO_2}}{MW_{NMVOC}} \end{cases}$$

NO_2
$$cFEA_{l,NO_2} = gFEA_{l,NH_3} \cdot \eta_{LGCS:l} \cdot \left(1 - \eta_{APC:NH_3,APC}\right) \cdot \frac{MW_{NO_2}}{MW_{NH_3}}$$

SO_2
$$cFEA_{l,SO_2} = gFEA_{l,H_2S} \cdot \eta_{LGCS:l} \cdot \left(1 - \eta_{APC:H_2S,APC}\right) \cdot \frac{MW_{SO_2}}{MW_{H_2S}}$$

On the other hand, trace gases such as carbon monoxide, nitrous oxide and dioxins and furans are calculated following the process-specific emission modelling approach. As a result, the process-specific coefficients given in Table 9-6 are used in Equation 9-12 to calculate the emission of trace gases. The emission of trace gases are a function of the amount of methane combusted, the type of trace gas and the landfill-gas fired unit type.

Equation 9-12 Controlled fugitive emissions from selected landfill-gas fired units

$$for\ FEA = \text{trace gases}:$$
$$cFEA_{l,FEA} = gFEA_{l,CH_4} \cdot TCLGFU_{FEA}$$

Table 9-6 Process-specific coefficients emission for selected landfill-gas fired units

Fired unit	Flare			Gas Turbine		Internal Combustion Engine	
Source	NPI,AP-42, Bjarnadóttir	Pitschke/Hogg		NPI,AP-42	Pitschke	NPI,AP-42	Pitschke
unit	kg/kg CH_4	mg/m^3 LFG		kg/kg CH_4	mg/m^3 LFG	kg/kg CH_4	mg/m^3 LFG
HCl		21	12				
N_2O					5		
NO_2	1.0768E-03	69	100	2.3192E-03	200	6.6262E-03	
H_2S			0.033				5
SO_2	5.12E-04	30	25		1.41		90
CO	1.9879E-02	87	800	5.9636E-03	162.5	1.2424E-02	650
CH_4					12		
NMVOC					15		
PM	4.4727E-04	5	4.3	5.7979E-4	5	1.2755E-03	5
PAH	6.77E-07						
PCDD	2.96E-13	1.5E-08	8E-07				7.4E-09

Adapted from (NPi 1999), (AP-42) and (Pitschke 2004).

9.2.3.5 Total Fugitive Emission to Air

The total fugitive emission to air from a landfill is the addition of the uncontrolled and controlled fugitive emissions to air. Total fugitive emissions to air generated in the landfill are calculated with Equation 9-13. The obtained emission values are in accordance with background and foreground sources as shown in Table 9-7.

Equation 9-13 Total fugitive emissions to air from landfills

$$FEA_{l,FEA} = uFEA_{l,FEA} + cFEA_{l,FEA}$$

Table 9-7 Total fugitive emissions to air from the disposal of municipal residual wastes in well managed landfills

	Source	UBA 2000	Gemis	Gemis	Pitschke 2004	Pitschke 2004	Pitschke 2004	LCIWM	Doka 2004	Doka 2004	**min**	**max**	**aver**
	CHP type:	n.a	n.a	GT	Flare	GT	ICE	ICE	n.a.	n.a.			
CO2	kg/kg	5.00E-01	1.25E-01	2.08E-02	1.99E-01	1.99E-01	1.99E-01	3.68E-02	1.20E-02	1.59E-01	1.20E-02	5.00E-01	1.61E-01
CH4	kg/kg	9.06E-02	8.54E-03	9.06E-02	2.30E-02	2.30E-02	2.30E-02	1.63E-02	2.82E-05	2.16E-02	2.82E-05	9.06E-02	3.30E-02
N2O	kg/kg	2.31E-07		2.31E-07		7.70E-07			-	-	-	7.70E-07	2.46E-07
HFC-23	kg/kg								1.32E-15	2.16E-15	1.32E-15	2.16E-15	1.74E-15
CF4	kg/kg								-	-	-	-	-
SF6	kg/kg								2.17E-10	7.22E-10	2.17E-10	7.22E-10	4.70E-10
SO2	kg/kg	1.27E-04		1.27E-04	4.62E-06	2.17E-07	1.39E-05	2.03E-05	2.13E-05	5.18E-05	2.17E-07	1.27E-04	4.58E-05
NOx	kg/kg	3.10E-04		3.10E-04	1.06E-05	3.08E-05		7.13E-05	2.51E-04	2.69E-04	1.06E-05	3.10E-04	1.79E-04
NH3	kg/kg	3.21E-06							3.32E-07	1.83E-06	3.32E-07	3.21E-06	1.79E-06
HCl	kg/kg	1.54E-05	7.75E-07		3.23E-06		3.08E-06	4.31E-06	1.36E-07	1.81E-05	1.36E-07	1.81E-05	6.43E-06
H2S	kg/kg	2.73E-05					7.70E-07	9.38E-06	7.25E-09	1.06E-08	7.25E-09	2.73E-05	7.49E-06
NMVOC	kg/kg	1.13E-05		4.47E-05		2.31E-06		3.99E-06	4.29E-05	4.37E-05	2.31E-06	4.47E-05	2.48E-05
PCDD/F	kg/kg	6.91E-15		6.91E-15	2.31E-15		1.14E-15	3.59E-14	2.33E-12	2.60E-12	1.14E-15	2.60E-12	7.11E-13
PAH	kg/kg	1.43E-08		1.04E-08				1.71E-08	5.07E-09	5.20E-09	5.07E-09	1.71E-08	1.04E-08
CO	kg/kg	5.14E-04		5.14E-04	1.34E-05	2.50E-05	1.00E-04		7.45E-05	8.71E-05	1.34E-05	5.14E-04	1.90E-04
PM2.5	kg/kg								2.42E-05	2.73E-05	2.42E-05	2.73E-05	2.57E-05
PM	kg/kg			1.53E-01					6.47E-06	7.42E-06	6.47E-06	1.53E-01	5.10E-02
PM10	kg/kg				7.70E-07	7.70E-07	7.70E-07	1.35E-06	8.91E-06	1.07E-05	7.70E-07	1.07E-05	3.88E-06
Cd	mg/kg	7.14E-05		7.14E-05					3.93E-04	1.67E-03	7.14E-05	1.67E-03	5.52E-04
Tl	mg/kg								6.11E-06	6.86E-06	6.11E-06	6.86E-06	6.48E-06
Hg	mg/kg	9.68E-11		9.68E-11				1.93E-06	5.85E-04	1.88E-03	9.68E-11	1.88E-03	4.93E-04
Sb	mg/kg								1.06E-04	2.76E-04	1.06E-04	2.76E-04	1.91E-04
As	mg/kg	9.82E-05		9.82E-05					5.95E-04	2.03E-03	9.82E-05	2.03E-03	7.04E-04
Pb	mg/kg	1.65E-10		1.65E-10				2.39E-04	9.52E-03	1.29E-02	1.65E-10	1.29E-02	4.54E-03
Cr	mg/kg	1.62E-04		1.62E-04				3.09E-05	1.66E-02	1.80E-02	3.09E-05	1.80E-02	6.98E-03
Co	mg/kg								4.17E-04	5.07E-04	4.17E-04	5.07E-04	4.62E-04
Cu	mg/kg	1.55E-11		1.55E-11					6.37E-03	9.74E-03	1.55E-11	9.74E-03	4.03E-03
Mn	mg/kg								5.96E-04	2.58E-03	5.96E-04	2.58E-03	1.59E-03
Ni	mg/kg	3.32E-03		3.32E-03					4.22E-03	6.62E-03	3.32E-03	6.62E-03	4.37E-03
V	mg/kg								5.47E-03	6.68E-03	5.47E-03	6.68E-03	6.08E-03

9.2.4 Fugitive Emissions to Water, FEW_l

Fugitive emissions to water are the result of uncontrolled leachate leakage thought the landfill barrier system and they are accounted to a period of 100 years. The leachate leakage rate is site specific and it will depend on parameters such as:

- leachate generation rate
- leachate collection rate
- configuration of the landfill engineering barrier system

9.2.4.1 Leachate Generation

The generation rate of leachate depends mainly on the initial waste moisture content and on the amount of rainfall that percolates into the landfill. Other parameters such as biologically water consumption and generation, condensation and the absorptive waste capacity play a secondary role in the generation of leachate but they are not less important. The likelihood of leachate generation rate is assessed with a water mass balance represented with Equation 9-14. This methodology is adapted from the water balance methods developed by (McBean 1995), (Carey 2000), (Alexander 2003), (Huber 2004) and (Reinhart 2005).

Equation 9-14 Annual leachate generation rate

$$gLeachate_l = \sum_w \left(mlw_{l,w} \cdot MCC_{w,H_2O}\right) + A_l \cdot PERC_l \cdot CF_{kg-Gg} + BWG_l - BWC_l - CON_l - AC_w \cdot mlw_{l,w}$$

where:

$gLeachate_l$	Annual leachate generation; [Gg]
$mlw_{l,w}$	Annual mass flow of waste category *w* entering to the landfill *l*; [Gg]
$MCC_{w,H2O}$	Matrix (waste category *w* vs. chemical composition *cc*), where *cc* = H_2O; [-]
A_l	Landfill surface; [m^2]
$PERC_l$	Annual percolation rate; [mmH_2O]
CF_{kg-Gg}	Conversion factor from kg to Gg = 1E-6; [-]
BEG_l	Annual biological water generation; [Gg]
BWC_l	Annual biological water consumption; [Gg]
CON_l	Annual condensation; [Gg]. Condensation factor ($0.01kgH_20/m^3$ LMG)
a_w	Absorptive capacity of waste, (m3/Mg · Gg = Gg) ; [m^3/Mg]

Every parameter of the water mass balance is solved separately, as follows:

a. Percolation

For the purpose of this model, it is assumed that considered landfills spread a covering material over the deposited waste at the end of every working day in order to minimise infiltration of water into the landfill cell and to maximise run-off. It is assumed as well that the covering material is clay loam. Having this on mind, the amount of water that percolates into the landfill can be calculated with Equation 9-15. This equation considers that the percolation rate is a function of the annual precipitation rate, surface runoff, evapotranspiration and the covering material moisture storage capacity.

Equation 9-15 Annual percolation rate

Precipitation = Surface runoff + Evapotranspiration + Soil moisture storage + Percolation

Surface runoff, evapotranspiration and soil moisture storage are calculated on a monthly time basis. This assessment considers site-specific weather conditions such as site latitude, average monthly temperature and monthly rainfall values. Every of these parameters are calculated as follows.

Surface runoff

Surface runoff is precipitation runoff over the topsoil. It is mainly affected by both meteorological factors and physical characteristics such as soil type, slope and vegetation.

Thus, the surface runoff coefficient ($C_{r/o}$) is a function of the type and slope of the landfill surface sealing system. This parameter is provided in standard tables. Subsequently, the monthly surface runoff (r/o_m) is calculated with Equation 9-16, which is directly proportional to the surface runoff coefficient and the average monthly precipitation rate (P_m).

Equation 9-16 LFS surface runoff

$$r/o_m = C_{r/o} \cdot P_m \cdot \left[\frac{1\,\text{in}H_2O}{25.4\,\text{mm}H_2O} \right]$$

and :

$$C_{r/o} = f\,(\text{landfill surface sealing system, slope})$$

where:

r/o_m	Monthly surface runoff, [inH_2O]
Cr/o	Surface runoff coefficient, [-]
P_m	Monthly precipitation rate, [inH_2O]

Evapotranspiration

Evapotranspiration is the amount of water that is removed from the surface due to evaporation and transpiration processes. Evaporation and transpiration are similar processes, where liquid water is vaporised and removed from the topsoil and the plant tissues, respectively. These processes depend mainly on the energy supply via solar radiation. Evaporation rates are calculated as a function of statistical average monthly temperatures (T_m) and average monthly precipitation (P_m) values. With the T_m is calculated the monthly heat index (h_m) and by summing each h_m is then possible to obtain the yearly heat index (H) as shown in Equation 9-17.

Equation 9-17 LFS Yearly and monthly heat index

$$H = \sum_m h_m$$

and :

$$h_m = \begin{cases} 0 & \text{if } T_m < 0.5°\text{C} \\ 0.0223 \cdot T_m^2 + 0.0939 \cdot T_m - 0.0255 & \text{if } 0.5 \le T_m \le 5°\text{C} \\ 0.0086 \cdot T_m^2 + 02559 \cdot T_m - 0.4151 & \text{if } T_m > 5°\text{C} \end{cases}$$

where:

H	Yearly heat index; [-]
h_m	Monthly heat index; [-]
T_m	Monthly temperature; [°C]

With the calculated yearly heat index and with the average monthly temperature is obtained from tables the monthly-unadjusted potential evapotranspiration ($UPET_m$) value. Subsequently, using the site latitude is possible to obtain the correction factor for sunlight duration (r_m). The r_m and the $UPET_m$ are multiplied to result in the monthly-adjusted potential evapotranspiration rate (PET_m) as shown in Equation 9-18.

Equation 9-18 LFS Adjusted potential evapotranspiration

$$PET_m = UPET_m \cdot r_m$$

and :

$$UPET_m = f(T_m, H) : Table$$

$$r_m = f(site\,latitud) : Table$$

where:

PET_m	Adjusted potential evapotranspiration; [inH_2O]
$UPET_m$	Correction factor for sunlight duration; [inH_2O]
r_m	Unadjusted potential evapotranspiration; [-]

Soil Moisture Storage

The soil moisture storage is the amount of rainfall that is absorbed by the soil used in the landfill sealing system. This parameter depends on the infiltration rate, the amount of water available for storage and the accumulated water loss. The last parameter is the potential deficiency of soil moisture associated with the moisture content below the water available for storage or water holding capacity of the soil.

The monthly infiltration rate (I_m) is calculated by subtracting the monthly surface runoff *r/o* value from the average monthly precipitation rate. This parameter is then required for the determination of the amount of water available for storage (WAS_m) as calculated in Equation 9-19.

Equation 9-19 LFS water available for storage & infiltration

$$WAS_m = I_m - PET_m$$

and :

$$I_m = P_m - r/o_m$$

where:

WAS_m	Monthly water available for storage; [inH_2O]. if $WASm \geq 0$ then wet month, otherwise: dry month
Im	Monthly infiltration; [inH_2O]

Subsequently, for the first month of evaluation, if there is water available for storage (WAS_m) then the soil will keep and it will not percolate. In this case, the accumulative water loss (AWL_m) is equal to zero, otherwise to value of WAS_m. For the following months, the value of AWL_m will depend on the relation of current and previous water available for storage values as calculated in Equation 9-20.

Equation 9-20 LFS accumulative water loss

for m = 1 :

$$AWL_m = \begin{Bmatrix} 0 & \text{if } WAS_m \geq 0 \\ WAS_m & \text{if } WAS_m < 0 \end{Bmatrix}$$

for m > 1 :

$$AWL_m = \begin{Bmatrix} 0 & \text{if } WAS_m \cup WAS_{m\text{-}1} > 0 \\ WAS_m + AWL_{m-1} & \text{if } WAS_m < 0 \\ - & \text{if } WAS_m > 0 \cup WAS_{m-1} < 0 \end{Bmatrix}$$

where:

AWL_m	Monthly accumulative water loss; [in H_2O]

In order to determinate the soil moisture storage is require to determinate initial soil moisture storage (ST_0). This initial value depends on the type and depth of the covering soil. Subsequently, for the first month if there is water available for storage then the soil moisture storage (ST_m) is equal to the initial soil moisture storage (ST_0) otherwise is a function of the monthly accumulative water loss. For the following months, the soil moisture storage will depend on its monthly water available for storage and on its previous value as shown in Equation 9-21. It is important not to exceed the soil field capacity. Thus, if the soil moisture exceeds the water available for storage, the soil moisture capacity is set equal to the water available for storage.

Equation 9-21 LFS soil moisture storage

for m = 1 :

$$ST_m = \begin{Bmatrix} ST_0 & \text{if } WAS_m \geq 0 \\ 3.9835e^{(-0.2554|AWL_m|)} & \text{if } WAS_m < 0 \end{Bmatrix}$$

for m > 1:

$$ST_m = \begin{cases} ST_{m-1} + WAS_m & \text{if } WAS_m \geq 0 \cup ST_{m-1} + WAS_m < ST_0 \\ ST_0 & \text{if } WAS_m \geq 0 \cup ST_{m-1} + WAS_m \geq ST_0 \\ 3.9835e^{\left(-0.2554 \cdot |AWL_m|\right)} & \text{if } WAS_m < 0 \end{cases}$$

where:

ST_m Soil moisture storage; [in H_2O]

Finally, the variation of the soil moisture rate over time (ΔST_m) is simply the difference between the ST and its previous value as shown in Equation 9-22.

Equation 9-22 LFS change of soil moisture over time

for m = 1:

$$\Delta ST_m = 0$$

for m > 1:

$$\Delta ST_m = ST_m - ST_{m-1}$$

where:

ΔST_m Change of soil moisture storage over time; [in H_2O]

Percolation

Percolation is the moisture flow rate that enters finally to the landfill cell and contributes to the generation of leachate. As a result, the monthly percolation rate ($PERC_m$) can be calculated by subtracting the water available for storage (WAS_m) from the change of the soil moisture over time (ΔST_m). The annual percolation value is the sum of the monthly values as shown in Equation 9-23.

Equation 9-23 LFS annual percolation

$$PERC = \sum_m \left(PERC_m \cdot \left[\frac{25.4\, mmH_2O}{1\, inH_2O} \right] \right)$$

and:

$$PERC_m = \begin{cases} WAS_m - \Delta ST_m & \text{if } WAS_m \geq 0 \\ 0 & \text{if } WAS_m < 0 \end{cases}$$

where:

$PERC$ Annual Percolation; [mmH_2O]

$PERC_m$ Percolation; [inH_2O]

The reliability of this methodology is crosschecked with the statement of (White 1995), who says that around 13% of the rainfall percolates into a well managed landfill and emerges as leachate. Thus, considering the average weather conditions and location of an imaginary landfill in Düsseldorf, Germany and solving the set of equations given before, it was calculated that 10.15% of the rainfall percolates into the landfill. This result is comparable to White's statement and thus the reliability of this sequence is good. Individual parameters of the water mass balance equation for this example are shown in Table 9-8.

Table 9-8 Example of a water mass balance flow for a landfill

Water Balance Components	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly Totals
T (°C)	2.30	2.10	8.30	10.50	14.70	19.90	20.10	21.20	15.60	7.70	8.90	4.30	**11.3**
P(mm)	68.00	11.00	43.00	32.00	55.00	49.00	62.00	28.00	45.00	82.00	34.00	56.00	**565.00**
r	22.20	23.40	30.60	34.50	39.90	40.80	41.10	37.50	31.80	27.90	22.80	21.00	
h	0.31	0.27	2.30	3.22	5.21	8.08	8.20	8.88	5.67	2.07	2.54	0.79	
H	Sum of monthly h values (monthly heat indices, H); H=												**47.54**
UPET	0.01	0.01	0.04	0.06	0.09	0.12	0.13	0.13	0.09	0.04	0.04	0.02	
PET	0.22	0.23	1.22	2.07	3.59	4.90	5.34	4.88	2.86	1.12	0.91	0.42	
P (in.)	2.68	0.43	1.69	1.26	2.17	1.93	2.44	1.10	1.77	3.23	1.34	2.20	
$C_{r/o}$	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	
r/o	0.24	0.04	0.15	0.11	0.19	0.17	0.22	0.10	0.16	0.29	0.12	0.20	
I	2.44	0.39	1.54	1.15	1.97	1.76	2.22	1.00	1.61	2.94	1.22	2.01	
WAS	2.21	0.16	0.32	-0.92	-1.62	-3.14	-3.12	-3.87	-1.25	1.82	0.31	1.59	
AWL	0.00	0.00	0.00	-0.92	-2.54	-5.68	-8.81	-12.68	-13.93	-	-	-	
ST	3.59	3.59	3.59	3.15	2.08	0.93	0.42	0.16	0.11	1.94	2.24	3.83	
DST	0.00	0.00	0.00	-0.44	-1.07	-1.15	-0.51	-0.26	-0.04	1.82	0.31	1.59	
AET	0.22	0.23	1.22	1.59	3.04	2.90	2.73	1.27	1.65	1.12	0.91	0.42	
PERC (in.)	2.21	0.16	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
PERC (mm)	**56.24**	**4.07**	**8.04**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**57.37**
% PERC													**10.15%**
P (check)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

Example assumptions:

- Landfill located in Düsseldorf, Germany, with site latitude equal to 50 north.
- Landfill surface condition is of heavy soil and 2-7% slope with a surface runoff coefficient equal to 0.18.
- A landfill surface sealing system of clay loam for shallow-rooted crops with soil moisture storage of four inH_2O.

b. Biological Water Generation

Water is generated by microorganisms during the aerobic degradation of waste and from the oxidation of methane in the landfill surface sealing system. Aerobic degradation of waste occurs mainly in the top layer of unmanaged landfills, where waste is not immediately covered and compacted after its disposal. Mathematically it can be calculated with Equation 9-24, where the first right term refers to the water generated during the aerobic degradation of waste, while the second one refers to the oxidation of non-recovered methane in the landfill sealing system.

Equation 9-24 Biological water generation

$$BWG_l = \sum_w \left[mlw_{l,w} \cdot MCC_{w,C} \cdot DOCF_w \cdot (1 - MCF_l) \cdot MCC_{w,C} \right] \cdot \left[\frac{MW_{H_2O}}{MW_C} \right] + \left[gFEA_{l,CH_4} \cdot (1 - \eta_{LGCS\text{-}l}) \cdot OX_l \cdot \left[\frac{2MW_{H_2O}}{MW_{CH_4}} \right] \right]$$

c. Biological Water Consumption

Water is consumed by microorganisms during the anaerobic degradation of waste. From Reaction 9-1, the amount of water that is biologically consumed under anaerobic conditions is stoichiometrically calculated with Equation 9-25.

Equation 9-25 Biological water consumption

$$BWC_l = MW_{H_2O} \cdot \left(\frac{4PDM_{l,C}}{MW_C} - \frac{PDM_{l,H}}{MW_H} - \frac{2PDM_{l,O}}{MW_O} + \frac{3PDM_{l,N}}{MW_N} + \frac{2PDM_{l,S}}{MW_S} + \frac{PDM_{l,Cl}}{MW_{Cl}} \right) / 4$$

where:

BWC_l Annual biological water consumption; [Gg]
MW_{cc} Molecular weight of the chemical compound *cc*; [g/gmol]
PDM_{cc} Annual potential degradable chemical compound *cc*; [Gg]

d. Condensation

It is assumed that 0.01kgH_20 are condensed per m^3 of generated methane LMG. (Carey 2000)

e. Absorptive Capacity

Disposed waste has the property to absorb certain amount of water without generating leachate. This property depends on the type of waste, its initial moisture content and the density to which it was compacted. Based on information provided by (Carey 2000), Equation 9-26 was developed to estimate the absorptive waste capacity. It can be observed that the higher the waste density the lower its absorptive capacity. This is because low dense wastes have the capability to absorb further amount of water before leachate is generated.

Equation 9-26 Absorptive waste capacity

$$AC_w = 0.2393 - 0.2143 \cdot \rho_w$$

where:

AC_w	Absorptive capacity of waste category *w*; [m^3/kg]
ρ_w	Density of waste category *w*; [m^3/kg]

9.2.4.2 Leachate Collection and Removal System

All landfills must have installed an effective leachate collection and removal system (LCRS). This system must ensure the removal of generated leachate from the landfill and minimise the leachate head above the liner. In well-managed landfills, the leachate collection and removal system ensures that the leachate hydraulic head never exceed the thickness of the mineral sealing layer. In this model, it is assumed that in all assessed landfills the leachate hydraulic head has the same thickness as its mineral sealing layer. Therefore, the annual collected leachate is the difference between the generated leachate and the accumulated leachate as shown in Equation 9-27.

Equation 9-27 Annual collected leachate

$$cLeachate_l = gLeachate_l - A_l \cdot h_l \cdot CF_{m^3-Gg}$$

where:

$cLeachate_l$	Annual leachate collection at the landfill *l*; [Gg]
$gLeachate_l$	Annual leachate generation at the landfill *l*; [Gg]
A_l	Landfill surface; [m^2]
h_l	Leachate hydraulic head at the landfill *l*; [m]
CF_{m3-Gg}	Conversion factor from m^3 to Gg; [Gg/m^3]

9.2.4.3 Leachate Control: Engineering Barrier Systems, EBS

Engineering barrier systems are used to contain the generated leachate within the landfill and to retard the migration of pollutants by adsorption processes (attenuation). The minimum requirements of every engineering barrier system will depend on the landfill class. This model considers only the liner systems for the landfills class LCI and LCII, which are used by landfills designed to contain non-hazardous biodegradable waste. The specific EBS configurations of considered landfills are shown in Figure 9-3 as recommended by the German Technical Instructions on Municipal Waste (TASi).

Engineering barrier systems are not 100 per cent effective and thus they cannot ensure total leachate containment inside the landfill. Existing leakage rates depend on the type of liner system installed on site and on the leachate hydraulic head. For example, landfills categorised as LCI with a mineral liner have higher leakage rates as LCII, which has a composite liner.

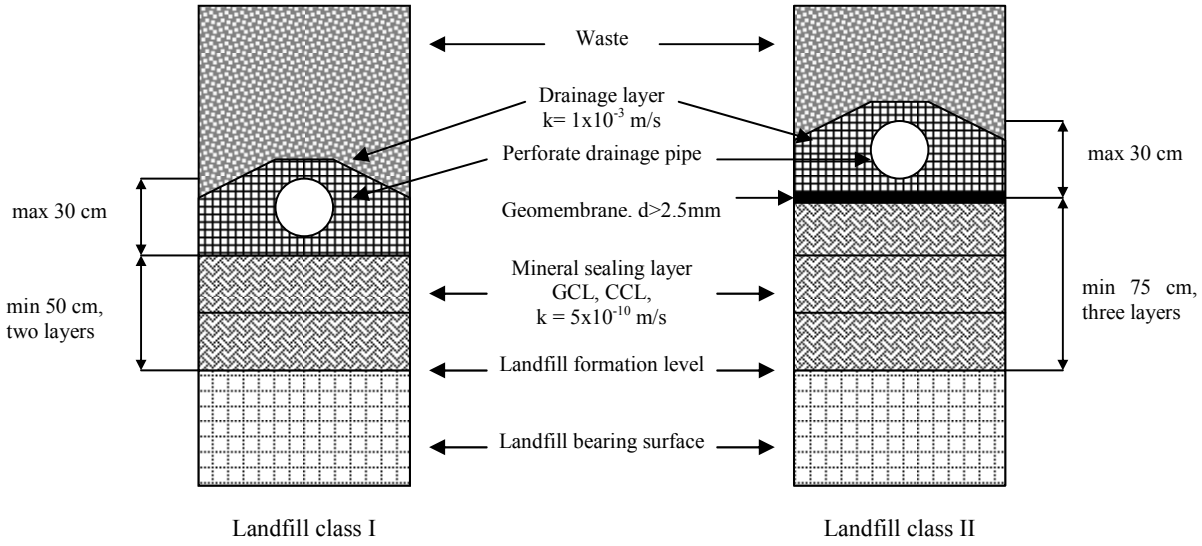


Figure 9-3 Engineering barrier systems as a function of the landfill class type (TASi).

a. Leakage rate through mineral liner, LC I

Leakage rate through mineral liners is governed by the thickness of the liner (d_l), the hydraulic leachate head above the liner (h_l) and the hydraulic conductivity of the liner material (k_l). This rate can be estimated with Darcy's Law, as shown in Equation 9-28. The application of this equation assumes steady state conditions. As mentioned before, in this model it is assumed that all assessed landfills fulfil minimum operation standards. Therefore, the maximum leachate hydraulic head is equal to the thickness of its mineral sealing layer. Additionally, the cross sectional area for flow is assumed to be equal to the base area of the landfill.

Equation 9-28 Darcy's Law

$$uLeachate_l = k_l \cdot i_l \cdot A_l$$

subject to :

$$i_l = \frac{h_l + d_l}{d_l}$$

where:

$uLeachate_l$	Annual leakage rate; [m^3]
k	Hydraulic conductivity of the liner material. For all landfills LCI it is assumed that they fulfil the minimum required of k=5E-10 m/s = 15.768E-03 m/y; [m]
i_l	Hydraulic gradient; [m/m]
A_l	Landfill area; [m^2]
h_l	Head of the leachate above the liner. It is assumed that the leachate hydraulic head has the same thickness as its mineral sealing layer. Therefore, $h_l = d$ = 0.5 m; [m]
d_l	Thickness of the liner. For all landfills LCI it is assumed that the fulfil the minimum required of d=0.5 m; [m]

b. Leakage rate through composite liner, LC II

The leakage rate through composite liner is governed by the defect area of the geomembrane (a_l), the hydraulic head of the leachate (h_l) and the quality contact between liners (QCF_l)during its installation. This is graphically shown in Figure 9-4.

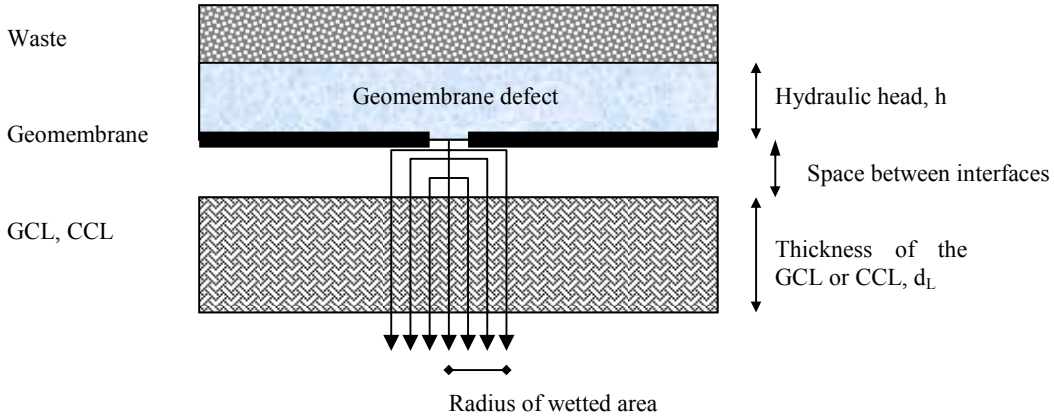


Figure 9-4 Leakage through composite liner

The defect area of a geomembrane is a function of the number of pinholes produced during its manufacture and installation. Typical geomembrane liners have a manufacture defect of one pinhole per acre with a theoretical diameter of 2 mm (Carey 2000, Giroud 1989a, Giroud 1989b). Similarly, depending on the quality assurance during the installation of the geomembrane, the number of pinholes can increase from one to twenty pinholes per acre. Under typical operation conditions, (Giroud 1989a) recommends to consider from one to two pinholes per 4000 m^2 with an individual area of 3.1 mm^2. If we assume two pinholes per acre, then the defect area of the geomembrane can be calculated with Equation 9-29.

Equation 9-29 Defect area of the geomembrane

$$a_l = \frac{6.2mm^2}{4000m^2} \cdot \left[\frac{1E-06m^2}{1mm^2} \right] \cdot A_l = 1.55E-09 \cdot A_l$$

where:

a_l Defect are of the geomembrane located at the landfill *l*; [m^2]

A_l Landfill surface; [m^2]

Subsequently, based on the studies of (Giroud 1989a) and (Giroud 1989b), the leakage rate through the composite liner can be predicted as a function of the defect liner area and the quality correction factor due to the quality contact between the composite liners. The final leakage rate is then calculated with Equation 9-30. This equation has been crosschecked and validated with the studies carried out by (Murphy 1998), (Reinhart 1999), (Carey 2000) and (Richardson 2000). Finally, it is assumed that all assessed landfills fulfil minimum operation standards. Therefore, the maximum leachate hydraulic head is equal to the thickness of its mineral sealing layer.

Equation 9-30 Leakage rate through composite liner

$$uLeachate_l = QCF_l \cdot a_l^{0.1} \cdot h_l^{0.9} \cdot k^{0.74}$$

where:

$uLeachate_l$ Annual leakage rate; [m^3]

QCF_l Quality correction factor due to the quality contact between the composite liners; [-]

$$QCFl = \begin{Bmatrix} 0.21 & \text{for Good Contact} \\ 0.60 & \text{for Average Contact} \\ 1.15 & \text{for Poor Contact} \end{Bmatrix}$$

a_l Defect area of the geomembrane; [m^2]

h_l Head of the leachate above the liner; [m]

k Hydraulic conductivity of the compacted soil below the geomembrane. ; [m].
For all landfills LCII it is assumed that they fulfil the minimum required of k=5E-10 m/s = 15.768E-03 m/y

[1] Good contact condition: installed geomembrane on top of a good compacted and smooth soil layer with low permeability.

[2] Poor contact condition: installed geomembrane on top of a poor compacted and not smooth soil layer with low permeability.

9.2.4.4 Uncontrolled Leachate Leakage

This model calculated uncontrolled leachate leakage flows during the first 100 years after its disposal. It is assumed as well that they are constant during this period. The model does not consider the retardation, advection and dispersion of leachate components to other species once it has been emitted. This assumption was taken due to the lack of specific site information related to the hydraulic properties of the unsaturated and saturated zones below the landfill. Therefore, the leachate concentration is assessed as soon as it is emitted from the frontier between the geomembrane and the mineral sealing liner. Leachate concentrations are calculated as process-specific emissions with Equation 9-31 and the process-specific coefficients given in Table 9-9.

Equation 9-31 LFS fugitive emission to water

$$FEW_{l,FEW} = uLeachate_l \cdot TC_{leachate:FEW} \cdot 100$$

Table 9-9 Uncontrolled process-specific coefficients for leachate leakages during the methanogenic phase

		NPi, AP-42	EPA 1995	Ehring 1987	Krümpelbeck 1999	Qasim 1994	Doka 2003	Umberto, Pitschke	Hogg 2002
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Biological Oxygen Demand	BOD5	-	180	252.42	290	1496.66	754	432	20-57000
Chemical Oxygen Demand	COD	-	3000	3122.55	1225	4000	2391.36	2430	140-152E3
Total Nitrogen	N-tot	425	1250	1250	-	-	852.398	985	
Total Phosphorous	P-tot	30	6	6	-	16.733	7.324	3.3	0.1-23
Mercury	Hg	6.04E-04	0.01	0.01	-	-	0.001529	0.01	5E-5-0.16

n.d. not detected
[1] as NH_4^+

9.2.5 Energy consumption

Distribution and compaction of waste requires special loaders, which consume diesel. Electricity is mainly consumed by administrative offices and by the use of landfill gas and leachate pumps. Typical energy consumption rates in landfill are shown in Table 9-10. These values are used in Equation 9-32 in order to determinate the total amount of energy used on site.

Equation 9-32 LFS energy consumption

$$EUL_{l,et} = \sum_{w} mlw_{l,w} \cdot EUTCL_{et}$$

where:
$EUL_{l,et}$ Energy type *et* consumed in the landfill *l*; [kWh or MJ]
$mlw_{l,w}$ Annual mass flow of waste category *w* disposed in the landfill *l;* [Gg]
$EUTCL_{et}$ Energy consumption process-specific coefficient; [kWh or MJ / Mg]

Table 9-10 LFS energy consumption process-specific coefficients

		Umberto	(Doka 2003)		(LCA-IWM 2005)	(UBA 2000)	Gemis
			LC0	LCI / LCII			
Electricity	kWh / Mg	2	1.35	0.01333	4.34	90.47	1.41
Diesel	MJ / Mg	33.024	46.74	26.96	38.4	-	-
Heat: Heavy fuel oil	MJ/Mg	-	-	-	-	45.78	43.60
Heat: natural gas	MJ / Mg	-	-	-	-	24.28	20.91

Diesel (38.4 MJ/l, 48MJ/kg); Heavy fuel oil (42 MJ/kg); Natural gas (52 MJ/kg, 40.2 MJ/m^3)

9.2.6 Costs

9.2.6.1 Disposal Costs

Disposal costs are affected by diverse parameters such as:

- Land acquisition
- Choice of technology (technical equipment of the site)
- Annual tipping rate
- Operational costs
- Closure costs
- Aftercare costs
- Landfill taxes

From all these variables is the annual tipping rate the one that affects most the unit disposal costs and it follows the economy of scale. This means that the lower the tipping rates the higher the disposal cost will be in order to cover fixed investment and operational costs. This effect can be seen in the German waste management infrastructure. With the implementation of stricter regulations related to the environmentally sound disposal of waste in June 2005, there is a considerable reduction of waste sent to disposal and thus an increase in the disposal cost. Before June 2005, typical disposal costs in Germany were between 26 and 280 €/Mg (EUWID 2000, Hogg 2001, Behrens 1998, Auksutat 1998 and MUNLV 1998). Nowadays, typical disposal costs are higher than before with values between 10 and 660 €/Mg, with an average value of 140 €/Mg. These costs are waste-specific related. Unfortunately, so far is difficult to determinate a common landfill cost because they are very volatile and they vary considerable from site to site. Process-specific models have been developed as a function of the plant treatment capacity as shown in Table 9-11.

Table 9-11 LFS disposal costs, €/Mg

Source	Min	Max	Aver	Comments
(Crowe 2002)	17	51	-	Treatment costs as a function of the plant treatment capacity (*PTC*): €/Mg= 8,747 $PTC^{-0.4795}$; R^2=1 Range: 50,000-500,000 Mg/a
(LCA-IWM 2005)	11	63	-	Treatment costs as a function of the plant treatment capacity (*PTC*): €/Mg= 625.12 $PTC^{-0.3706}$; R^2=1 Range: 500-60,000 Mg/a
(LCA-IWM 2005)	7	18	-	Treatment costs as a function of the plant treatment capacity (*PTC*): €/Mg=480.38 $PTC^{-0.3}$; R^2=1 Range: 60,000-1,500,000 Mg/a

In order to minimise uncertainty due existing variability in disposal costs, the model uses the mean disposal costs from exiting German landfills class LCI and LCII. Disposal costs are given not only for primary wastes but also for the secondary wastes as shown in Table 9-12 and Table 9-13, respectively. In case the practitioner has specific disposal costs, these costs can be changed in the model's input section. Finally, the disposal cost of the waste category w in a landfill is calculated with Equation 9-33.

Equation 9-33 LFS disposal cost

$$TC_l = \sum_i PWDC_i \cdot m_{l,i} + \sum_{si} SWDC_{si} \cdot m_{l,si}$$

Table 9-12 Primary waste disposal costs for landfills in Germany (*PWDCi*)

		EWC	min	max	mean	SD
1	Mixed municipal waste (Household waste)	200301	38.50	229.00	139.63	56.14
2	Similar to h.w. commercial waste	200301	38.50	229.00	139.63	56.14
3	Bulky waste	200307	66.00	229.00	140.42	53.37
4	Waste from markets	200302	38.50	229.00	140.47	56.99
5	Street-sweeping waste	200303	10.00	229.00	113.80	65.42
6	Mixed construction and demolition waste	170904	38.50	229.00	144.77	53.28
7	Waste from sewage cleaning	200306	38.50	229.00	124.62	57.02
8	No hazardous hospital residues	180101/04	38.50	257.90	145.23	64.35
9	Household problematic waste	200199	38.50	290.55	140.87	66.93
10	Biodegradable waste	200108	38.50	205.00	109.37	51.15
11	Green waste (garden, parks and grave yards)	200201	38.50	205.00	94.48	60.80
12	Paper and board	200101	10.00	660.00	156.43	141.86
13	Glass	200102	35.60	660.00	147.34	137.30
14	Lightweight packaging	200139	38.50	660.00	210.56	141.96
15	Metals	200140	10.00	660.00	141.20	138.00
16	Waste Wood	200138	38.50	322.40	136.30	68.25
17	WEEE containing CFC	200135	38.50	500.00	142.73	105.59
18	WEEE without CFC	200136	38.50	500.00	147.06	103.56
19	Clothes and textiles	200110	38.50	322.40	143.95	67.36
20	Mixed fraction waste	200199	38.50	290.55	140.14	68.03

Table 9-13 Secondary waste disposal costs for landfills in Germany (*SWDCsi*)

		EWC	min	max	mean	SD
Secondary waste mechanical treatment		191200				
	Sorted construction and demolition waste	170904	10.00	229.00	112.38	66.27
	Paper and board	191201	38.50	257.90	127.37	66.38
	Ferrous metals	191202	0.00	229.00	111.52	64.87
	Non-ferrous metals	191203	0.00	229.00	111.52	64.87
	Plastic and rubber	191204	38.50	376.20	144.33	84.07
	Glass	191205	38.50	660.00	142.32	144.36
	Wood	191207	38.50	322.40	134.69	72.85
	Textiles	191208	38.50	322.40	136.23	74.95
	Inert material	191209	37.60	229.00	87.17	51.06
Secondary waste aerobic biological treatment		190500				
	No composted fraction of MSW	190501	38.50	229.00	113.99	63.21
	Compost out of specification	190503	38.50	229.00	113.99	63.21
	Residual waste	190599	38.50	290.55	114.32	70.07
Secondary waste anaerobic biological treatment		190600				
	Liquor	190605	38.50	229.00	112.86	60.05
	Digestate	190606	38.50	229.00	112.86	60.05
	Residual waste	190699	38.50	290.55	120.48	70.40
Secondary waste thermal treatment		190100				
	Solid wastes from gas treatment	190107	30.20	110.00	69.88	27.80
	Bottom ash and slag other than those mentioned in 19 01 11	190111	30.20	110.00	69.88	27.80
	Boiler dust containing dangerous substances	190115	30.20	110.00	69.88	27.80

9.2.7 Benefits

9.2.7.1 Recovered Energy

Energy can be recovered from the combustion of the recovered landfill gas in landfill gas-fired units. Mathematically it is calculated with Equation 9-34. This equation is restricted to the digestion temperature in the landfill, the landfill gas collection efficiency and the conversion efficiency of the landfill gas-fired unit. In this equation, it is assumed that the landfill gas collection system operates with an efficiency of 75%. The selection of this value is justified in subchapter 9.2.3.2. The power conversion efficiency is fixed to the landfill gas-

fired unit type (GE 2004a, GE 2004b, GE 2004c, GE 2004d, GE 2000a, EPA 2002c, Hogg 2002). Gas turbines have overall power recovery efficiencies between 22 and 36 %, with an average value of 29%. Similarly, internal combustion engines have overall power recovery efficiencies between 22 and 40%, with an average value of 31%. In this model is not considered the recovery of heat. Finally, the economical revenue from the sale of the recovered energy is integrated in Equation 3-21.

Equation 9-34 Total recovered energy in BTD units

for $k = 7$:

$$RE_k = \sum_l gFEA_{l,CH_4} \cdot \nu_{CH_4} \cdot HHV_{CH_4} \cdot \eta_{LGCS:l} \cdot \eta_{CHP} \cdot CF_{kJ-kWh}$$

where:

RE_k	Recovered energy in the waste management operation *k(x)*, [kWh]
$gFEA_{l,CH4}$	Annual mass flow of methane generated in the landfill *l*; [Gg]
ν_{CH4}	Methane specific volume: 1.5796 m^3/ kg (Mesophilic) ; 1.7335 m^3/ kg (Thermophilic)
η_{BGCS}	Biogas collection system efficiency
η_{CHP}	Combined heat and power conversion efficiency
HHV_{CH4}	Higher heating value of methane: 33,810 kJ/m^3
CF_{kJ-kWh}	Conversion factor kJ to kWh: 1kWh=3.6x10^3 kJ

9.2.7.2 Recovered Material

Landfills are no source of recovered or diverted material.

9.2.7.3 Displaced resources and emissions

Displaced resources and emissions from landfills are related to the amount of energy that is recovery in the landfill gas-fired units installed on site. Recovered energy will be proportional to the amount of displace fugitive emissions associated to the country-specific power plant technology and the fuel source that is used to generate the same amount of energy. Displaced environmental costs from landfills are calculated with Equation 3-20.

10 PRACTICAL CASE OF STUDY

A practical case of study is carried out in order to prove the functionality and capability of this model. The waste management infrastructure of the German federal state of Nordrhein-Westfalen (NRW) is selected as reference point. NRW is selected because it has installed all the waste management operations modelled in *SUWAMAS* and because there is enough background and foreground information that can be used to compare results of the model with current practices. With this information a sustainable waste management concept is proposed, which provide an outline of the different waste streams and waste management operations. Specifically, the proposed sustainable waste management concept provides a planning framework for the following actions:

1. The compliance with existing European and national waste policy and target achievements
2. The outline of generated waste fractions and existing waste management infrastructure
3. The outline of sustainable production and consumption patterns of generated waste fractions
4. The outline of economy and investment requirements

The development of the sustainable waste management concept for NRW is based on its current waste management infrastructure and on the implementation of the community's waste legislation. Considerable attention is given to the fulfilment of sustainable principles such as prevention, precautionary, polluter pays, proximity and self-sufficiency. The prevention principle ensures the conservation of nature and resources, while waste generation is minimised or avoided where possible. Through the precautionary principle is secured the minimum impact on health and the environment derived from the generation of fugitive emissions to air, water and land. Generated fugitive emissions pay the full cost (direct and external) of their impact through the polluter pays principle. Finally, with the principle of proximity and self-sufficiency is possible to ensure an adequate waste management infrastructure by defining the required number and location of waste management operations.

The development of the sustainable waste management concept for NRW is based on some important assumptions. A) Contrary to the provisions of the Waste Framework Directive and EU Strategy for waste management, in this proposal the hierarchy of waste is not followed. Instead, the model follows the integrated product policy approach. Therefore, the model looks for the optimal combination of waste flow distribution and waste management operations with the lowest environmental impact through the complete life cycle of the product system. B) The model assesses existing amount and types of waste fractions as defined by the last published waste balance report of the region (MUNLV 2005). Considered parameters that influence waste generation are effects of policy changes. Contrary, parameters such as population growth, changes in economic situation, changes in manufacturing methods, changes in demand for consumer goods are not considered.

10.1 Waste Management Infrastructure in NRW, Germany

In this subchapter are given legal considerations and background information related to the current waste management infrastructure in NRW. Specifically, it is given the legislative framework, the geographical coverage, the amount of generated waste fractions, characteristics of installed waste management operations and the current waste management concept of NRW.

10.1.1 Legislative Framework

Germany, as a Member State of the European Union, follows the provisions of the European waste legislation. These include the horizontal legislation, the legislation on waste management operations and the legislation on specific waste streams (please refer to chapter 1.2.2 for more details). From this legal framework, the legislation related to landfill of waste is the most relevant strategic driver. The Council Directive 1999/31/EC on landfill of waste was transposed into German national law and it is represented by the Technical Instructions on Waste (TA Abfall[52]), the Technical Instructions on Municipal Waste (TA Siedlungsabfall: TASi[53]), the Waste Storage Ordinance (Abfallablagerungsverordnung: AbfAblV[54]) and the Landfill Sites Ordinance (Deponieverordnung: DepV[55]). The scope of this set of regulations is wider and more accurate than the Council Directive 1999/31/EC. Their most important provisions are *inter alia*:

- Discontinuation of all landfilling of untreated waste not conforming to landfill waste classification criteria by 01.06.2005
- Mechanical-biological and thermal treatment are the only accepted waste management operations to pre-treat municipal solid waste prior landfilling
- The high calorific fraction obtained in MBT shall be separated before disposal
- Mineral waste shall be landfilled in construction rubble disposal sites, even though that they fulfil designation criteria for landfill class LCI
- Closure of technically obsolete landfill sites placing a burden to the environment by 16.07.2009

The implementation of these provisions will have a drastic effect in the waste management system in Germany. It is expected that the installed thermal and mechanical-biological treatment capacity may not satisfy the total demand of waste generated. This may produce capacity bottlenecks over the waste management system. Organisations such as Prognos, LAGA and DBE have forecast the behaviour of the waste management system by 2005 and concluded that Germany has a treatment capacity deficit between 0.6 and 7 Mio Mg per year. This can be observed in Figure 10-1 . Additionally to the capacity deficit, it is expected a considerable increase of the waste disposal cost due to the required investments in landfill technology, waste pre-treatment, closure and post-closure care of obsolete landfills. As a result, landfill diversion will promote recovery and recycling practices as required by the community's waste legislation.

Due the complexity and size of the problem, the practical case of study is reduced to the assessment of the waste management infrastructure installed in the German federal state of Nordrhein-Westfalen (NRW). This study considers existing waste management strategic drivers, the amount and composition of generated waste and the waste disposal and recovery infrastructure of the federal state of NRW. With this information, the model is able to assess the waste management infrastructure in NRW and as a result suggest a sustainable waste management concept for the region.

[52] Zweite Allgemeine Verwaltungsvorschrift zum Abfallgesetz (TA Abfall) vom 12. März 1991 (GMBI. S.139, 167, 469)
[53] Dritte Allgemeine Verwaltungsvorschrift zum Abfallgesetz (TA Siedlungsabfall) vom 14. Mai 1993 (Banz. Nr. 99a)
[54] Verordnung über die umweltverträgliche Ablagerung von Siedlungsabfällen (Abfallablagerungsverordung – AbfAblV) vom 20.02.2001 (BGBI. I S. 305)
[55] Verordnung über Deponien und Langzeitlager (Deponieverordnung – DepV) vom 24 Juli 2002(BGBI. I S. 2807)

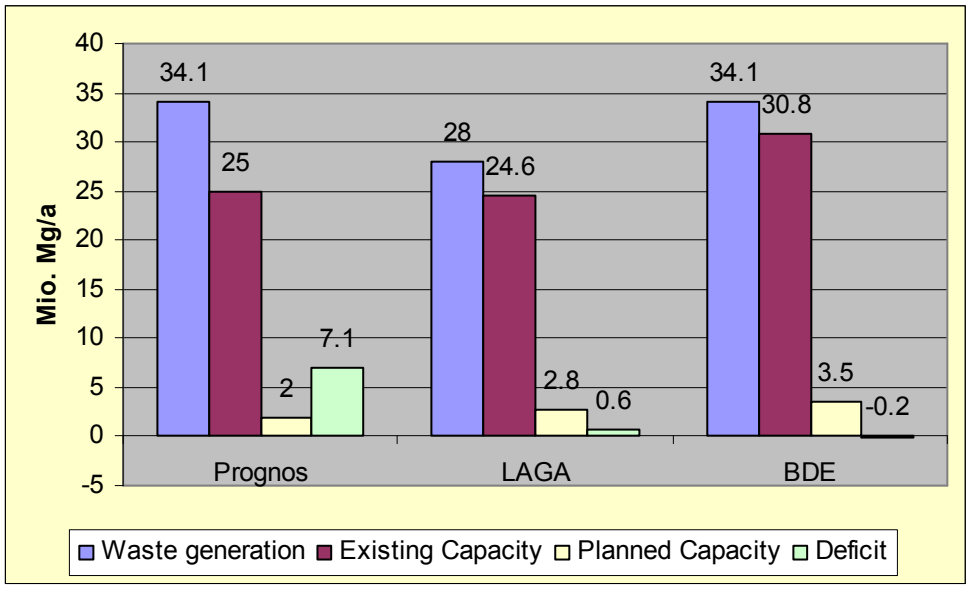


Figure 10-1 Waste management forecast for Germany in 2005.

10.1.2 Geographical coverage

The German federal state of Nordrhein-Westfalen (NRW) is divided in 5 administrative districts (Regierungsbezirk). These administrative districts are Arnsberg, Detmold, Düsseldorf, Köln and Münster as shown in Figure 10-2. Subsequently, these administrative districts are divided in 23 free district towns (kreisfreien Städte) and 31 districts (Kreise) (MUNLV 2005, MUNLV 2005a). According to the German Act for promoting closed substance cycle waste management and ensuring environmentally compatible waste disposal (Kreislaufwirtschafts- und Abfallgesetz – KrW-/AbfG), the districts and free district towns are the public-law parties responsible for waste management. In NRW, there are 54 public-law parties responsible for waste management. They are obligated to recover and to dispose generated solid waste from private households. Public-law parties responsible for waste management are classified in regions according to their number of habitants. These regions are big urban regions (>2000 h/km^2), urban regions (1000-2000 h/km^2), highly populated rural regions (250-1000 h/km^2) and rural regions (<250 h/km^2).

10.1.3 Waste quantities and composition

The amount and composition of the municipal solid waste generated in NRW is taken from the Waste Balance NRW for Municipal Solid Waste 2004 (MUNLV 2005). This waste balance was developed and reported by the Ministry for Environment and Nature Protection, Agriculture and Consumer Protection. In this report, municipal solid waste fractions are grouped in 24 primary waste categories and 2 secondary waste categories. These primary waste categories correspond to the same ones indicated in within the scope of the model in chapter 2.4.1. Subsequently, these categories are classified in seven groups. The total amount and composition of municipal solid waste generated in NRW and its five administrative districts are shown in Table 10-1. Similarly, in Table 10-2 are shown the total recovery and disposal flow distribution of municipal solid waste generated in NRW.

Figure 10-2 Geographical representation of NRW (MUNLV 2005a)

Table 10-1 Municipal waste balance for NRW and its 5 Administrative Districts (MUNLV 2005)

Nr.	Nordrhein-Westfalen and its 5 Administrative Districts Primary waste generation	NRW	Ansberg	Detmold	Düsseldorf	Köln	Münster
		Mg	Mg	Mg	Mg	Mg	Mg
1	Mixed municipal waste (Household waste)	3,479,834	711,920	247,558	1,196,719	876,498	447,139
2	Similar to h.w. commercial waste	645,216	51,508	193,382	204,423	58,313	137,590
3	Bulky refuse	652,225	121,651	38,256	239,825	168,061	84,432
4	Waste from markets	18,860	3,239	66	7,852	5,310	2,394
5	Street-sweeping waste	180,151	48,442	6,760	70,189	33,284	21,476
6	Mixed construction and demolition waste	359,659	152,412	2,865	98,967	70,890	34,526
7	Waste from sewage cleaning	20,582	1,137	2,217	9,548	4,447	3,232
8	No hazardous hospital residues	42,845	10,848	2,092	7,709	15,794	6,401
9	Household problematic waste	10,576	2,169	442	3,463	2,193	2,309
10	Biowaste (Biodegradable kitchen waste)	1,125,615	185,414	203,624	229,128	276,730	230,719
11	Green waste (garden, parks and grave yards)	715,189	141,719	61,744	213,637	154,510	143,579
12	Paper and cardboard	1,230,721	261,410	128,183	352,413	316,825	171,890
13	Glass	425,000	88,630	61,913	110,505	102,292	61,660
14	Lightweight packaging	560,007	127,056	61,606	156,610	130,825	83,911
15	Metals	46,879	5,784	2,700	25,875	6,756	5,764
16	Waste Wood	79,888	20,990	7,890	14,317	17,386	19,305
17	WEEE containing CFC	529,105	77,652	39,548	174,928	167,518	69,459
18	WEEE without CFC	40,806	8,059	3,513	16,642	4,835	7,756
19	Clothes and textiles	12,838	2,206	14	6,257	1,364	2,997
20	Mixed fraction waste	11,632	168	407	9,979	249	828
	SECONDARY WASTE						
25	Secondary waste from mechanical treatment units	2,804,504	625,332	31,976	200,535	1,806,475	140,186
26	Secondary waste from thermal treatment units	665,773	37,558	60,400	153,452	414,363	0
	TOTALS						
I	**Residual municipal solid waste (row 1 to 9, excl. 2 & 6)**	4,405,073	899,407	297,390	1,535,305	1,105,587	567,383
II	**Segregated biowaste (row 10 and 11)**	1,840,804	327,134	265,368	442,764	431,240	374,299
III	**Segregated recyclable material (row 12 to 14)**	2,215,729	477,096	251,703	619,527	549,941	317,462
IV	**Commercial waste (row 2, 6 and 21)**	2,371,863	619,140	253,208	772,671	467,785	259,060
V	**Other recyclable material (row 15 to 20, excl. 17)**	192,042	37,207	14,524	73,069	30,591	36,651

Table 10-2 Municipal solid waste flow distribution in NRW (MUNLV 2005)

Nr.	Nordrhein-Westfalen Primary waste	Generation	Recovered	Disposed			
				Total	at MBT	at THT	at LFS
		Mg	Mg	Mg	Mg	Mg	Mg
1	Mixed municipal waste (Household waste)	3,479,834	42,348	3,437,486	314,925	2,624,605	497,956
2	Similar to h.w. commercial waste	645,216	46,258	598,958	15,033	343,841	240,084
3	Bulky refuse	652,225	83,185	569,040	36,954	404,767	127,319
4	Waste from markets	18,860	6,041	12,819	28	9,632	3,160
5	Street-sweeping waste	180,151	58,052	122,098	4,632	66,095	51,371
6	Mixed construction and demolition waste	359,659	171,127	188,533	2,215	27,946	158,371
7	Waste from sewage cleaning	20,582	8,762	11,820	1,513	2,938	7,369
8	No hazardous hospital residues	42,845	0	42,845	1,199	29,034	12,611
9	Household problematic waste	10,576	6,042	4,534	40	3,983	510
10	Biowaste (Biodegradable kitchen waste)	1,125,615	1,070,320	55,295	7,382	11,737	36,177
11	Green waste (garden, parks and grave yards)	715,189	691,900	23,288	113	3,516	19,660
12	Paper and cardboard	1,230,721	1,222,645	8,076	0	5,539	2,537
13	Glass	425,000	418,803	6,197	0	0	6,197
14	Lightweight packaging	560,007	439,967	120,041	1,348	77,705	40,988
15	Metals	46,879	46,812	67	0	10	57
16	Waste Wood	79,888	78,790	1,099	0	835	264
17	WEEE containing CFC	529,105	514,625	14,480	0	2,091	12,389
18	WEEE without CFC	40,806	38,581	2,224	1,221	330	673
19	Clothes and textiles	12,838	12,002	836	0	657	179
20	Mixed fraction waste	11,632	1,935	9,696	0	9,696	0
	SECONDARY WASTE						
25	Secondary waste from mechanical treatment units	2,804,504	355,689	2,448,815	59,762	273,340	2,115,713
26	Secondary waste from thermal treatment units	665,773	251,240	414,533	0	1,776	412,757
	TOTALS						
I	**Residual municipal solid waste (row 1 to 9, excl. 2 & 6)**	4,405,073	204,429	4,200,643	359,292	3,141,055	700,297
II	**Segregated biowaste (row 10 and 11)**	1,840,804	1,762,220	78,583	7,494	15,253	55,836
III	**Segregated recyclable material (row 12 to 14)**	2,215,729	2,081,415	134,314	1,348	83,244	49,722
IV	**Commercial waste (row 2, 6 and 21)**	2,371,863	457,494	1,914,369	43,463	456,430	1,414,476
V	**Other recyclable material (row 15 to 20, excl. 17)**	192,042	178,120	13,923	1,221	11,529	1,172

10.1.4 Waste management operations

Installed waste management operations in charge of the recovery and disposal of municipal solid waste in NRW are classified in mechanical recycling facilities (dirty and clean), biological treatment (composting and fermentation), mechanical-biological treatment, thermal treatment (municipal solid waste incineration) and landfill sites (LCI and LCII). Recovery facilities have the highest number of installed units. More than 900 recovery facilities operate in NRW with an installed capacity of over 83,500 Gg/a. From this group, mechanical recycling facilities for building rubble and mineral waste have the highest number of process lines and installed capacity (ca. 300 facilities with a installed capacity of 50 Gg/a). Contrary, disposal facilities for municipal solid waste have an effective installed capacity for ca. 6,500 Gg/a and 44.7 Mm^3 for final disposal (MUNLV 2001, MUNLV 2005). Figure 10-4(a) shows the location of the different waste management operations installed in NRW. These facilities recover and dispose the municipal solid waste that is controlled by the public-law parties responsible for waste management.

10.1.4.1 Mechanical recycling facilities

Mechanical recycling facilities are classified in “clean” and “dirty” ones. “Clean” mechanical recovery facilities are in charge for the recovery of source-segregated waste fractions such as waste paper, waste glass, lightweight packaging waste, metals, waste wood, WEEE, construction and demolition waste and textiles. “Dirty” mechanical recycling facilities have the duty to recover valuable material from mixed waste fractions such as mixed municipal waste (household), similar to h.w. commercial waste and bulky waste. In NRW, there are more than 850 mechanical recycling facilities with more than 1080 process lines (MUNLV 2001). Together, these waste management operations have an effective installed capacity of ca. 82,000 Gg/a, as shown in Table 10-3.

Table 10-3 Mechanical recycling facilities installed in NRW (MUNLV 2001)

Primary waste	Number of process lines	Effective capacity, Gg/a
"Clean" MRF		
Paper and cardboard	66	1,950
Lightweight packaging waste	35	940
Commercial waste and building rubble	168	7,610
Building rubble, mineral residues from road	303	34,030
Asphalt from road restoration	92	8,800
Waste from heavy industry (metals)	21	8,000
Mixed waste from construction sites	28	5,500
Ferrous metals	65	5,430
Other mineral waste	13	3,770
Bottom slag and ashes from incinerators	8	2,000
Waste wood	23	1,210
Waste glass	9	1,080
WEEE	47	230
Textiles	1	18
"Dirty" MRF:		
Mixed municipal solid waste (RDF)	9	1,330

10.1.4.2 Biological treatment

In NRW, there are more than 70 biological treatment facilities from where only four operate as anaerobic biological treatment units. The remainder facilities are composting treatment plants (MUNLV 2005). Both aerobic and anaerobic biological treatment units offer an effective treatment capacity of 1,450 Gg/a. In the one hand, composting treatment plants are designed to handle segregated biological waste in four process lines. These lines are for biowaste ($BTCT_a$=1), greenwaste ($BTCT_a$=2), sludge ($BTCT_a$=3) and biowaste/greenwaste ($BTCT_a$=4). Most of the generated compost is issued in agriculture (50%) and in recultivation (25%). Other market shares like horticulture, hobby gardening and earth works consume the remainder 25% (MUNLV 2001). Installed composting plants in NRW are shown in Table 10-4. On the other hand, fermentation treatment plants handle exclusively biowaste. In general, the input material is transformed into biogas (70-120 m^3/Mg), compost (43%), fluid fertiliser (54%) and secondary waste (3%). Anaerobic plants are indicated in Table 10-5. Both aerobic and anaerobic biological treatment facilities are localised in Figure 10-3.

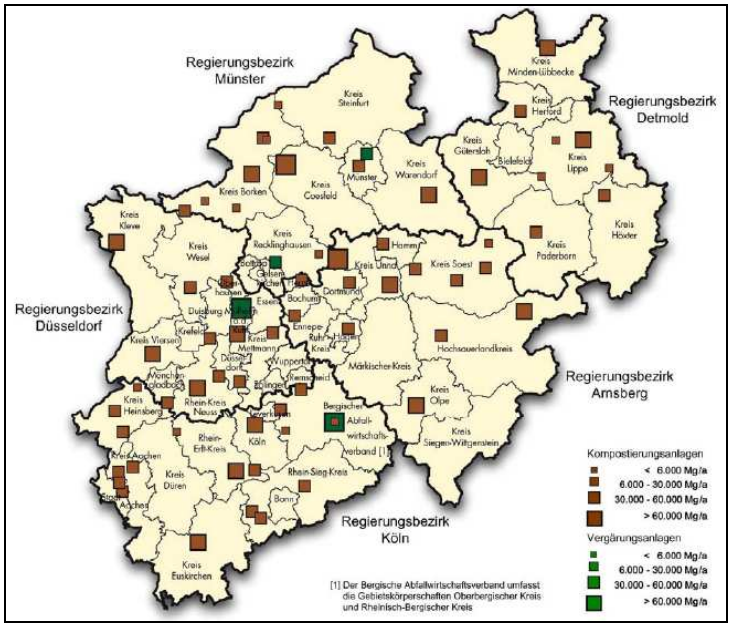


Figure 10-3 Installed aerobic and anaerobic biological treatment facilities in NRW (MUNLV 2005)

10.1.4.3 Mechanical-biological treatment

In NRW, there are installed six mechanical-biological treatment units with an effective treatment capacity of 807 Gg/a, as shown in Table 10-6. The output from the MBT nr 1 to 4 is disposed in a landfill; while the output from MBT nr 5 and 6 are thermally disposed (MUNLV 2005, MUNLV 2005b). They are located in four administrative districts but mainly in highly populated rural areas.

10.1.4.4 Municipal solid waste incineration

The sixteen municipal solid waste incineration plants (MSWI) installed in NRW have a total effective treatment capacity of 5,500 Gg/a (MUNLV 2005, MUNLV 2005b). This treatment capacity is related to the calorific value of the input waste. MSWI are distributed in the five administrative districts as shown in Figure 10-4b and summarised in Table 10-7 . All the MSWI installed in NRW work with grate firing systems, from where the roller grate type is the most common used technology (ca. 65%). These waste management operations have installed flue-gas treatment units for the control of particular matter (e.g. electrostatic precipitator, fabric filter and cyclone), nitrogen oxides (e.g. selective catalytic reduction), sulphur dioxide and mercury (e.g. wet scrubbers and adsorption units with activated carbon and lime).

10.1.4.5 Landfill

From the 01.06.2005, pre-treated municipal solid waste can be disposed exclusively in authorised LCII. Both Table 10-8 and Figure 10-4(a) show the landfill sites, which are allowed to operate in NRW after June 2005. It can be observed that there are only 17 accepted landfills LCII with a total disposal capacity of 44.7 Mio m^3. Landfills in Bochum-Kornharpen, Solinger Straße and Leppe will be closed by 2009 (MUNLV 2005b).

Table 10-4 Aerobic biological treatment capacity in NRW 2004 (MUNLV 2005)

A	Code	Name, BTC_a	$BTCT_a$	PTC_a [Gg/a]	Location	Administrative District
1	E15413106	Kompostwerk und Gewerbeabfallsortieranlage in Goch, Fa. Schönmackers	1	50,000	Kreis Kleve	Düsseldorf
2	E15813042	Kompostierungsanlage Deponie Plöger Steinbruch Fa. GKR Velbert	1	11,500	Kreis Mettman	Düsseldorf
3	E15813V04	Kompostierungsanlage Breitscheid-Rehhecke, Fa. KDM	1	25,000	Kreis Mettman	Düsseldorf
4	E16213302	Kompostierungsanlage Frimmersdorf-Süd, Fa.WURM	1	12,000	Kreis Neuss	Düsseldorf
5	E16213V03	Kompostierungsanlage Korschenbroich Fa. WURM / Kreis Neuss	1	40,000	Kreis Neuss	Düsseldorf
6	E17013V02	Kompostwerk AEZ Asdonkshof, Kreis Wesel KWA	1	25,000	Kreis Wesel	Düsseldorf
7	E31533025	Kompostierungsanlage Köln-Niehl, Fa. KVK	1	42,000	Kreisfreie Stadt Köln	Köln
8	E35433V02	Kompostierungsanlage Würselen der AWA GmbH	1	11,000	Kreis Aachen	Köln
9	E36233046	Kompostierungsanlage VZEK Verwertungzentrum Erftkreis, Fa.WURM	1	54,000	Erftkreis	Köln
10	E36633001	Kompostwerk auf der Deponie Mechernich des Kreises Euskirchen	1	30,000	Kreis Euskirchen	Köln
11	E37433V01	Kleinkompostierungsanlage Reichshof der SSK Bergneustadt	1	400	Bergischer AV	Köln
12	E38233V02	Kompostierungsanlage Gut Müttinghoven, Fa.WURM	1	12,000	Rhein-Sieg-Kreis	Köln
13	E55453V08	Kompostwerk und mech.-biolog. Behandlungsanlage, Nord Gescher-Estern, Fa. EGW	1	37,500	Kreis Borken	Münster
14	E55853005	Kompostierungsanlage „Coesfeld-Hoeven“ Fa. Rethmann	1	60,000	Kreis Coesfeld	Münster
15	E56255020	Behandlungsanlage von verunreinigten Böden und Bioabfallkompostierung in Gladbeck	1	40,000	Kreis Recklinghausen	Münster
16	E56653003	Kompostierungsanlage und Ersatzbrennstoffherstellung, Altenberge, Fa. Rethmann	1	18,000	Kreis Steinfurt	Münster
17	E57053V02	Kompostwerk zur Biomüllkompostierung Ennigerloh,Warendorf	1	38,000	Kreis Warendorf	Münster
18	E75473011	Kompostwerk des Kr. Gütersloh in Gütersloh	1	52,500	Kreis Gütersloh	Detmold
19	E76273001	Kompostwerk Nieheim-Oeynhausen, Fa. Kompotec	1	25,000	Kreis Höxter	Detmold
20	E77073001	Kompostanlage Hille Pohl’sche Heide d. GVOA mbH & Co.KG	1	40,000	Kreis Minden-Lübbecke	Detmold
21	E91393126	Kompostierungsanlage Dortmund-Wambel für Biomüll, EDG	1	24,000	Stadt Dortmund	Arnsberg
22	E95893084	Kompostwerk Brilon, Fa. Stratmann	1	32,000	Hochsauerlandkreis	Arnsberg
23	E95893128	Kompostwerk in Sundern, Hellefelder Höhe GmbH	1	20,000	Hochsauerlandkreis	Arnsberg
24	E96693123	Kompostwerk Olper Entsorgungszentrum, Alte Scheune 1	1	40,000	Kreis Olpe	Arnsberg
25	E97493121	Kompostierungsanlage Werl der ESG	1	14,000	Kreis Soest	Arnsberg
26	E97493122	Kompostierungsanlage für Biomüll in Soest	1	12,000	Kreis Soest	Arnsberg
27	E97493V05	Kompostierungsanlage Fa. Kleeschulte in Rüthen	1	n.a.	Kreis Soest	Arnsberg
28	E97893124	Kompostwerk Lünen Fa. Rethmann	1	80,000	Kreis Unna	Arnsberg
1	E11113V03	Kompostierungsanlage Fa. IDR, Oerschbachstraße	2	6,500	#N/A	#N/A
2	E11113V05	Kompostierungsanlage Hamm, Fa. IDR	2	11,500	Kreisfreie Stadt Düsseldorf	Düsseldorf
3	E11213100	Kompostierungsanlage „Huckingen“ der Stadt Duisburg	2	25,000	Kreisfreie Stadt Duisburg	Düsseldorf
4	E11413V01	Kompostplatz für Grünabfälle Fa. Schönmackers in Krefeld	2	20,000	Kreisfreie Stadt Krefeld	Düsseldorf
5	E11913V01	Kompostierungsanlage auf der Deponie Hühnerheide, Fa. AGR	2	3,000	Kreisfreie Stadt Oberhausen	Düsseldorf
6	E12213V01	Kompostierungsanlage Focher Straße, Stadt Solingen	2	6,500	Kreisfreie Stadt Solingen	Düsseldorf
7	E16613302	Kompostanlage Tönisvorst, Fa.WURM	2	6,570	Kreis Viersen	Düsseldorf
8	E17013V03	Kompostierungsanlage ZD Hünxe, Fa. AGR	2	10,000	Kreis Wesel	Düsseldorf
9	E31333V01	Kompostplatz „Aachen-Brand“ der Stadt Aachen	2	6,500	Kreisfreie Stadt Aachen	Köln
10	E31333V02	Kompostierungsanlage in Aachen-Soers, Aachener Stadtbetrieb	2	9,600	Kreisfreie Stadt Aachen	Köln

11	E35433017	Kompostierungsanlage auf der ZD Alsdorf-Warden, Fa. gabco	2	12,000	Kreis Aachen	Köln
12	E36233011	Kompostierungsanlage Fa. Poensgen Recycling GmbH,Wesseling	2	12,000	Erftkreis	Köln
13	E37033V01	Kompostierungsanlage Heinsberg der Fa. Frauenrath Recycling	2	20,000	Kreis Heinsberg	Köln
14	E37033V02	Pflanzenabfallkompostieranlage in Geilenkirchen, Fa. Pyls	2	6,570	Kreis Heinsberg	Köln
15	E37433022	Grünabfallkompostierung Lindlar auf der ZMD Leppe der BAV	2	5,000	Bergischer AV	Köln
16	E37433073	Kompostierungsanlage in Wiehl, Fa. Küpper	2	6,570	Bergischer AV	Köln
17	E37833V01	Kompostierungsanlage Burscheid Heiligeneiche der AWL	2	10,000	Bergischer AV	Köln
18	E37833V02	Kompostierungsanlage Birkerhof in Bergisch-Gladbach	2	3,000	Bergischer AV	Köln
19	E37833V03	Kompostierungsanlage in Wermelskirchen, Fa. Rethmann	2	8,500	Bergischer AV	Köln
20	E38233V01	Kompostierungsanlage in Hennef, Fa. Sauer	2	n.a.	Rhein-Sieg-Kreis	Köln
21	E38233V03	Grünabfallkompostierungsanlage der Gemeinde Wachtberg	2	6,000	Rhein-Sieg-Kreis	Köln
22	E51553V01	Grünabfallkompostierungsanlage auf der ZD Münster II	2	12,500	Kreisfreie Stadt Münster	Münster
23	E51553V02	Kompostierungsanlage Münster -Gartenbauamt-	2	1,400	Kreisfreie Stadt Münster	Münster
24	E55453V02	Kompostierungsanlage Fa. Stenau in Ahaus	2	6,900	Kreis Borken	Münster
25	E55453V04	Kompostierungsanlage Alstätte des Kreises Borken in Ahaus	2	5,200	Kreis Borken	Münster
26	E55453V05	Grünabfallkompostierungsanlage Hoxfeld des Kreises Borken	2	6,000	Kreis Borken	Münster
27	E55453V06	Kompostierungsanlage Rhede, DRK Jugendhof	2	1,000	Kreis Borken	Münster
28	E55453V07	Kompostierungsanlage Gronau	2	4,000	Kreis Borken	Münster
29	E55455019	Brech-/Klassieranlage und Kompostierungsanlage in Bocholt, EGB	2	6,500	Kreis Borken	Münster
30	E56253V01	Kompostierungsanlage Datteln für Grünabfälle, Fa. AGR	2	3,000	Kreis Recklinghausen	Münster
31	E56655519	Abfallentsorgungsanlage in Ochtrup, Fa. Kockmann	2	2,000	Kreis Steinfurt	Münster
32	E75873V01	Kompostwerk Kreis Herford, Fa. Kompotec	2	25,000	Kreis Herford	Detmold
33	E75873V02	Kompostierungsanlage in Kirchlengern, Fa. Lückemeier	2	2,500	Kreis Herford	Detmold
34	E76273V01	Grünabfallkompostierungsanlage in Warburg, Fa. Grundkötter	2	1,920	Kreis Höxter	Detmold
35	E76673001	Kompostierungsanlage Augustdorf der Fa. Freise	2	3,650	Kreis Lippe	Detmold
36	E76673V01	Grünabfallkompostierungsanlage in Detmold	2	2,100	Kreis Lippe	Detmold
37	E76673V05	Kompostierungsanlage in Bad Salzuflen, Fa. Hölsen Kompost	2	5,000	Kreis Lippe	Detmold
38	E76673V06	Kompostierungsanlage Blomberg, Fa. Naturkompost	2	3,750	Kreis Lippe	Detmold
39	E77073002	Grünschnittkompostierungsanlage Hille in Hille, Fa. AML	2	6,500	Kreis Minden-Lübbecke	Detmold
40	E77473001	Kompostierungsanlage Entsorgungszentrum Alte Schanze, AVE	2	6,500	Kreis Paderborn	Detmold
41	E91493111	Grünabfallkompostierungsanlage Hagen-Donnerkuhle	2	8,800	Stadt Hagen	Arnsberg
42	E91493V01	Rindenkompostierungsanlage Fa. Edelhoff in Hagen	2	n.a.	Stadt Hagen	Arnsberg
43	E91493V02	Treibzeugkompostierungsanlage des Ruhrverbands in Hagen	2	n.a.	Stadt Hagen	Arnsberg
44	E91693132	Grünabfallkompostierungsanlage in Herne, Fa. Müntefering	2	5,000	Stadt Herne	Arnsberg
45	E91695326	Abfallsortier- und Kompostieranlage in Herne, Fa. MABEG	2	6,750	Stadt Herne	Arnsberg
46	E95493V01	Kompostierungsanlage ZD Hattingen für Grünabfälle	2	6,500	Ennepe-Ruhr-Kreis	Arnsberg
47	E95893090	Kompostierungsanlage für Grünabfälle Fa. Klute in Sundern	2	6,000	Hochsauerlandkreis	Arnsberg
48	E95893V01	Kompostierungsanlage f. Grünabfälle d. St. Arnsberg in Neheim-Hüsten	2	275	Hochsauerlandkreis	Arnsberg
49	E97493V02	Kompostierungsanlage Lippstadt für Grünabfälle	2	2,500	Kreis Soest	Arnsberg
1	E55453V10	Klärschlammkompostierung in Vreden, Fa. Strabag	3	5,000		
2	E71173001	Klärschlamm-Kompostierungsanlage Bielefeld der Fa. IAA	3	6,500		
3	E75473001	Kompostierungsanlage Rheda-Wiedenbrück, Fa. IAA	3	6,500		

4	E76673002	Kompostierungsanlage Bad Salzuflen-Retzen, der Fa. IAA	3	6,500		
5	E76673V02	Abwasserschlammkompostierung in Horn-Bad Meinberg	3	650		
6	E96693V04	Kompostierungsanlage Hilchenbach, Kläranlage Ferndorftal	3	600		
1	E16613V03	Kompostierungsanlage auf der Deponie „Viersen II“ des Kreises Viersen	4	30,000	Kreis Viersen	Düsseldorf
2	E36635039	Kompost-Dünger-Erdenwerk in Zülpich, Fa. Diefenthal	4	6,000	Kreis Euskirchen	Köln
3	E38233000	Kompostwerk in Swisttal-Miel, Fa. UP (RSAG)	4	27,000	Rhein-Sieg-Kreis	Köln
4	E38233035	Kompostwerk St.Augustin, RSAG	4	26,000	Rhein-Sieg-Kreis	Köln
5	E91593133	Kompostierungsanlage ZD Hamm für Bio- und Grünabfälle	4	12,400	Stadt Hamm	Arnsberg
6	E97493127	Kompostierungsanlage in Anröchte der ESG	4	15,000	Kreis Soest	Arnsberg
7	E97893129	Kompostierungsanlage ZD Fröndenberg	4	31,500	Kreis Soest	Arnsberg

Table 10-5 Anaerobic biological treatment capacity in NRW 2004 (MUNLV 2005)

d	Code	Name, BTD_d	PTC_d [Gg/a]	Location	Administrative District
1		Service-Zentrum-Entsorgung (Vergärungsanlage). Mülheimer Entsorgungsgesellschaft	30,000	Mulheim	Düsseldorf
2	E37433065	Vergärungsanlage auf der ZD Leppe Fa. BAV	40,000	Bergischer AV	Köln
3	E56253V04	Integrierte Methanisierungs- und Kompostierungsanlage, Herten	18,000	Kreis Recklinghausen	Münster
4	E51553V03	Bioabfallvergärungsanlage Stadtwerke Münster	22,000	Kreisfreie Stadt Münster	Münster

Table 10-6 Mechanical-biological treatment capacity in NRW 2004 (MUNLV 2005, MUNLV 2001, ASA 2004)

m	Code	Name, MBT_m	PTC_m [Gg/a]	Biological Section	APC	Location	Administrative District
1	E77075002	MBA Pohlsche Heide	100	BTD	RTO, BF	D. Minden-Lübbecke	Detmold
2	E51555200	MBA Münster	100	BTC (ERS)	BF	Münster	Münster
3	E55455099	MBA Gescher	115	BTC (ERS-Tunnel)	RTO, BF	D. Borken	Münster
4	E57055111	MA, BA Ennigerloh	160	BTC(ERS-Tunnel)	RTO, BF	D. Warendorf	Münster
5		WSAA Neuss	220			Rhein D. Neuss	Düsseldorf
6		MA “Haus Forst”	112			Rhein-Erft D.	Köln

APC: Air pollution control system; RTO: regenerative thermal oxidation, BF: biofilter
BTC: biological treatment composting; NRS: non reactor system, ERS: enclosed reactor system
BTD: biological treatment digestion

Table 10-7 Thermal treatment capacity in NRW 2004 (MUNLV 2005a, MUNLV 2001, LUA-NRW 2001)

t	Code	Name, THT_t	PTC_t [Gg/a]	Effluent Gas Treatment Technology Sequence	Location	Administrative District
1	E91492042	MVA Hagen	120	CC, DSI/ESP, SCR, FF (hose filter)	Hagen	Arnsberg
2	E91592039	MVA Hamm	230	SNCR, CC, SD/FF	Hamm	Arnsberg
3	E96292190	MHKW Iserlohn	260	ESP, ClS, SS, SCR, FF	Iserlohn	Arnsberg
4	E71172270	MVA Bielefeld-Herford	360	ESP, SD/ESP, ClS, SS, SCR, CFB, FF	Bielefeld-Herford	Detmold
5	E11112015	MVA Düsseldorf-Flingern	450	DSI/ESP, FF, SCR	Düsseldorf-Flingern	Düsseldorf
6	E11312162	MHKW Essen-Karnap	740	ESP, ClS/SS, SCR, CFB	Essen-Karnap	Düsseldorf
7	E11412175	MKVA Krefeld	350	FF, ClS, SS, SCR, CFB	Krefeld	Düsseldorf
8	E11912127	GMVA Oberhausen	580	ESP, ClS, SS, SCR, CFB	Oberhausen	Düsseldorf
9	E12212030	MVA Solingen	100	SD, ESP, SCR, CFB	Solingen	Düsseldorf
10	E12412080	MHKW Wuppertal	390	ESP, ClS, SS, DSI/ESP, CFB, SCR	Wuppertal	Düsseldorf
11	E17012100	MVA Asdonkshof	270	ESP, SD, ESP, ClS, SS, SCR, DSI	Asdonkshof	Düsseldorf
12	E31432032	MVA Bonn	240	SNCR, SD/ESP, ClS/SS, FF (hose filter)	Bonn	Köln
13	E31532029	RMVA Köln	210	SD/FF, ClS, SS, SCR, FF	Köln	Köln
14	E31632090	MHKW Leverkusen	370	ESP, ClS, SS, CFB, SCR	Leverkusen	Köln
15	E35432002	MVA Weisweiler	570	SD, FF, ClS, SS, SCR	Weisweiler	Köln
16	E56252039	RZR-Herten	260	CC, SD/ESP, ClS/SS, SCR	Herten	Münster

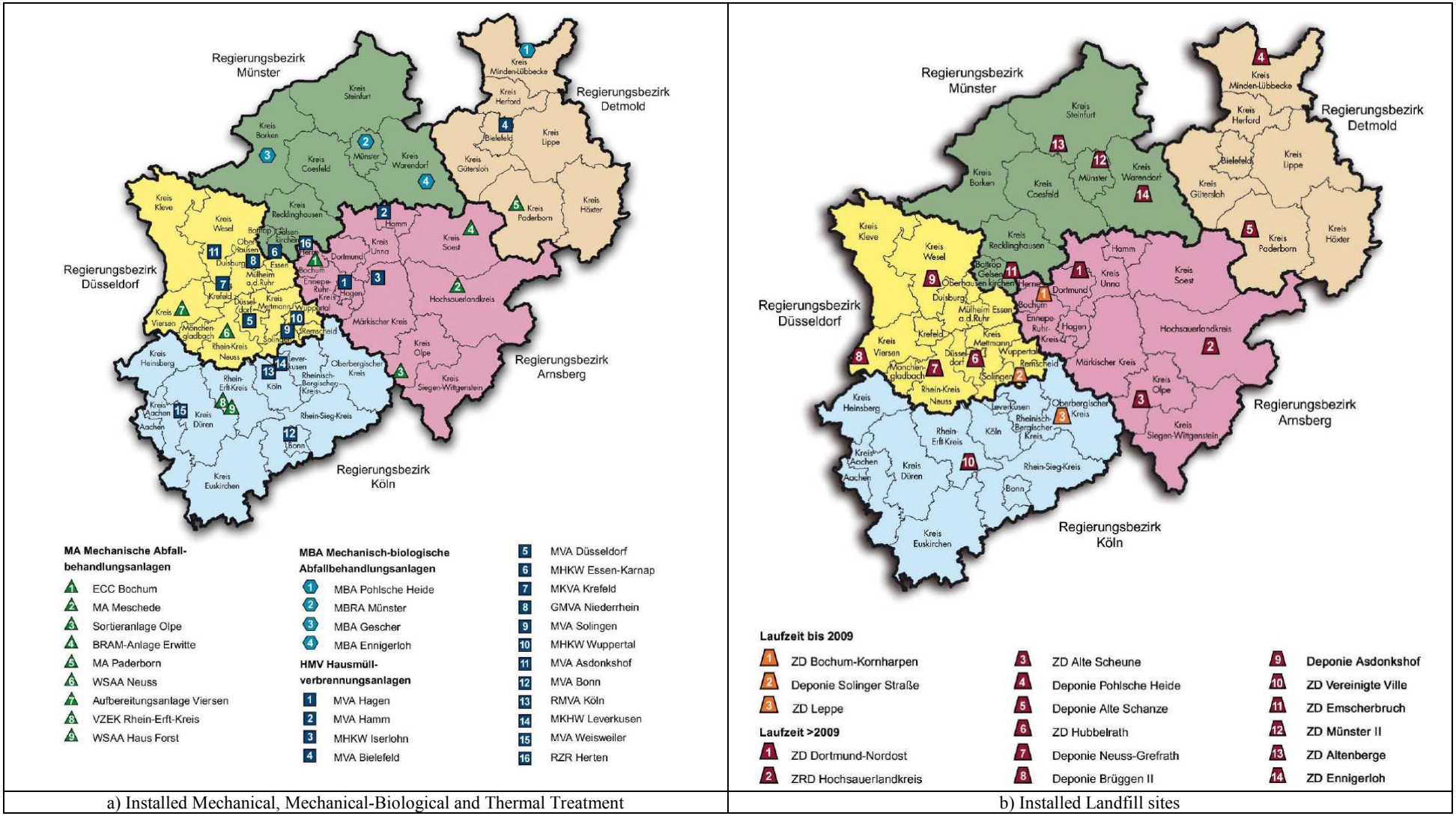
Effluent Treatment Technology

CC: cyclone, FF: fabric filter, ESP: electrostatic precipitator, ClS: HCl wet scrubber, SS: SO_2 wet scrubber, SD: spray dryer, DSI: duct sorbent injection, SCR: selective catalytic reduction, SNCR: selective noncatalytic reduction, CFB: catalytic filter bag.

Table 10-8 Disposal capacity in NRW (LCII accepted to operated after 2005 (MUNLV 2005a, MUNLV 2005b, MUNLV 2001)

l	Code	Name, LFS_l	PTC_l [Mio m^3]	Landfill type	A (ha)	LGCS	BGRT	EBS	LLCS	Location	Administrative District
1	E91191018	ZD Bochum-Kornharpen	0.85	MSWL	34	Y	GT	TASi	Y	Bochum	Arnsberg
2	E91391032	ZD Dortmund-Nordost	0.45	LCII	64	Y	GT	TASi	Y	Dortmund	Arnsberg
3	E95891190	ZRD Hochsauerlandkreis	6.97	LCII	24.5	Y	F	TASi	N	Meschede	Arnsberg
4	E96691230	ZD Alte Scheune	1.15	MSWL	16	Y	F	n.a.	Y	Olpe	Arnsberg
5	E77071301	Deponie Pohlsche Heide	3.19	LCII	80	Y	GT	TASi	Y	Minden-Lübbecke	Detmold
6	E77471253	Deponie Alte Schanze	2.85	MSWL	90	Y	ICE	TAA	Y	Paderbon	Detmold
7	E11111027	ZD Hubbelrath	0.98	LCII	27	Y	F	n.a.	Y	Düsseldorf	Düsseldorf
8	E12018012	Deponie Solinger Straße	0.10	LCII	2,4	Y	F	TASi	Y	Remscheid	Düsseldorf
9	E16211224	Deponie Neuss-Grefrath	2.29	MSWL	10,7	Y	ICE	TASi	Y	Neuss	Düsseldorf
10	E16611311	Deponie Brüggen II	4.70	LCII	33,2	Y	F	TASi	Y	Viersen	Düsseldorf
11	E17016123	Deponie Asdonkshof	10.90	LCII	52,5	Y	F	TASi	Y	D.Wesel,Kamp-Lintfort	Düsseldorf
12	E36231027	ZD Vereinigte Ville	4.10	MSWL	85,57	Y	GT	n.a.	Y	Rhein-Erft-Kreis	Köln
13	E37431240	ZD Leppe	3.80	LCII	39	Y	GT	TASi	Y	Oberbergischer Kreis	Köln
14	E51351047	ZD Emscherbruch	0.32	TAAL	85	Y	GT	TAA	Y	Gelsenkirchen	Münster
15	E51551119	ZD Münster II	0.33	MSWL	24	Y	ICE	TASi	Y	Münster	Münster
16	E56651227	ZD Altenberge	0.34	MSWL	42,5	Y	GT	TASi	Y	Kreis Steinfurt	Münster
17	E57051312	ZD Ennigerloh	1.36	MSWL	38	Y	GT	TASi	Y	Kreis Warendorf	Münster

Where:
Y: yes; N: no
Landfill type: TASi Landfill (LC 1), TASi Landfill (LC II), TA Abfall Landfill (TAAL), municipal solid waste landfill (MSWL)
A: Disposal area of the landfill
LGCS: Landfill gas collection system
LSW: Landfill sealing wall
BGRT: Biogas recovery technology (F: flare; GT: gas turbine; ICE: internal combustion engine)
EBS: Engineering barrier system type
LLCS: Landfill leachate collection system and control



a) Installed Mechanical, Mechanical-Biological and Thermal Treatment

b) Installed Landfill sites

Figure 10-4 Installed (a) treatment and (b) disposal waste management operations in NRW (MUNLV 2005b)

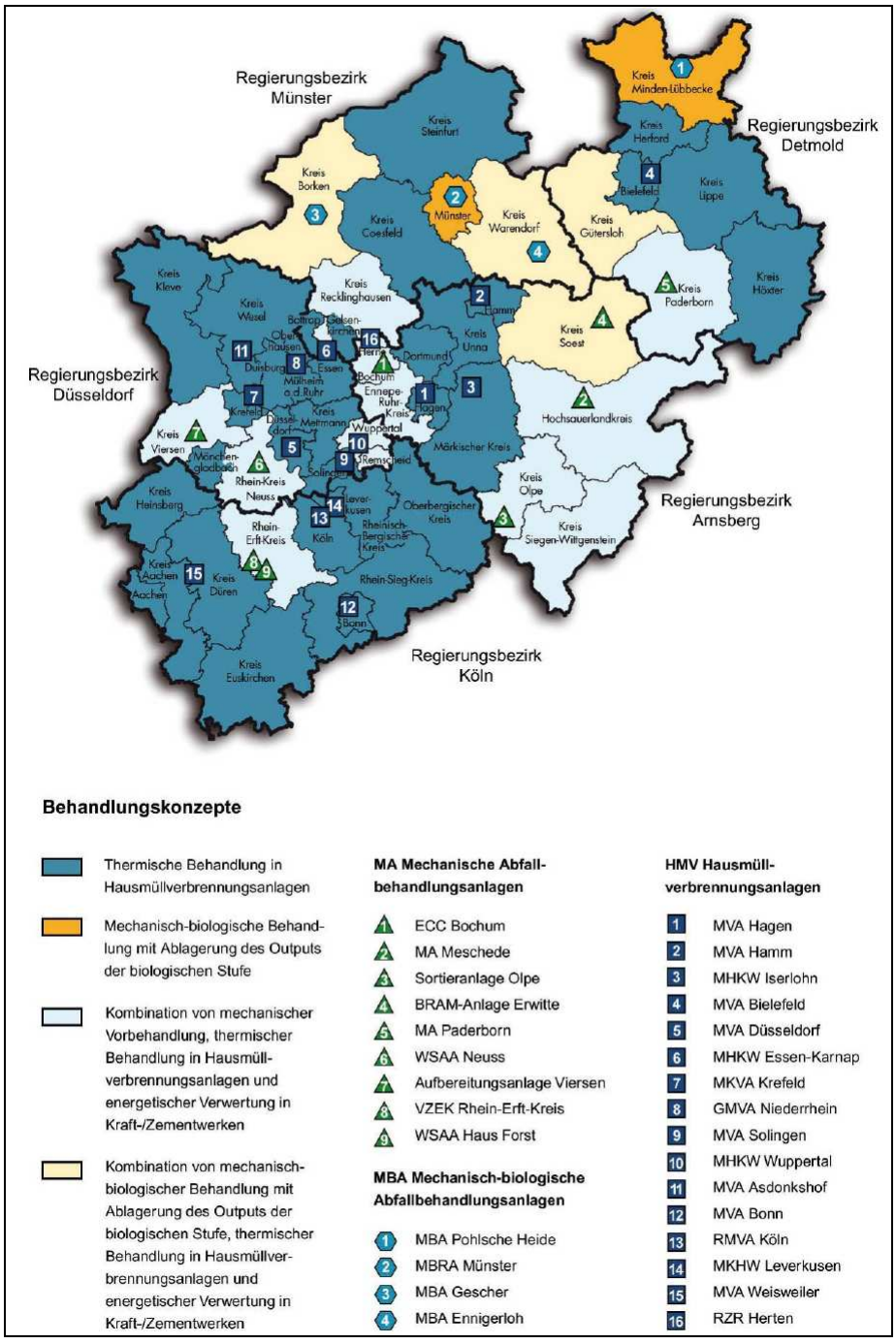


Figure 10-5 Waste management concept in NRW (MUNLV 2005b)

10.1.5 Waste management concept in NRW

According to the Waste Directive (Art 7, 75/442/EEC) and to its transposition into German national law (§29 KrW-AbfG), every administrative district is responsible to develop a waste management plan (WMP). This plan needs to be updated every five years. Similarly, public-law parties responsible of waste management prepare waste management concept (WMC), which provides *inter alia* the description of measures that have to be taken and planned for waste avoidance, recovery and disposal. Every WMC must take into account the requirements specified by the administrative district in their respective WMP.

The most important waste management driver in the development of these WMC is the diversion of residual municipal solid waste from landfills. Authorised landfills accept exclusively waste that has been previously treated in either mechanical-biological or thermal treatment facilities. As a result, the current waste management concepts, which must be followed by the public-law parties responsible of waste management, are the following ones (MUNLV 2005b):

- Complete thermal treatment in municipal solid waste incineration plants
- Complete mechanical-biological treatment with disposal in landfills of the secondary waste produced in the biological section
- Combination of mechanical pre-treatment, thermal treatment in municipal solid waste incineration plants and energy recovery in co-incineration plants (e.g. power and cement plants)
- Combination of mechanical-biological treatment with disposal of the secondary waste produced in the biological section, thermal treatment in municipal solid waste incineration plants and energy recovery in co-incineration plants (e.g. power and cement plants).

In Figure 10-5 can be observed that public-law parties responsible of waste management in NRW follows the "proximity principle" for the selection and use of their waste management operations. For example, districts and cities located near thermal treatment units base their WMC exclusively on this waste management operation. However, if there is as well other waste management operations such as mechanical treatment facilities, public-law parties responsible of waste management follow a combination approach and make use of them as well. Districts and cities located in the north of NRW are the only ones that use existing mechanical-biological treatment plants. The installed treatment capacity of this waste management operation is still so low that is not able to handle waste coming from other sources.

10.2 Proposed Sustainable Waste Management Concept for NRW

In this subchapter is given the proposed waste management concept for NRW. This concept is based on the requirements of EU and national waste legislation. Firstly, it is compared the current amount of generated waste against the installed recovery and disposal capacity. Recovery and disposal capacity deficits are outlined. Subsequently, a detailed primary and secondary waste flow distribution is given providing a comparison with the *status quo*. Both economical and environmental impacts are considered. The findings of this assessment provide the required information to identify required changes both to improve the sustainable performance of the system and to secure the recovery and disposal capacity of the system.

10.2.1 Current situation

As shown in Table 10-9, public-law parties responsible of waste management in NRW have the required disposal capacity for managing the residual municipal solid waste (Group I)

generated by its own districts and free district towns. The excess of disposal capacity is approximately 3,500 Gg/a. This value is excluding disposal in landfills. This excess of capacity could be used by the public-law parties responsible of waste management to manage other waste fractions such as commercial waste (Group IV). Likewise, there is an excess of recovery capacity for managing source segregated waste fractions that belong to Group III (segregated recyclable material) and Group V (other recyclable material). Exception exists for the management of mixed waste fraction. The recovery deficit of this waste fraction is 11.6 Gg/a. Additionally, there is a recovery deficit of ca. 360 Gg/a of segregated biowaste (Group II: biowaste and greenwaste). Public-law parties responsible of waste management can absorb these deficits with the existing disposal capacity surplus. After making use of this surplus, public-law parties responsible of waste management may have a buffer treatment capacity of ca. 2400 Gg/a.

Table 10-9 Waste management security in NRW (2004)

Nr.	Nordrhein-Westfalen Primary waste	Generation	Effective Installed Capacity	Variation	Comments
		Gg	Gg	Gg	
I	**Residual municipal solid waste (row 1 to 9, excl. 2 & 6)**	**4,405.07**	**7,884.80**	**3,479.73**	Addition of MRF(RDF) + MBT + THT
II	**Segregated biowaste (row 10 to 12)**	**1,840.80**	**1,482.11**	**-358.69**	
10	Biowaste (Biodegradable kitchen waste)	1,125.62	1,046.35	**-79.26**	For disposal in MBT-THT
11	Green waste (garden, parks and grave yards)	715.19	410.01	**-305.18**	
12	Waste from sewage cleaning	20.58	25.75	5.17	
III	**Segregated recyclable material (row 12 to 14)**	**2,215.73**	**3,970.00**	**1,754.27**	
12	Paper and cardboard	1,230.72	1,950.00	719.28	
13	Glass	425.00	1,080.00	655.00	
14	Lightweight packaging	560.01	940.00	379.99	
IV	**Commercial waste (row 2)**	**645.22**		**-645.22**	For disposal in MRF(RDF)-MBT-THT
V	**Other recyclable material (row 15 to 20, excl. 17)**	**192.04**	**14,888.00**	**14,695.96**	
15	Metals	46.88	13,430.00	13,383.12	
16	Waste Wood	79.89	1,210.00	1,130.11	
18	WEEE	40.81	230.00	189.19	For disposal MRF(RDF)-MBT-THT
19	Clothes and textiles	12.84	18.00	5.16	
20	Mixed fraction waste	11.63		**-11.63**	
VI	**Mineral construction waste (row 6)**	**359.66**	**7,610.00**	**7,250.34**	
VII	**Total (row 1 to 20, excl. 17)**	**9,658.52**	**35,834.91**		
	SECONDARY WASTE				
25	Secondary waste from mechanical treatment units	2,804.504	-	**-2,804.504**	For disposal in LFS
26	Secondary waste from thermal treatment units	665.773	-	**-665.773**	For disposal in LFS

Adapted from (MUNLV 2005)

In 2004, waste management operations in NRW generated around 3,500 Gg/a of secondary waste. Approximately 80% of this waste was generated by mechanical recycling facilities. In that year, secondary waste was mostly disposed in landfills (ca. 73%), followed by its disposal in incineration plants (ca. 8%) and in mechanical-biological treatment facilities (ca. 2%). However, with the implementation of stricter regulations on environmentally compatible disposal of waste starting in 01.06.2006, secondary waste could be disposed in a landfill only if it fulfils existing waste acceptance criteria in landfills. Contrary, it should be pre-treated either in a mechanical-biological or in a thermal treatment unit. The worst scenario will be when generated secondary waste does not fulfil the acceptance criteria in landfills. Under this scenario, public-law parties responsible of waste management in NRW do not have the required disposal capacity for handling this secondary waste. The treatment deficit would be around 1,000 Gg/a.

10.2.2 Material Flow Distribution

The implementation of stricter regulations related to the environmentally sound disposal of waste has a considerable impact on the waste management infrastructure of NRW.

The flow distribution of primary and secondary waste within the system is defined by the decision variables $\delta JXIj,x,i$ and $\delta KYSx,y$, respectively (for more information refer to chapter 3.4.1 of this document). These decision variables represent the percent of generated waste that

is transported from a waste generation point to a recovery/disposal facility. The terms *X* and *Y* define the waste management operations that are suitable to receive the generated primary and secondary waste, respectively. Similarly, the terms *x* and *y* are the individual treatment facilities that belong to the *X* or *Y* waste management operation. Consequently, the terms *x* and *y* are substituted by (*s ,c, a, d, m, t, l*). In this practical case of study there are considered 20 different primary waste fractions (*i*), generated by five administrative districts (*j*), which are either recovered or disposed in seven different types of waste management operations (*k*). Considered waste management operations include eight different types of "clean" mechanical recycling facilities (*s*), nine "dirty" mechanical recycling facilities (*c*), four different types of aerobic biological treatment facilities (*a*), five anaerobic biological treatment facilities (*d*), six mechanical-biological treatment facilities (*m*), 16 incineration plants (t) and 17 landfills (*l*). Every treatment facility is further assessed according to its installed choice of technology. Additionally, modelled waste management operations may generate eleven types of secondary waste (*si*). As a result, for this practical case of study there are more than 6,500 ($P(i,j,\Sigma(s,c,a,d,m,t,l))$) and 20,600 ($P(si,\Sigma(s,c,a,d,m,t),\Sigma(m,t,l))$) decision variables for the material flow distribution of primary and secondary waste, respectively. These variables ensure that the waste flow distribution is logistically optimised. Therefore, the model fulfils the proximity and self-sufficiency principles.

The effects of the implementation of stricter regulations related to the environmentally sound disposal of waste can be clearly seen in the results of the material flow distribution, as shown in Figure 10-6 and Figure 10-7. These figures represent total and individual flows of primary waste, respectively. In both figures are compared the *status quo* with the proposed waste management concept. In the one hand, the *status quo* indicates that in NRW, 48% of the total waste municipal solid waste was recovered. The remainder 52% was split up in disposal activities, from where incineration is the predominant one with 36% of the total waste generation. Mechanical-biological facilities treated only 4%, while landfill received the remainder 12%. On the other hand, the proposed waste management concept considers the implementation of the landfill ban, which allows only the disposal of pre-treated waste under certain criteria. As a result, this model determined the most efficient and cost-effective material flow distribution for the primary and secondary waste generated in NRW. The main differences between the *status quo* and the proposed waste management concept are the following ones:

- Untreated primary waste has been move away from landfills. Landfill diversion encourages the use of recovery waste management operations such as mechanical, biological, mechanical-biological and thermal treatment. Therefore, the proposed waste management concept is based on the combination of mechanical-biological treatment with disposal of the secondary waste produced in the biological section, thermal treatment in municipal solid waste incineration plants and energy recovery in co-incineration plants (e.g. power and cement plants).
- Mechanical recycling and biological treatment facilities do not present considerable variations in the acceptance of segregated waste fractions. This is attributed to the reason that they reduce environmental impacts from avoiding the ones associated to the use of the substituted resources. They reflect considerable energy savings due to the lower energy requirements in their recovery operations in comparison to those based on the transformation of raw resources. However, "dirty" mechanical recycling facilities and biological treatment facilities operate at its maximum recovery capacity, while "clean" mechanical recycling facilities have a considerable surplus of recovery capacity.
- Both incineration and mechanical-biological treatment plants absorb the amount of waste that was previously sent to landfills. Incineration plants could receive maximum

41% of the total waste municipal solid waste generated, while mechanical-biological treatment units could receive maximum 8%.

- Generated secondary waste represents approximately 20.5% (ca 2,000 Gg/a from 9,700 Gg/a) of the total generated municipal waste. According to its chemical composition, only 29% of the generated secondary waste could be disposed of while the remainder 71% could require further treatment in either mechanical-biological or incineration treatment plants. However, existing mechanical-biological treatment units are already saturated with generated primary waste. Thus, secondary waste that does not fulfil the landfill acceptance criteria should be sent to existing incineration plants.
- Generated tertiary waste or recyclable products consist of approximately 735 Gg/a of RDF and 840 Gg/a of stabilised organic material (e.g. compost). However, it is still required to define legally when a waste fraction ceases to be waste, so it can have better commercialisation opportunities in the recyclable market.

The proposed waste flow distribution fulfils the community's legislation on waste and the integrate product policy approach. Every recovery and disposal facility fulfils as well the overall objectives and targets of the EU and national waste legislation in terms of its choice of technology and installed capacity. As a result, the proposed material flow distribution is efficient and cost-effective. Additionally, the proposed waste flow distribution provides the following benefits:

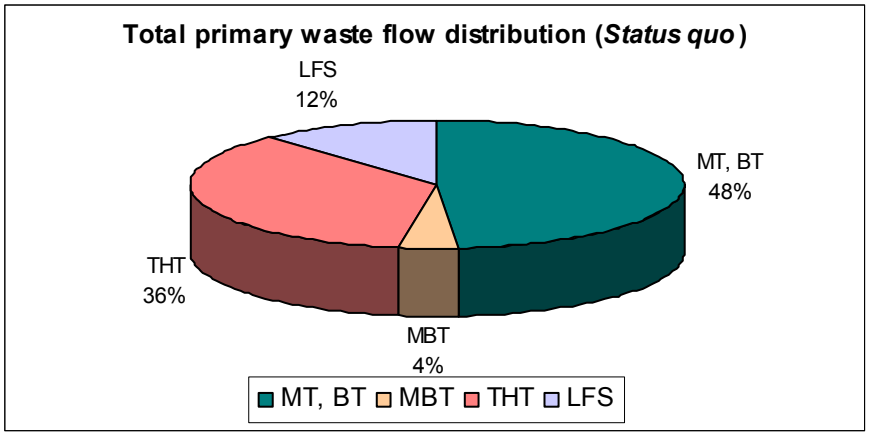
- It guarantees sustainable consumption and production patterns by minimising and avoiding the amount of secondary waste generated from the recovery and disposal waste management operations (prevention principle). This action determinates how resources are used and shifts to more sustainable production and consumption patterns.
- It ensures the most environmentally effective material flow distribution by minimising the amount of waste going to disposal and consequently the amount of generated fugitive emissions to air, water and land derived from its management through the complete life cycle of the product system. Additionally, it enhances the reuse of recovered material. This has the lowest impact to the environment and to the economy in comparison to its similar manufactured from virgin resources (substitution principle). This action avoids the generation of environmental impacts derived from the extraction of primary raw materials, its conversion to consumer products and from its final disposal (precautionary principle, life cycle thinking). In Figure 10-8 and Figure 10-9 are shown the environmental impacts derived from the proposed waste management concept. These two graphics consider the generation of both direct and displaced fugitive emissions. The environmental impact of the system are defined by environmental pressure indicators (GWP, AP, EP, TOFP, PFP, CRP, HTP, POCP and ADP)[56], which are plotted against existing waste management operations. In the one hand, Figure 10-8 represents the total environmental impact of the system in Gg-eq per year. In this figure, it can be observed that almost all the environmental pressure indicators have a higher environmental burden to the system than a environmental benefit. Only the CRP and ADP environmental pressure indicators provide a environmental benefit through the displacement of fugitive emissions. Incineration plants are the main disposal route and consequently the main source of fugitive emissions to the system (positive values). Mechanical and biological treatment facilities, specifically the "clean" mechanical recycling facilities and the aerobic

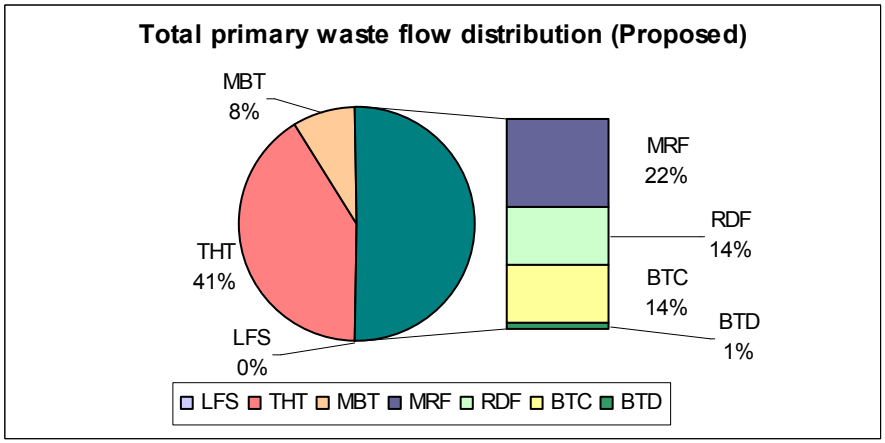
[56] The environmental pressure indicators are defined by the following abbreviations. GWP: Global Warming Potential, AP: Acidification Potential, EP: Euthrophication Potential, TOFP: Tropospheric Ozone Formation Potential, PFP: Particle formation potential, CRP: Carcinogenic Risk Potential, HTTP: Human Toxicity Potential, POCP: Photochemical Ozone Creation Potential, ADP: Abiotic Depletion Potential

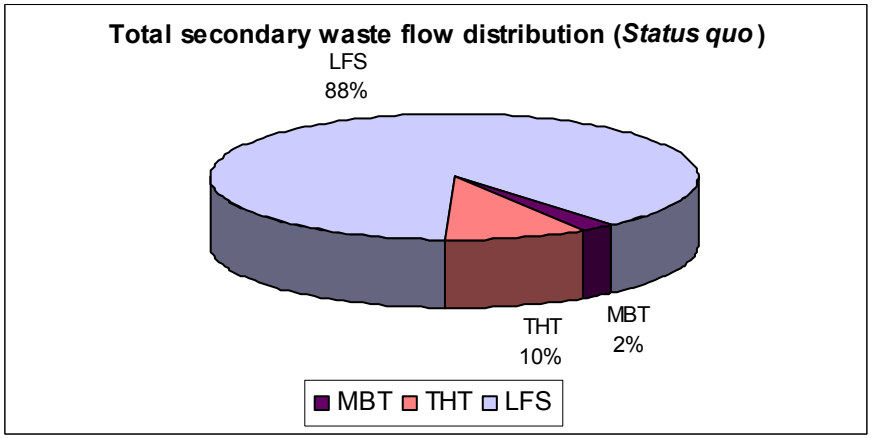
biological treatment facilities, are the main source of environmental benefit to the system due to displaced fugitive emissions (negative values). This statement is crosschecked with the total environmental impact of every waste management operation as shown in Figure 10-9. This figure plots separately every environmental pressure indicators from both direct and displaced fugitive emissions as a function of one kg of input waste. In these sub-figures can be observed that the principal environmental burden of the system is generated from incineration plants, while the environmental benefits come from both mechanical and biological treatment facilities. Finally, it can be concluded from previous figures that the management of waste in NRW is a burden to the environment.

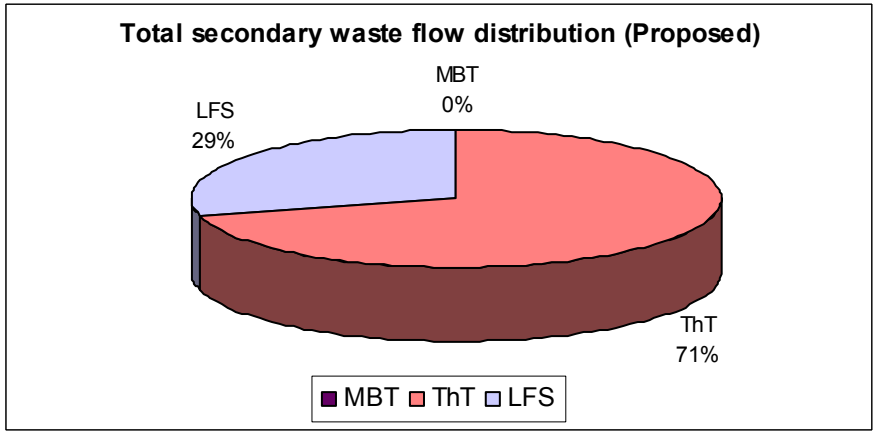
- It provides the most economically affordable waste distribution flow with the highest benefit derived from the recovery of resources and with the lowest recovery/disposal cost. It internalises external environmental costs (externalities) derived from the generation of direct and displaced fugitive emissions through the entire life cycle of the product system. Therefore, generated and displaced fugitive emissions pay the full cost of their impact (polluter pays principle, life cycle thinking). The economical performance of the system derived from the proposed waste flow distribution is shown in Figure 10-10. This figure plots the net social cost of the system as a function of its net private cost (e.g. labour and capital costs for operation and maintenance), environmental costs (e.g. direct and displaced environmental costs) and social saving costs (e.g. revenues). Additionally, this figure is divided in a) specific economical impacts and in b) total economical impacts. In the one hand, in Figure 10-10a are plotted the economical impact of every waste management operation as a function of one kg of input waste. In this figure is observable that MRF performs economically the best with a net social saving cost of 90 €/Mg. This facility is followed by the BTC, MBT, RDF and BTD, whose social saving costs are around 41 €/Mg, 23 €/Mg, 15 €/Mg and 8 €/Mg, respectively. Contrary, THT and LFS have the highest net social cost of 33 €/Mg and 89 €/Mg, respectively. On the other hand, in Figure 10-10b can be observed that the environmental cost (*ECk*) represents 21% of the net social costs. Similarly, the net private cost (e.g. disposal costs (*DCk*) and transportation costs (*TC*)) account to 30% of the net social cost. Both displaced environmental costs (*DECk*) and social saving costs (*REV*) represent together 49% of the net social costs, which are in reality a economical benefit to the system. As a result, the proposed waste flow distribution generates a net social costs equal to 50 M€ per year.
- It ensures the most socially acceptable concept with the highest social benefit. In the one hand, the material flow distribution reflects the preferences of the different stakeholders (public participation). On the other hand, the diversion of waste from landfills and consequently the increased levels of recovery and disposal promote more labour-intensive practices. Additionally, it catalyzes the generation and availability of more low-skills within the waste management system (social equity).
- It guarantees the most logistically optimised waste distribution flow with the shortest disposal routes between generation and treatment sources and the required number and location of the waste management operations (proximity and self-sufficiency).

Figure 10-6 Total waste flow distribution for a) *status quo* and b) proposed waste management concept









a) *Status Quo*

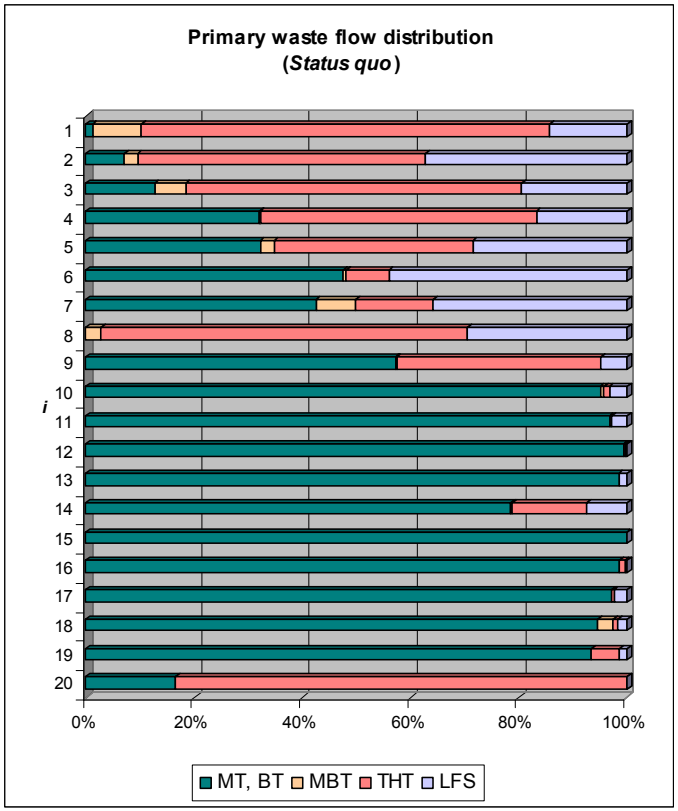
b) Proposed waste management concept

% numbers are given in weight fractions

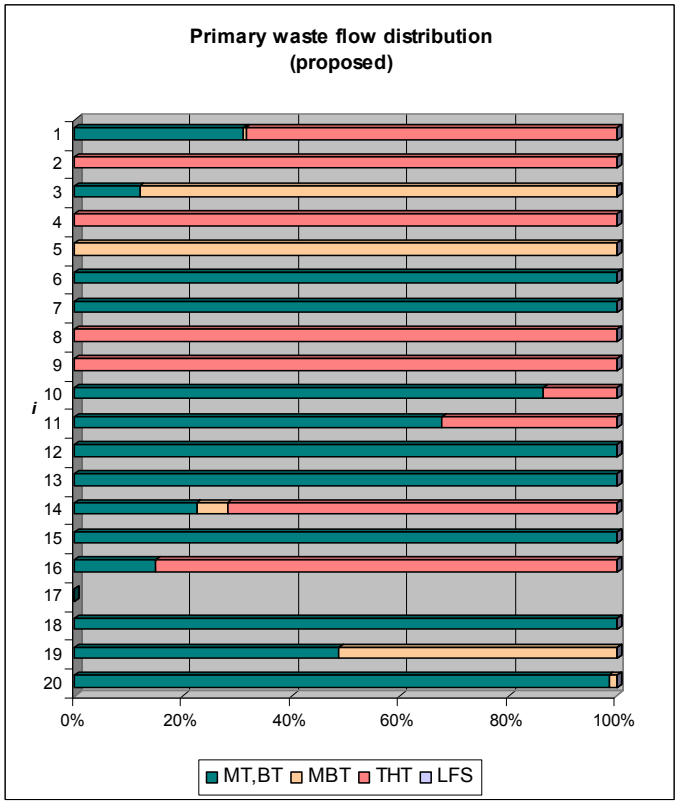
Total primary waste generation is equal to 9,658 Gg/a. Total secondary waste generation is equal to 2,863 Gg/a (*Status Quo*) and 1,766 Gg/a (Proposed). Source: (MUNLV 2005)

Abbreviations. MT: Mechanical Treatment, BT: Biological Treatment, MBT: Mechanical-Biological Treatment, THT: Thermal Treatment, LFS: Landfill Site, MRF: "clean" Mechanical recycling Facility, RDF: "dirty" Mechanical Recycling Facility, BTC: Aerobic Biological Treatment, BTD: Anaerobic Biological Treatment.

Figure 10-7 Specific primary waste flow distribution: a) *Status quo*, b) Proposed waste management concept



a) *Status Quo*

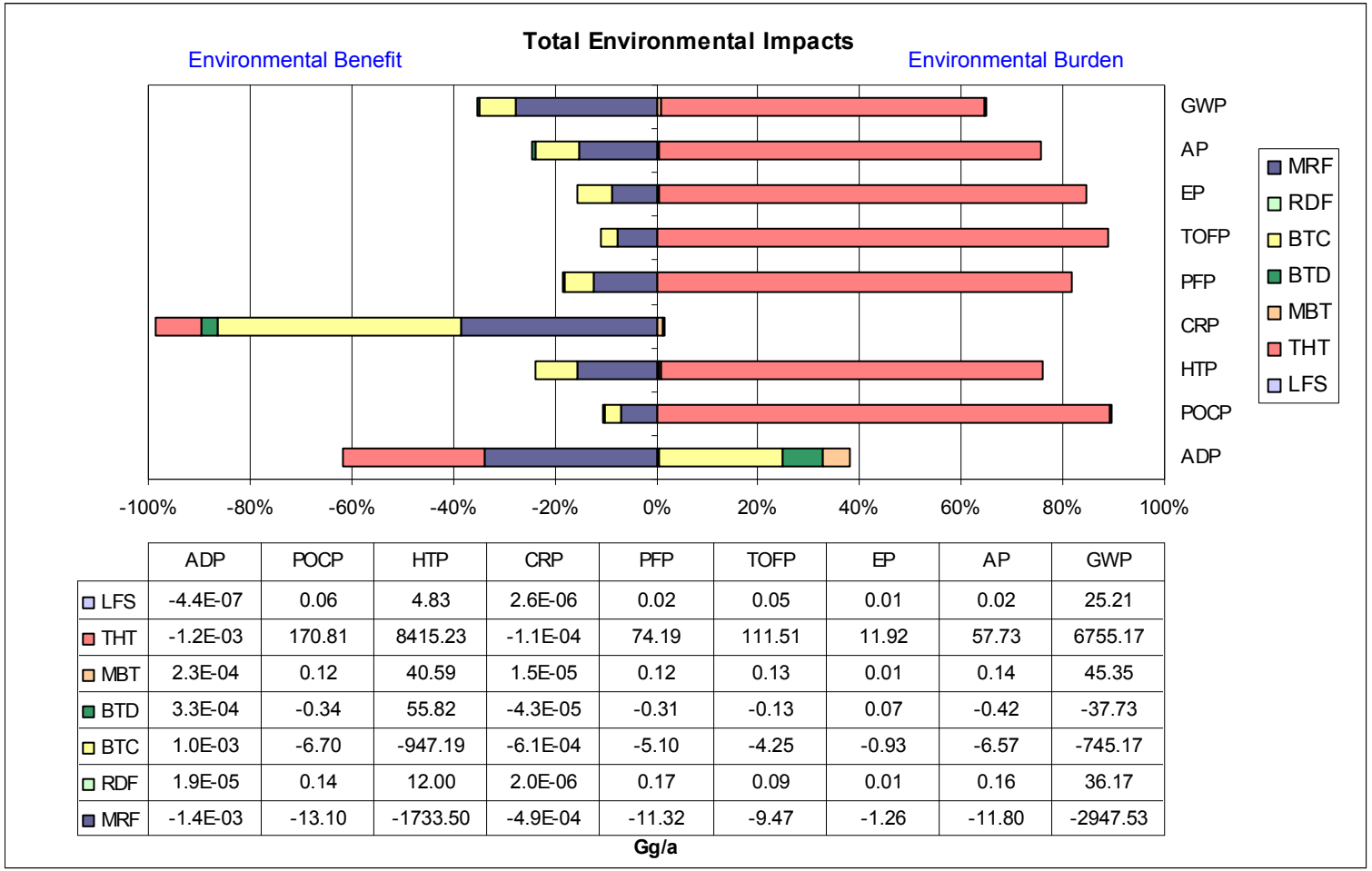


b) Proposed waste management concept

i	Primary waste category
1	Mixed municipal waste (Household waste)
2	Similar to h.w. commercial waste
3	Bulky refuse
4	Waste from markets
5	Street-sweeping waste
6	Mixed construction and demolition waste
7	Waste from sewage cleaning
8	No hazardous hospital residues
9	Household problematic waste
10	Biowaste (Biodegradable kitchen waste)
11	Green waste (garden, parks and grave yards)
12	Paper and cardboard
13	Glass
14	Lightweight packaging
15	Metals
16	Waste Wood
17	WEEE containing CFC
18	WEEE without CFC
19	Clothes and textiles
20	Mixed fraction waste

Where:
i = 1…20, (primary waste category as defined)
% numbers are given in weight fractions
MT: Mechanical Treatment, BT: Biological Treatment, MBT: Mechanical-Biological Treatment, THT: Thermal Treatment, LFS: Landfill Site

Figure 10-8 Environnemental Impacts (Gg/a)

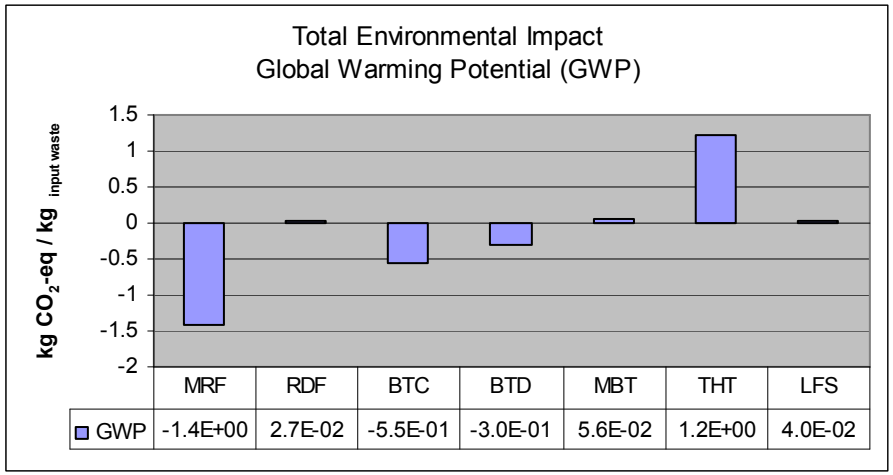


	ADP	POCP	HTP	CRP	PFP	TOFP	EP	AP	GWP
LFS	-4.4E-07	0.06	4.83	2.6E-06	0.02	0.05	0.01	0.02	25.21
THT	-1.2E-03	170.81	8415.23	-1.1E-04	74.19	111.51	11.92	57.73	6755.17
MBT	2.3E-04	0.12	40.59	1.5E-05	0.12	0.13	0.01	0.14	45.35
BTD	3.3E-04	-0.34	55.82	-4.3E-05	-0.31	-0.13	0.07	-0.42	-37.73
BTC	1.0E-03	-6.70	-947.19	-6.1E-04	-5.10	-4.25	-0.93	-6.57	-745.17
RDF	1.9E-05	0.14	12.00	2.0E-06	0.17	0.09	0.01	0.16	36.17
MRF	-1.4E-03	-13.10	-1733.50	-4.9E-04	-11.32	-9.47	-1.26	-11.80	-2947.53

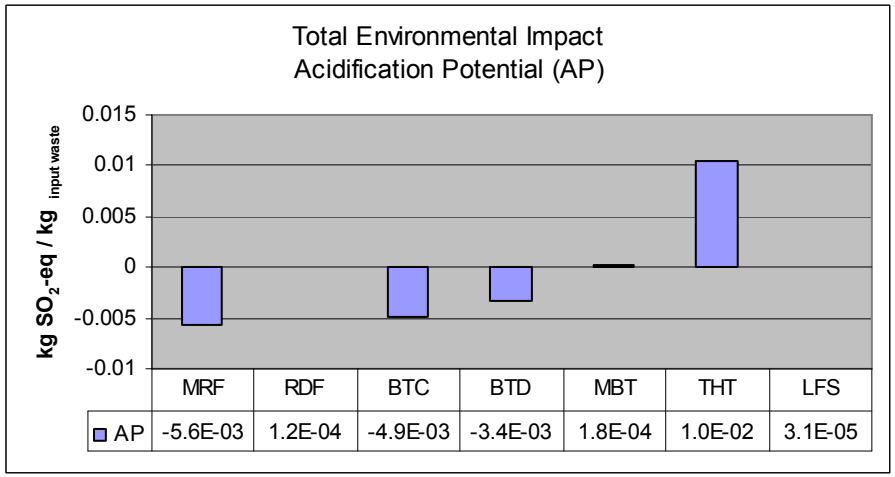
Gg/a

where:
GWP: Global Warming Potential, AP: Acidification Potential, EP: Euthrophication Potential, TOFP: Tropospheric Ozone Formation Potential, PFP: Particle formation potential, CRP: Carcinogenic Risk Potential, HTTP: Human Toxicity Potential, POCP: Photochemical Ozone Creation Potential, ADP: Abiotic Depletion Potential.
MT: Mechanical Treatment, BT: Biological Treatment, MBT: Mechanical-Biological Treatment, THT: Thermal Treatment, LFS: Landfill Site, MRF: "clean" Mechanical recycling Facility, RDF: "dirty" Mechanical Recycling Facility, BTC: Aerobic Biological Treatment, BTD: Anaerobic Biological Treatment

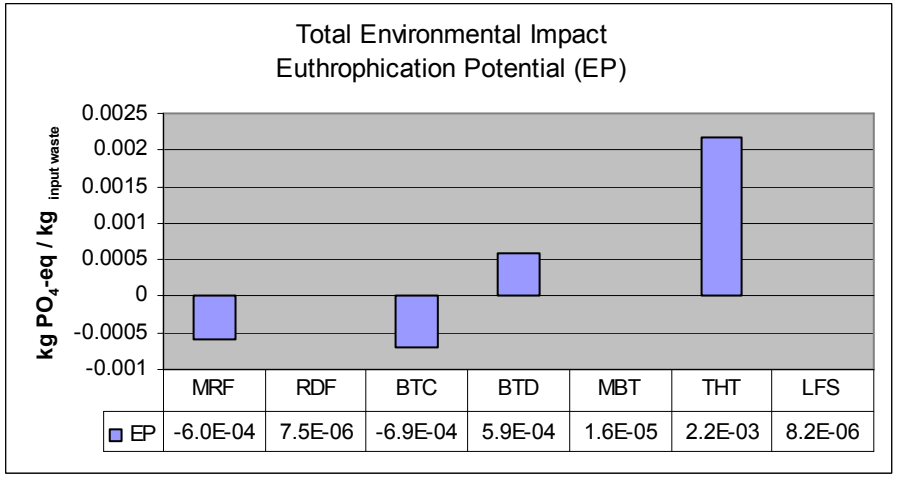
Figure 10-9 Environnemental Impacts (kg/kg)



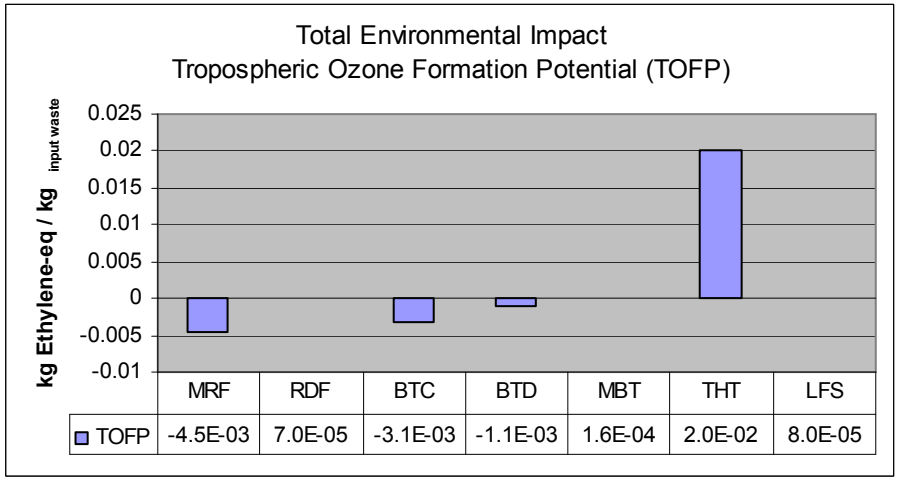
a) Global Warming Potential



b) Acidification Potential

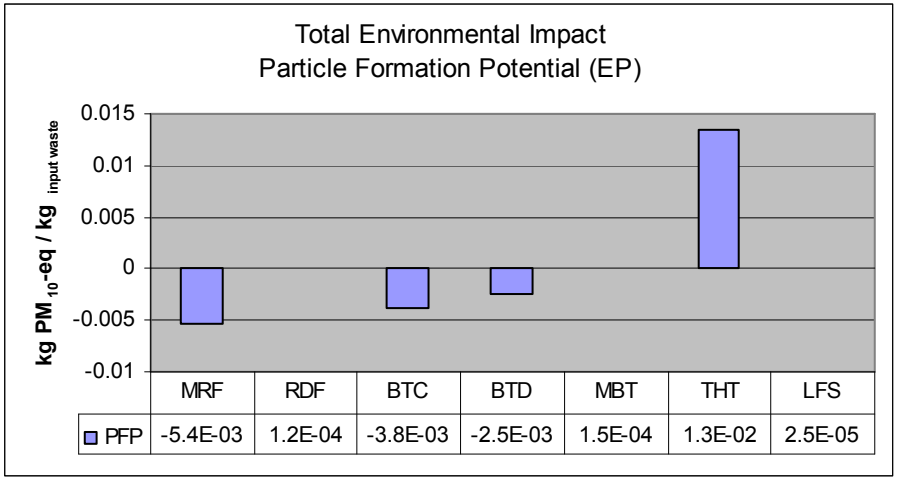


c) Euthrophication Potential

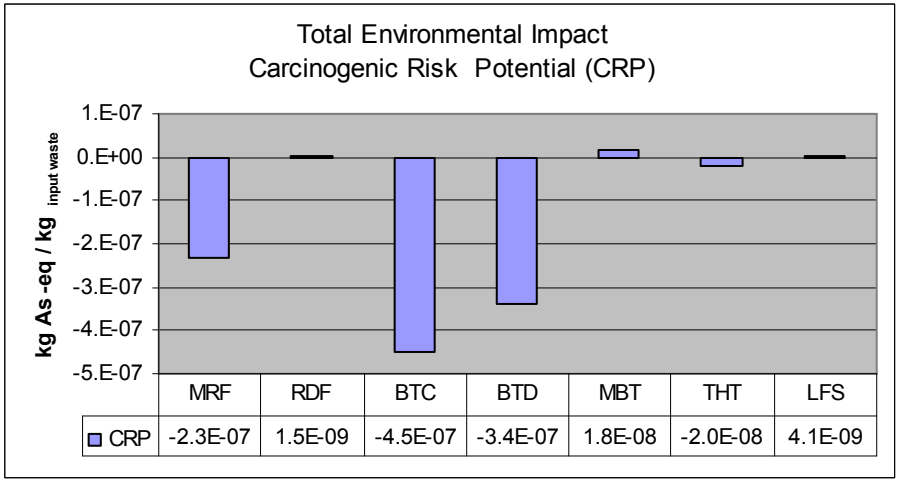


d) Tropospheric Ozone Formation Potential

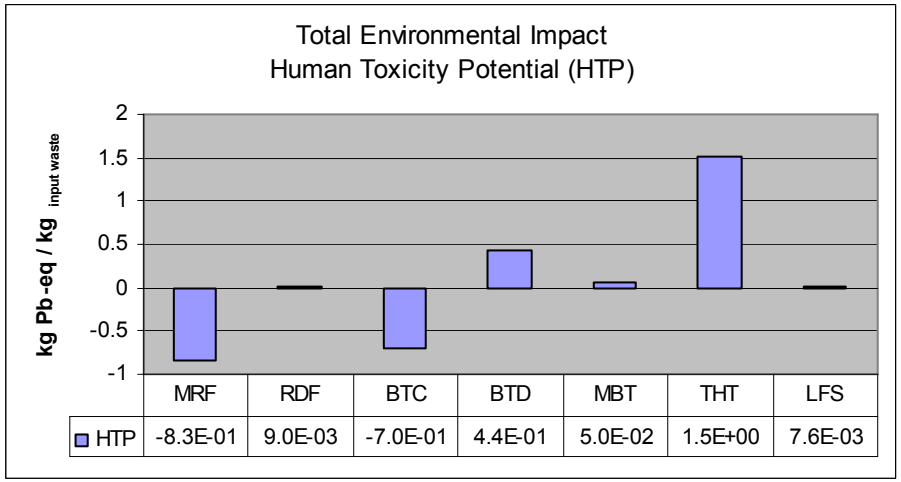
Continue…



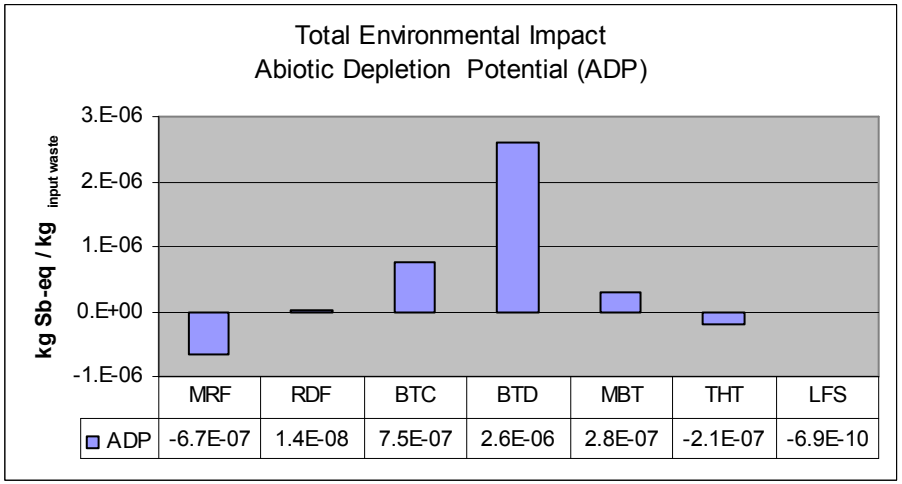
e) Particle Formation Potential



f) Carcinogenic Risk Potential

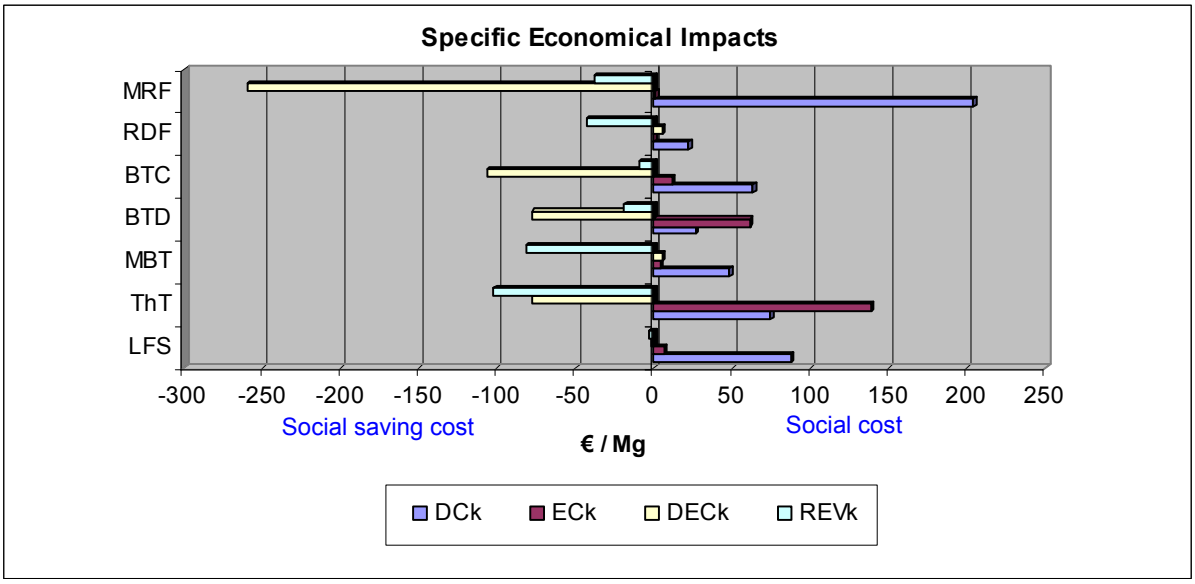


g) Human Toxicity Potential

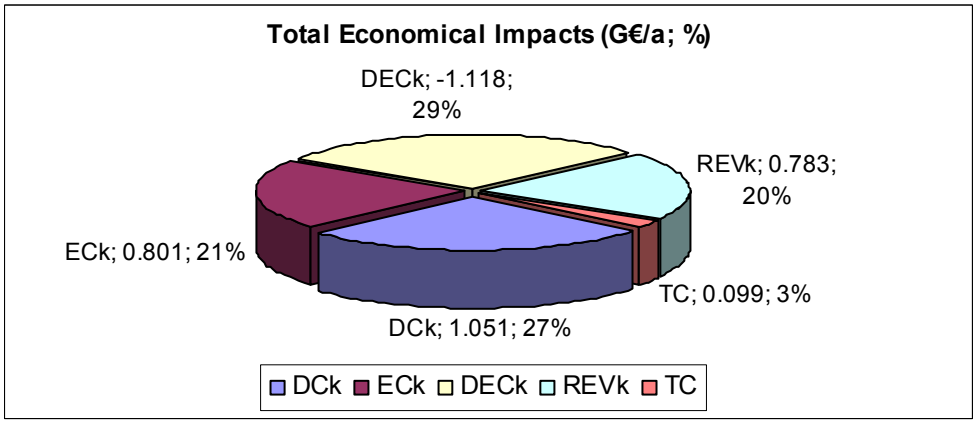


h) Abiotic Depletion Potential

Figure 10-10 Economical Impacts



a) Specific Economical Impacts, € / Mg



b) Total Economical Impacts, G€ / a, %

where:
DCk: Disposal Costs, ECk: Environmental Costs, DECk: Displaced Environmental Costs, REVk: Social saving Costs, TC: Transportation Costs

10.3 Sensitivity Analysis

A sensitivity analysis is carried out to validate the results of the model and to determinate the reliability and robustness of the indicator results. In the one hand, the results of the model are validated by comparing the calculated life cycle inventory of modelled waste management operations with the ones obtained from background and foreground sources. On the other hand, the reliability and robustness of the results is determined by the variations in the result due to changes in the variables values, characterisation models and life cycle inventories for recovered energy and resources (ISO 14042:2000). These changes are representative to the model when their deviation is higher than 25% (ISO 14043:2000).

The parameters that are evaluated in this sensitivity analysis are the following ones:

1. Life cycle inventory results of modelled waste management operations
2. Decision variables: $\delta JXI_{j,x,i}$ and $\delta XY_{x,y}$
3. Characterisation models: Life cycle impact assessment (LCIA)
4. Dissimilable organic carbon fraction (*DOCF*)

5. Life cycle inventory of MRF facilities
6. Life cycle inventory of displaced energy

The results of the sensitivity analysis are plotted in volume-high-low-close stock charts, as shown in Figure 10-11. These charts illustrate the value of the indicator as a vertical bar. The fluctuations or variations of every indicator are represented with a maximum-minimum range plotted as a vertical line. The average value derived from these fluctuations or variations are drawn within the maximum-minimum range as a point. This methodology is repeated in every sensitivity analysis.

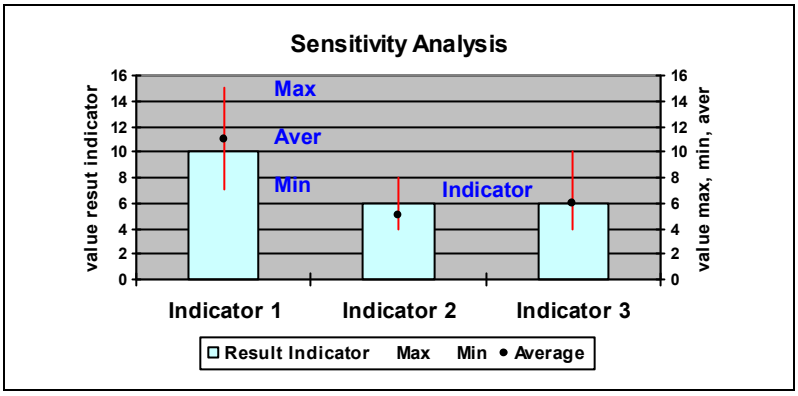


Figure 10-11 Sensitivity analysis stock chart example

10.3.1 Life cycle inventory results of modelled waste management operations

The results of the model are validated by comparing the calculated life cycle inventory of modelled waste management operations with already accepted and validated life cycle inventories. Selected life cycle inventories are taken from background and foreground sources/models such as Wisard, Umberto, Gemis, Ecoinvent, IWM2, LC-IWM, IPPC, IPCC, LUA, etc. Every waste management operation is represented by a sub-model and named as MRF, BTC, BTD, MBT, THT and LFS. The life cycle inventory of every waste management operation is calculated as a function of the input waste composition and its choice of technology. Waste-specific and process-specific equations are used for this purpose. However, only the mechanical recycling facility (MRF) submodel is calculated with process-specific equations. The transfer coefficients of this submodel were adapted from existing background sources, so their inventory is similar to those ones. Therefore, this sensitivity analysis is carried out for all waste management operation with exception of the MRF submodel. The results of the analysed waste management operations are plotted separately in stock charts as follows.

Biological Treatment Composting (BTC) submodel

The life cycle inventory of the BTC submodel depends mainly on the composition of the input waste and on the used choice of technology. Main fugitive emissions such as carbon dioxide, methane, nitrous oxide, nitrogen oxides and ammonia are calculated with waste-specific models, while trace gases such as non-methane volatile compounds, particular matter and heavy metals are calculated with process-specific models. The BTC´s life cycle inventory corresponds to a typical aerobic biological treatment plant, which operates as a non-reactor system with a rotting time of 12 weeks. The considered input waste is a biodegradable waste fraction with the following composition: 5.2% paper, 0.5% glass, 0.9%wood, 12.7% biowaste, 78.8% greenwaste and 1.9% mixed waste. With these parameters, the calculated life cycle inventory of the BTC submodel is shown in Figure 10-12. In this figure, it can be observed that the calculated life cycle inventory is within the maximum-minimum range of existing background and foreground sources. Only the calculated amount of HCl differs with

the compared inventories. This difference is attributed to possible variations in the chlorine content from the input waste.

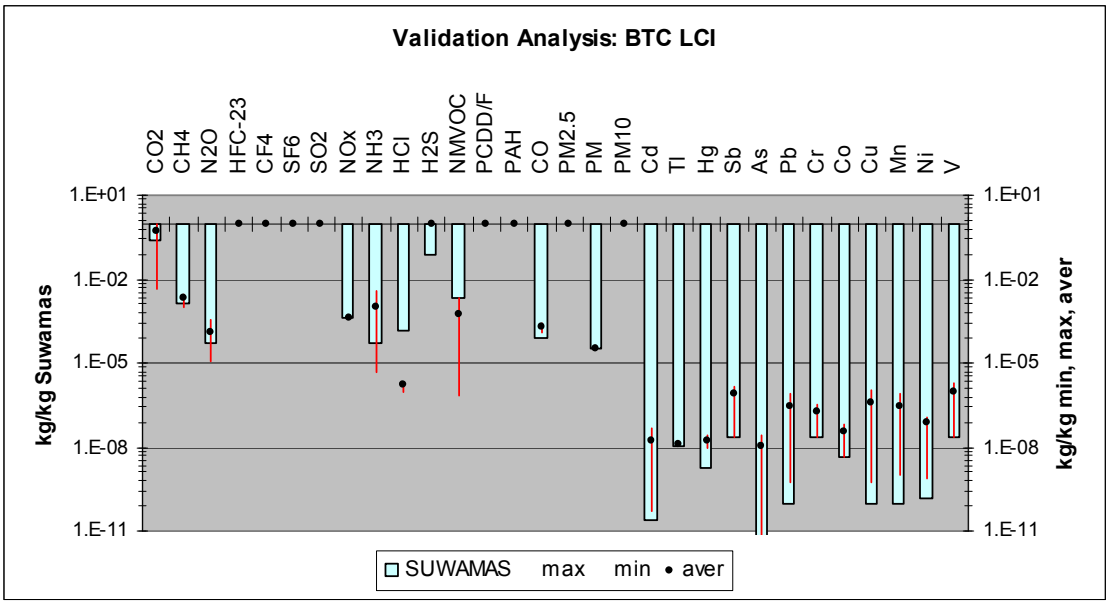


Figure 10-12 Life cycle inventory of the aerobic biological treatment submodel (BTC), kg/kg

Adapted and compared from: (IPPC 2005, Pitschke 2004, Coe 2004, Bjarnadottir 2002, Beck-Friss 2001, Bidlingaier 2000, MUNLV 1998, LCWM, IWM2, Wizard, OWARE, NPI, API-42)

Biological Treatment Digestion (BTD) submodel

The BTC submodel provides the life cycle inventory of an anaerobic biological treatment unit, which consist of both digestion and curing processes. Similarly, to the BTC submodel, the inventory of the BTD submodel depends on the composition of the input waste and the used choice of technology. The main components of the biogas and combusted biogas (e.g. CH_4, CO_2, NH_3, H_2S, SO_2 and HCl) are calculated with waste-specific equations, while trace gases such as volatile organic compound and heavy metals are calculated with process-specific equations. The calculated BTD´s life cycle inventory corresponds to a single stage, wet process operating under mesophilic conditions. There are no fugitive emissions of generated biogas. Energy is recovered from the biogas in a gas turbine. Generated digestate is aerobically cured for a period of 4 weeks in an enclosed-reactor system. Respiration gases are collected in a biofilter and emitted to the atmosphere. The biodegradable waste composition is the same as the one taken for the BTC submodel. With these parameters, the life cycle inventory of the BTD submodel is shown in Figure 10-13. The sensitivity analysis of this submodel shows that all parameters are within the maximum-minimum range. Only the amounts of NH_3 and HCl differ with existing models. In the one hand, existing models report no emission of NH_3, which is probably due to its difficult measurement. NH_3 is generated in both anaerobic and aerobic section. On the other hand, once again the emission of HCl differs to the ones reported. This difference is attributed to variations in selected waste input composition.

Mechanical-Biological Treatment (MBT) submodel

The life cycle inventory of the mechanical-biological treatment (MBT) submodel is calculated as a function of the input waste and choice of technology. In the mechanical section, it is assumed that there is no generation of fugitive emissions. Thus, fugitive emissions are generated in the biological treatment section. In this section is treated the fine fraction, which is segregated in the mechanical section. The biological treatment section corresponds to an enclosed reactor system with a rotting time of 12 weeks. Generated respiration gases are

collected and treated in a biofilter. This inventory considers the treatment of mixed municipal solid waste with the following composition: Fe-metal packages 1.2%, NFe-metal packages 0.5%, mixed metal 0.7%, waste paper 7.8%, glass 4.4%, waste textiles 2.8%, waste wood 1.2%, WEEE 0.8%, plastic packages 5.4%, polystyrene 0.1%, mixed plastic 1.4%, composite packages 2.0%, mixed composites 2.7%, biowaste 20.4%, green waste 2.0%, sewage sludge 0.0%, shoes 0.9%, vacuum cleaner dirt 0.6%, inert 2.5%, refurbishment waste 1.4%, hazardous waste 0.4%, leather 0.1%, rubber 0.2%, diapers & hygienic paper 14.5%, fine fraction 10.8%, middle fraction 14.2% and mixed waste 0.8%. With these parameters, the calculated life cycle inventory of the MBT submodel is shown in Figure 10-14. The calculated inventory is in accordance with existing background and foreground inventories. Only the calculated amount of hydrogen sulphide differs to the one reported by existing sources. However, only one source reports this emission so its reliability is uncertain.

Thermal Treatment (THT) submodel

The inventory of the thermal treatment (THT) submodel is calculated with both waste-specific and process-specific equation as a function of the input waste and its choice of technology. In this sensitivity analysis, it is considered as input waste a mixed municipal solid waste fraction. The composition of this waste fraction is the same as the one considered for the analysis of the MBT submodel. The choice of technology selected for this inventory consists of a typical grate incinerator with a flue gas treatment section (e.g. electrostatic precipitator, wet flue gas scrubber and a selective no catalytic reduction section). With these assumptions, the inventory of the THT submodel was calculated and plotted in Figure 10-15 . The calculated inventory is inline with the ones reported by background and foreground sources. Existing difference are related to the emission of particular matter ($PM_{2.5}$ and PM_{10}), thallium, chrome and vanadium. In the one hand, in this model particular matter is modelled as PM. Only one background source (Ecoinvent) reports it as $PM_{2.5}$ and PM_{10}. On the other hand, the calculated inventory present none emission for heavy metals such as thallium, chrome and vanadium. The reason is that the input waste fraction has no presence of these metals. Heavy metals are calculated with waste-specific equations, thus their emission is equal to zero.

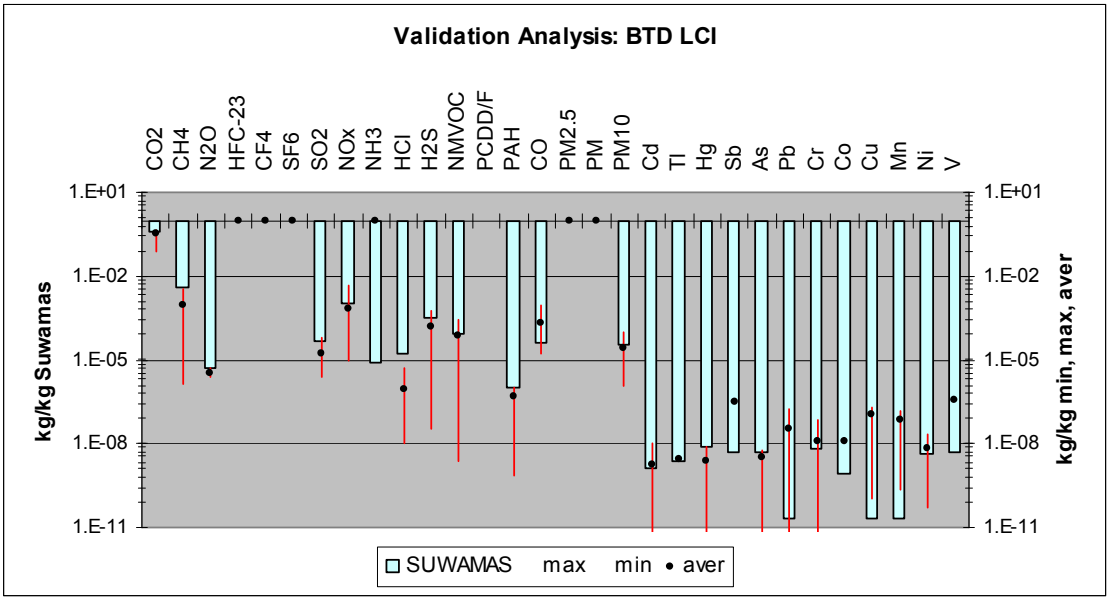


Figure 10-13 Life cycle inventory of the anaerobic biological treatment submodel (BTD), kg/kg

Adapted and compared from: (IPPC 2005, Pitschke 2004, Coe 2004, Hogg 2002, Bjarnadottir 2002, Ris 2002, Beck-Friis 2001, Bidlingmaier 2000, MUNLV 1998, LCIWM, NPI, AP-42, IWM2, Wizard)

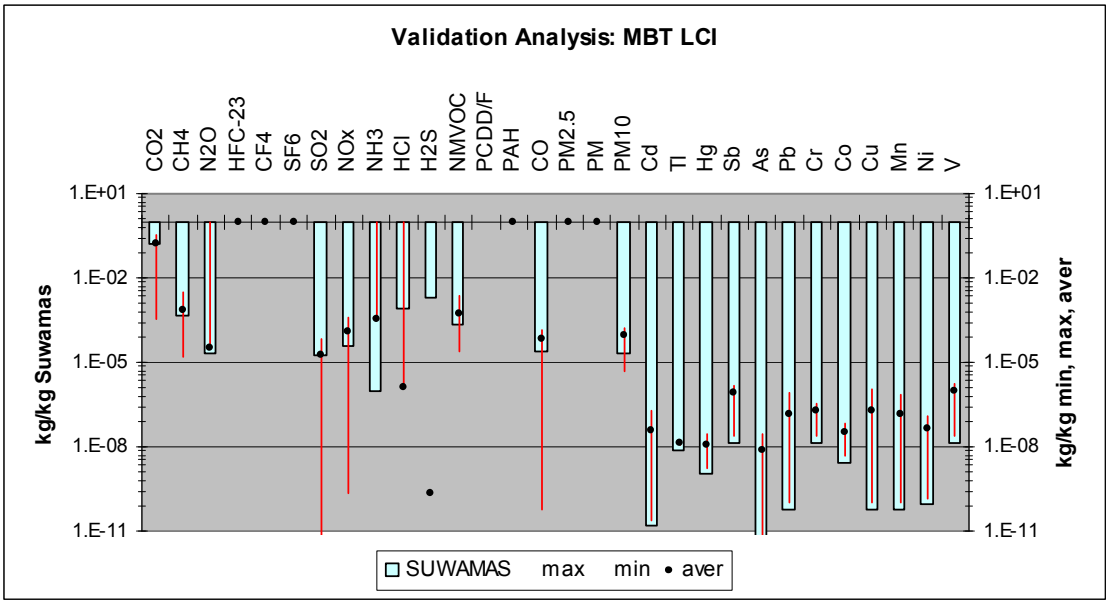


Figure 10-14 Life cycle inventory of the mechanical-biological treatment submodel (MBT), kg/kg

Adapted and compared from: (IPPC 2005, Coe 2004, Pitschke 2004, Greenpeace 2003, Soyez 2002, Beck-Friis 2001, MUNLV 1998, Hauesler 1999, Hauesler 1998, Angerer 1992, LCIWM, Wizard)

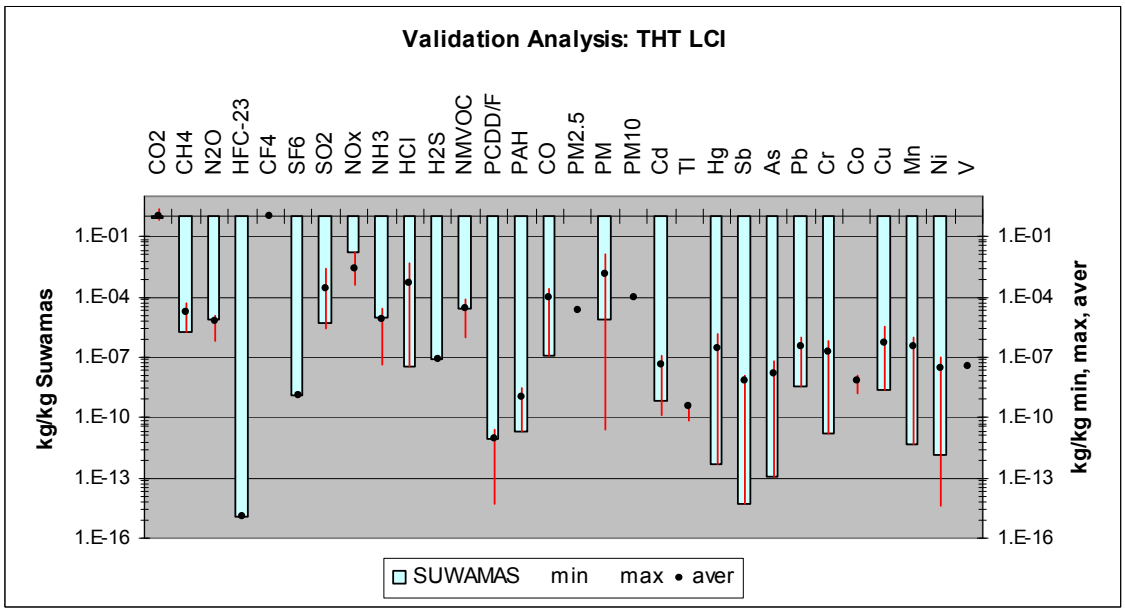


Figure 10-15 Life cycle inventory of the thermal treatment submodel (THT), kg/kg

Adapted and compared from: (IPPC 2005, Belevi 2005, Pitschke 2004, Doka 2003, LUA-NRW 2001, UBA 2000, IPPC 2000, Angened 1990, LCIWM, Ecoinvent, Gemis, IWM2, NPI, API-42)

Landfill Site (LFS) submodel

The inventory of the landfill site (LFS) submodel is as well calculated as a function of the input waste and the choice of technology. For this sensitivity analysis, it is considered the disposal of a mixed municipal solid waste fraction, whose composition is the same one as the one used in both MBT and THT submodels. As a choice of technology is considered a well-managed landfill site categorised as LCII. It is assumed that 75% of the generated landfill gas is collected and combusted in a gas turbine for energy recovery. The remainder 25% is emitted to the atmosphere. It is assumed as well that 10% of the no collected landfill gas is oxidised in the covering cap. With these assumptions, the inventory of the LFS submodel is

shown in Figure 10-16. In this figure it can be observed that the calculated inventory aggress completely with the ones provided by other background and foreground sources.

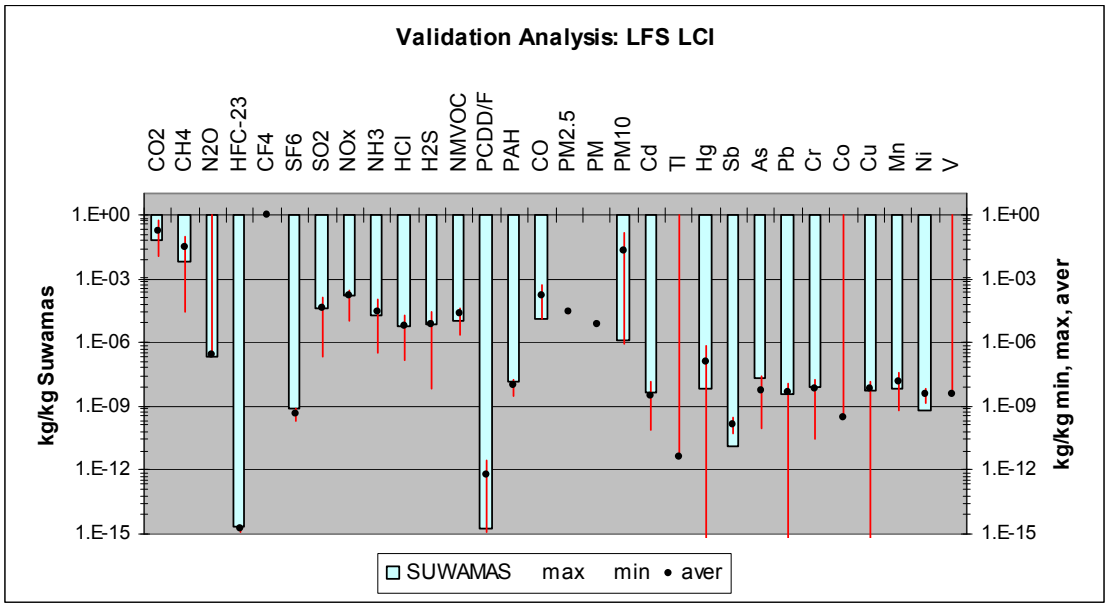
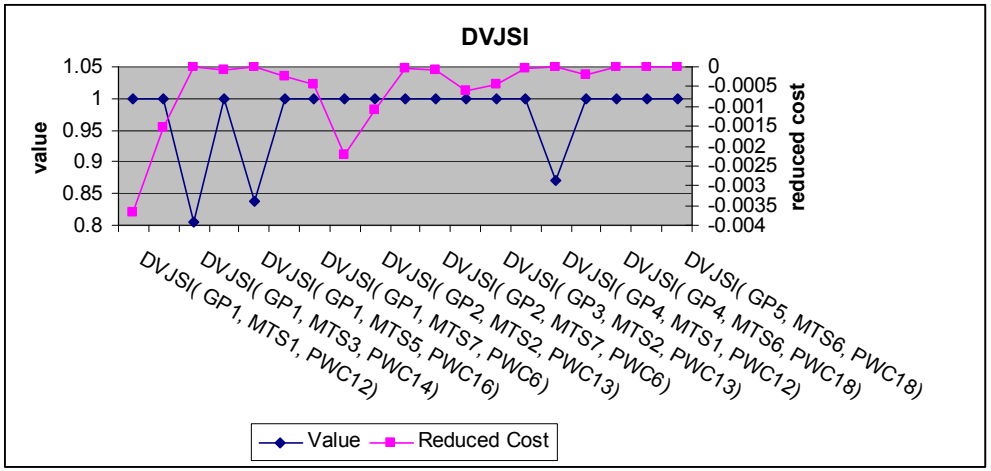


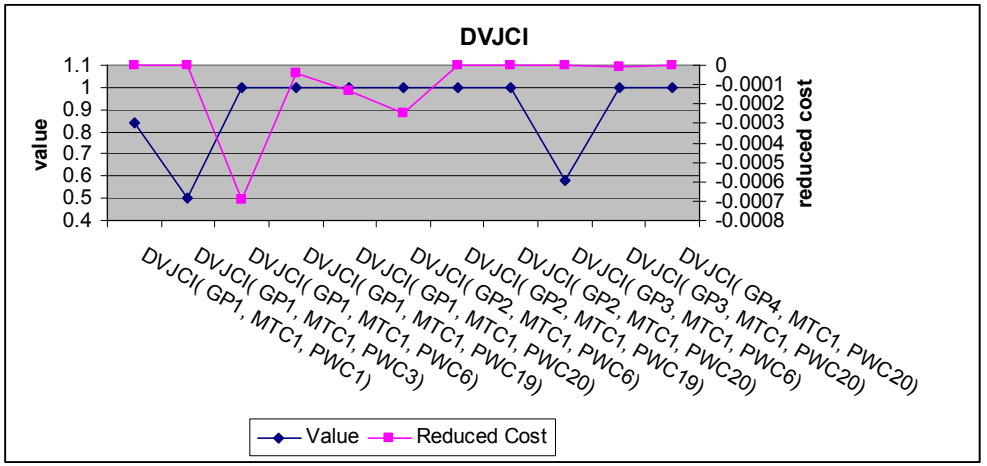
Figure 10-16 Life cycle inventory of the landfill site submodel (LFS), kg/kg

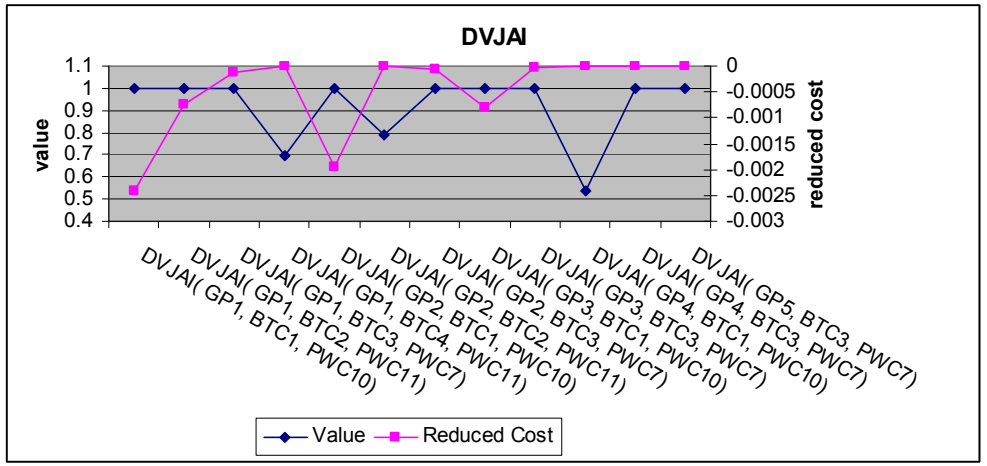
Adapted and compared from: (UBA 2000, Pitschke 2004, Doka 2003, LCIWM, Ecoinvent, Gemis, Wizard, NPI, API-42)

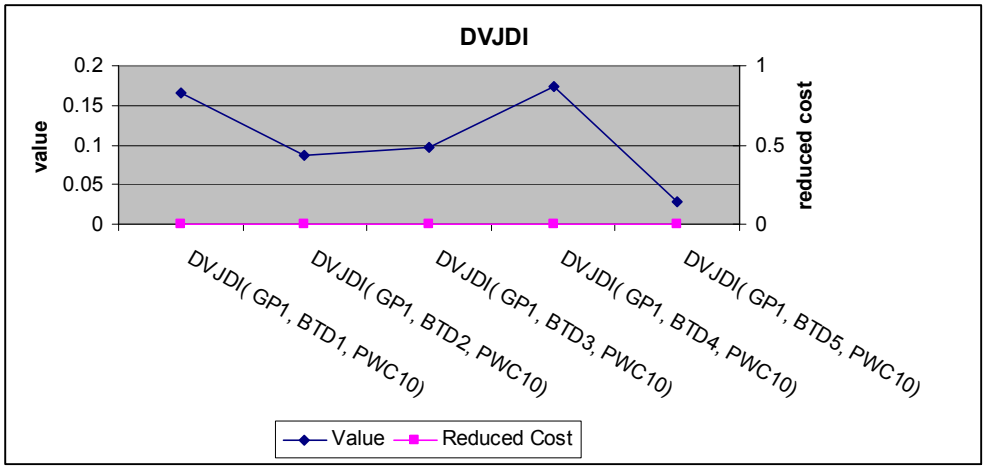
10.3.2 Decision variables values: $\delta IXI_{j,x,i}$ and $\delta XY_{x,y}$

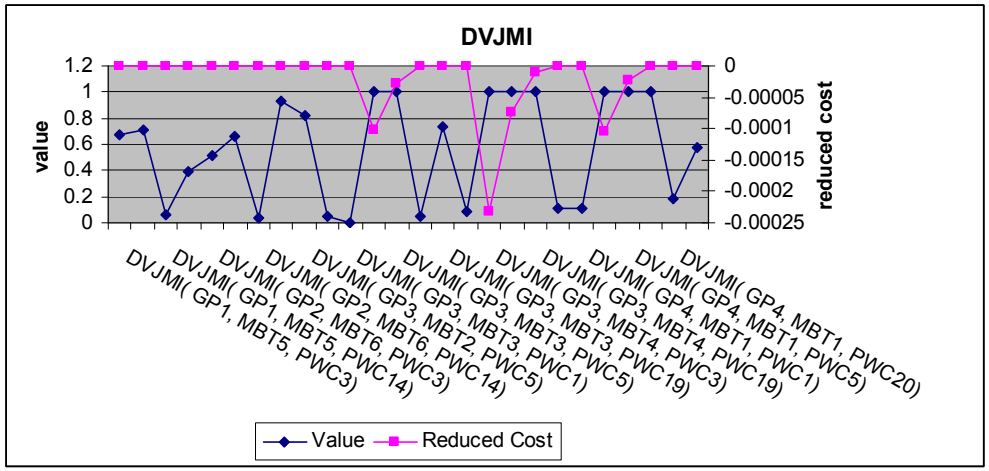
The decision variables are the most important variables within the model because they define the optimal material flow distribution of primary and secondary waste. They influence directly the indicator results derived from the optimisation of the objective function. The material flow distribution is defined by the set of decision variables $\delta IXI_{j,x,i}$ and $\delta XY_{x,y}$. The first one corresponds to distribution flow of primary waste, while the second one defines the material flow of secondary waste. The sensitivity of these variables is assessed with their respective reduced cost. The reduced cost for any variable that belongs to the optimal solution is always equal to zero. For variables that are not included in the optimal solution, the reduced cost determinates quantitatively how much the value of the objective function would increase (minimisation problem) if one unit of the variable is added to the solution. Therefore, Figure 10-17 shows the reduced cost of the decision variables responsible for the flow distribution of both primary and secondary waste. There is one figure per waste management operation for better description. Additionally, in these figures there are plotted only the non-zero decision variables. In the one hand, the reduced cost of the decision variables corresponding to primary waste tell us that waste sent to the anaerobic biological (BTD) and incineration (THT) facilities are optimal values. Their reduced costs are equal to zero. Contrary to the other waste management operations (MRF, RDF, BTC and MBT) , whose reduced costs have an average value of -9.624E-05 and a standard deviation of 4.14E-04. Decision variables are defined between the range of zero and one, and a change of these decision variable do not represent an impact to the result. On the other, the reduced costs of the secondary decision variables are equal to zero. Thus, these variables are optimal ones.

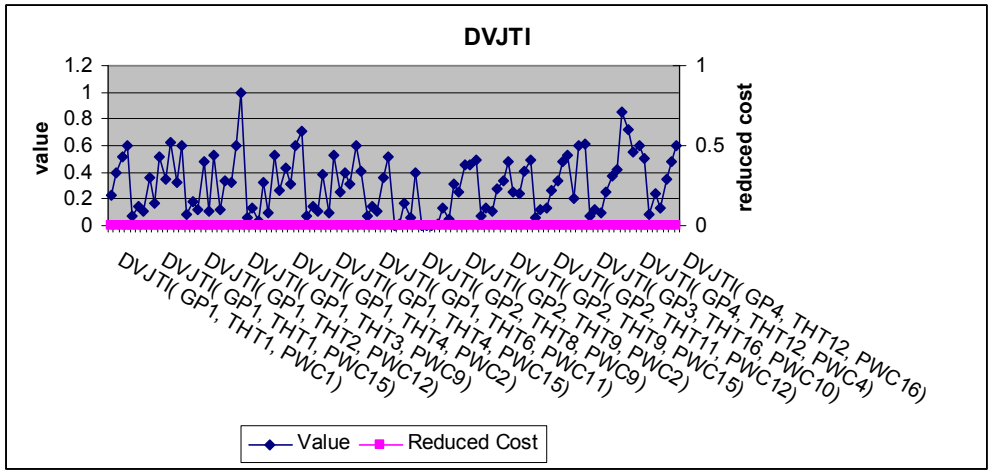

DVJSI
value
reduced cost
1.05
1
0.95
0.9
0.85
0.8
0
-0.0005
-0.001
-0.0015
-0.002
-0.0025
-0.003
-0.0035
-0.004
DVJSI(GP1, MTS1, PWC12)
DVJSI(GP1, MTS3, PWC14)
DVJSI(GP1, MTS5, PWC16)
DVJSI(GP1, MTS7, PWC6)
DVJSI(GP2, MTS2, PWC13)
DVJSI(GP2, MTS7, PWC6)
DVJSI(GP3, MTS2, PWC13)
DVJSI(GP4, MTS1, PWC12)
DVJSI(GP4, MTS6, PWC18)
DVJSI(GP5, MTS6, PWC18)
Value
Reduced Cost

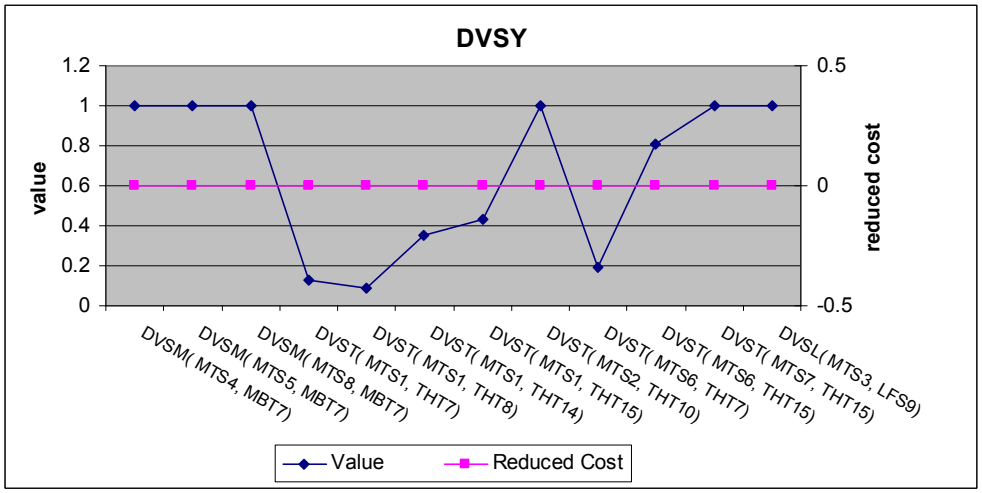

DVJCI
value
reduced cost
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
-0.0001
-0.0002
-0.0003
-0.0004
-0.0005
-0.0006
-0.0007
-0.0008
DVJCI(GP1, MTC1, PWC1)
DVJCI(GP1, MTC1, PWC3)
DVJCI(GP1, MTC1, PWC6)
DVJCI(GP1, MTC1, PWC19)
DVJCI(GP1, MTC1, PWC20)
DVJCI(GP2, MTC1, PWC6)
DVJCI(GP2, MTC1, PWC19)
DVJCI(GP2, MTC1, PWC20)
DVJCI(GP3, MTC1, PWC6)
DVJCI(GP3, MTC1, PWC20)
DVJCI(GP4, MTC1, PWC20)
Value
Reduced Cost

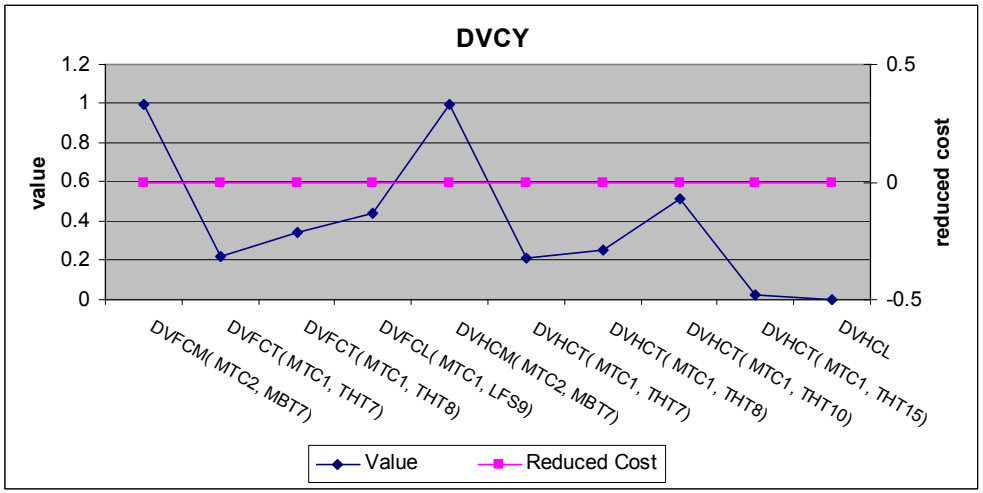

DVJAI
value
reduced cost
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
-0.0005
-0.001
-0.0015
-0.002
-0.0025
-0.003
DVJAI(GP1, BTC1, PWC10)
DVJAI(GP1, BTC2, PWC11)
DVJAI(GP1, BTC3, PWC7)
DVJAI(GP1, BTC4, PWC11)
DVJAI(GP2, BTC1, PWC10)
DVJAI(GP2, BTC2, PWC11)
DVJAI(GP2, BTC3, PWC7)
DVJAI(GP3, BTC1, PWC10)
DVJAI(GP3, BTC3, PWC7)
DVJAI(GP4, BTC1, PWC10)
DVJAI(GP4, BTC3, PWC7)
DVJAI(GP5, BTC3, PWC7)
Value
Reduced Cost


DVJDI
value
reduced cost
0.2
0.15
0.1
0.05
0
1
0.5
0
DVJDI(GP1, BTD1, PWC10)
DVJDI(GP1, BTD2, PWC10)
DVJDI(GP1, BTD3, PWC10)
DVJDI(GP1, BTD4, PWC10)
DVJDI(GP1, BTD5, PWC10)
Value
Reduced Cost


DVJMI
value
reduced cost
1.2
1
0.8
0.6
0.4
0.2
0
0
-0.00005
-0.0001
-0.00015
-0.0002
-0.00025
DVJMI(GP1, MBT5, PWC3)
DVJMI(GP1, MBT5, PWC14)
DVJMI(GP2, MBT6, PWC3)
DVJMI(GP2, MBT6, PWC14)
DVJMI(GP3, MBT2, PWC5)
DVJMI(GP3, MBT3, PWC1)
DVJMI(GP3, MBT3, PWC5)
DVJMI(GP3, MBT4, PWC19)
DVJMI(GP4, MBT1, PWC3)
DVJMI(GP4, MBT1, PWC19)
DVJMI(GP4, MBT1, PWC5)
DVJMI(GP4, MBT1, PWC20)
Value
Reduced Cost


DVJTI
value
reduced cost
1.2
1
0.8
0.6
0.4
0.2
0
1
0.5
0
DVJTI(GP1, THT1, PWC1)
DVJTI(GP1, THT1, PWC15)
DVJTI(GP1, THT2, PWC12)
DVJTI(GP1, THT3, PWC9)
DVJTI(GP1, THT4, PWC2)
DVJTI(GP1, THT6, PWC15)
DVJTI(GP2, THT8, PWC11)
DVJTI(GP2, THT9, PWC9)
DVJTI(GP2, THT9, PWC2)
DVJTI(GP3, THT11, PWC15)
DVJTI(GP4, THT16, PWC12)
DVJTI(GP4, THT12, PWC10)
DVJTI(GP4, THT12, PWC4)
DVJTI(GP4, THT12, PWC16)
Value
Reduced Cost


DVSY
value
reduced cost
1.2
1
0.8
0.6
0.4
0.2
0
0.5
0
-0.5
DVSM(MTS4, MBT7)
DVSM(MTS5, MBT7)
DVSM(MTS8, MBT7)
DVST(MTS1, THT7)
DVST(MTS1, THT8)
DVST(MTS1, THT14)
DVST(MTS1, THT15)
DVST(MTS2, THT10)
DVST(MTS6, THT7)
DVST(MTS6, THT15)
DVST(MTS7, THT15)
DVSL(MTS3, LFS9)
Value
Reduced Cost


DVCY
value
reduced cost
1.2
1
0.8
0.6
0.4
0.2
0
0.5
0
-0.5
DVFCM(MTC2, MBT7)
DVFCT(MTC1, THT7)
DVFCT(MTC1, THT8)
DVFCL(MTC1, LFS9)
DVHCM(MTC2, MBT7)
DVHCT(MTC1, THT7)
DVHCT(MTC1, THT8)
DVHCT(MTC1, THT10)
DVHCL
DVHCT(MTC1, THT15)
Value
Reduced Cost

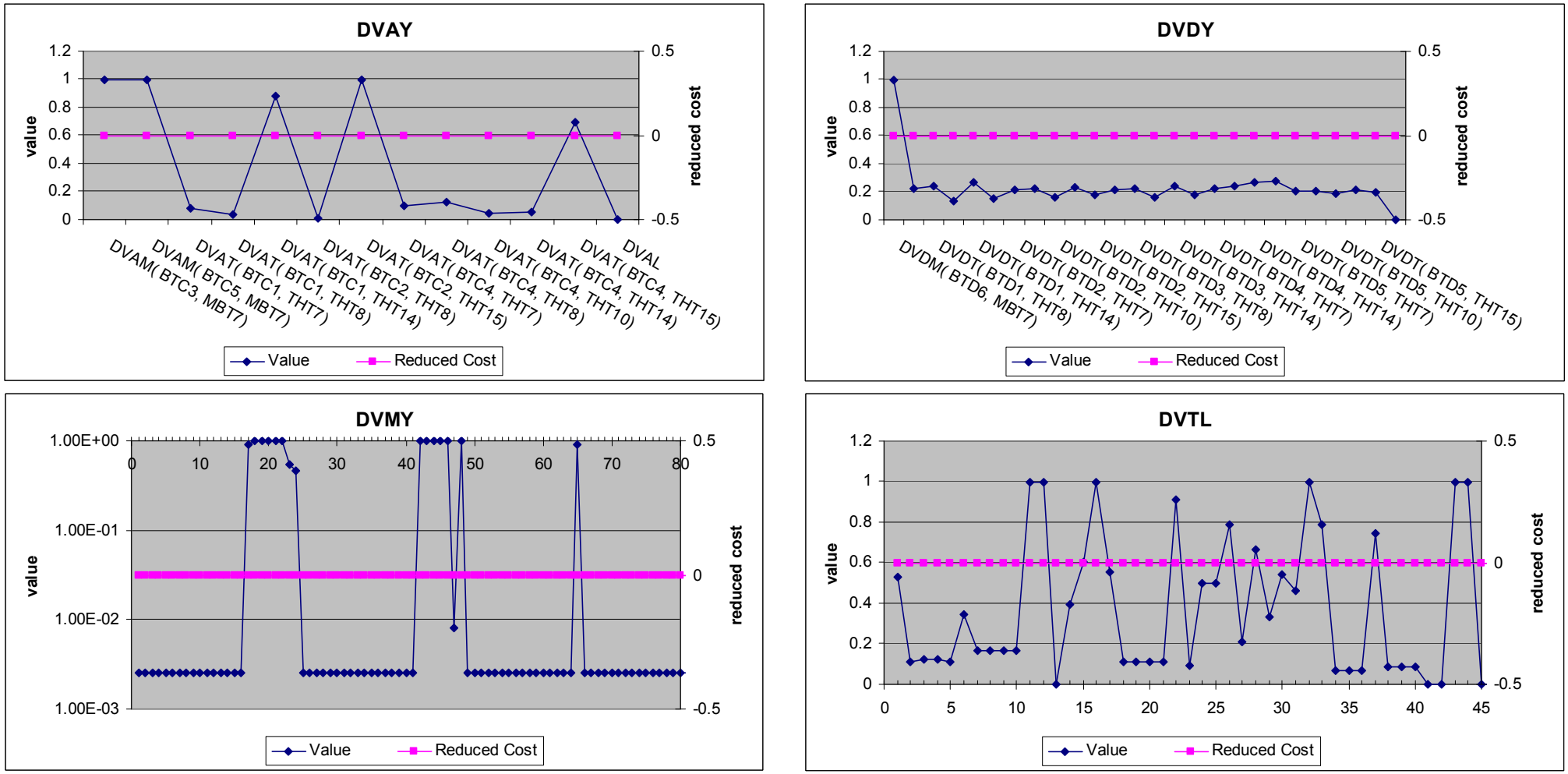


Figure 10-17 Sensitivity Analysis: decision variables

10.3.3 Characterisation models: Life cycle impact assessment (LCIA)

The model assesses per default the life cycle inventory of the waste management system with the characterisation method named environmental priority strategies in product development (EPS-2000). As sensitivity analysis, the model is evaluated considering the minimisation of the net social cost (objective function) with the use of other characterisation models. This determinates the influence of the characterisation model on the indicator result. Selected characterisation methods include:

1. Environmental Priority Strategy (EPS-2000)
2. Cost benefit analysis in the clean air for Europe (CAFE) programme
3. BeTa 1: rural
4. BeTa 2: urban
5. ExternE
6. New ExternE

In Figure 10-18 are plotted the parameter of the objective function as a function of the characterisation models. Error lines are horizontally plotted in the max-min line considering ± 25% error from the average value. In this figure is clearly observed that changes on the characterisation model mainly affects the environmental cost indicator (*EC*). The variation of this indicator between its default and average value is of 58%. The disposal cost (*DC*), transportation cost (*TC*), displaced environmental cost (*DEC*) and revenue (*REV*) indicators are minimally influenced due to variations on the characterisation model. The variations of these indicators are between 0.3 and 10%. However, the variation of the economical cost indicator is significantly reflected on the objective function (*OF*), whose final variation value is of 112%.

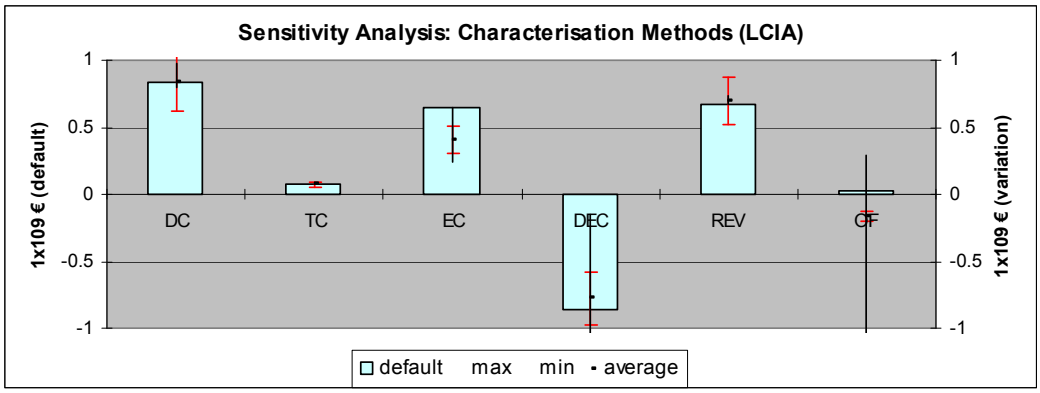


Figure 10-18 Sensitivity Analysis: characterisation methods

10.3.4 Dissimilable Organic Carbon Fraction (*DOCF*)

The dissimilable organic carbon fraction (*DOCF*) is the estimated carbon fraction that is ultimately degraded. The model assumes that the *DOCF* value is related to the choice of biological treatment and it applies similarly to all degradable waste categories. Aerobic biological facilities have assigned *DOCF* values as defined by Equation 5-8. This equation is subject to the degradation time. On the other hand, under anaerobic conditions the *DOCF* is defined by Equation 6-7, which is related to the operational temperature of the system. Affected waste management operations include aerobic biological, anaerobic biological, mechanical-biological and landfill. As sensitivity analysis, the model assesses the system considering the *DOCF* values proposed by three different background sources (e.g. IPCC (IPCC 2000), Ecoinvent (Doka 2003) and MUNLV (MUNLV 1998)). The values of these background sources are waste-specific values. In Figure 10-19 are plotted the parameter of the objective function as a function of the dissimilable organic carbon fraction source. Once gain,

the error lines are horizontally plotted in the max-min line considering ± 25% error from the average value. In this figure, it can be observed that this variable affects principally the environmental (EC) and displaced environmental cost (DEC) indicators. Both indicators have a variation between their default and average values of 64% and 71%, respectively. The disposal cost (*DC*), transportation cost (*TC*) and revenue (*REV*) indicators have variations between 1% and 4%. Finally, the objective function (*OF*) is as well influenced due to variations on the value of dissimilable organic carbon fraction. The variation between the default and average value of the objective function is of 76%.

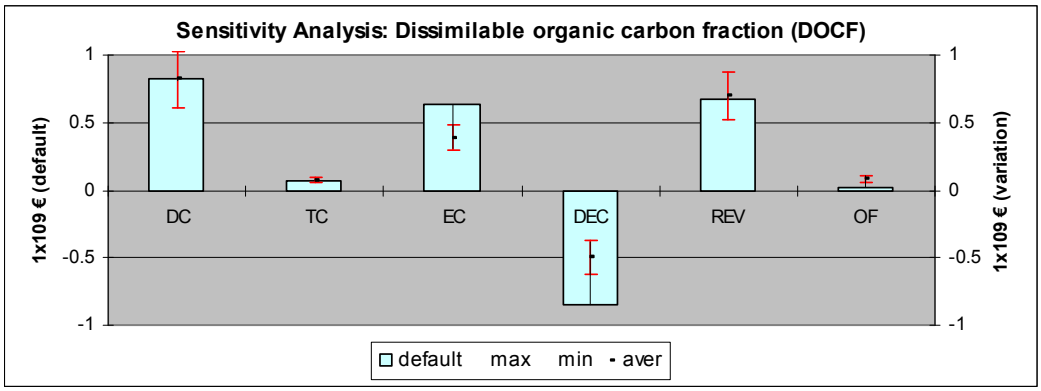


Figure 10-19 Sensitivity Analysis: dissimilable organic carbon fraction (*DOCF*)

10.3.5 Life cycle inventory of MRF facilities

The model assesses per default the waste management infrastructure as if existing mechanical recycling facilities perform both segregation and conditioning of the recyclable waste. As a sensitivity analysis, it is considered that the mechanical recycling facilities carry out exclusively sorting operations. Sorting facilities have a lower impact to the environment because they have lower energy consumption rates and the generated fugitive emissions to air, water and land are practically insignificant. In Figure 10-20, it is shown the result of this analysis. In this figure are plotted the parameter of the objective function as a function of the life cycle inventory of the mechanical recycling facilities. The error lines are horizontally plotted in the max-min line considering ± 25% error from the average value. With exception of the objective function, the indicators are minimally affected. Disposal cost, transportation cost and the revenue indicators have variation of 1.7%, 2.7% and 2.7%, respectively. Similarly, both the environmental cost and the displaced environmental cost indicator have a variation of 5.7 and 11%, respectively. However, in this figure can be observed that the objective function indicator is influenced by the LCI of the MRF. The variation between the default and average value of the objective function is of 123%.

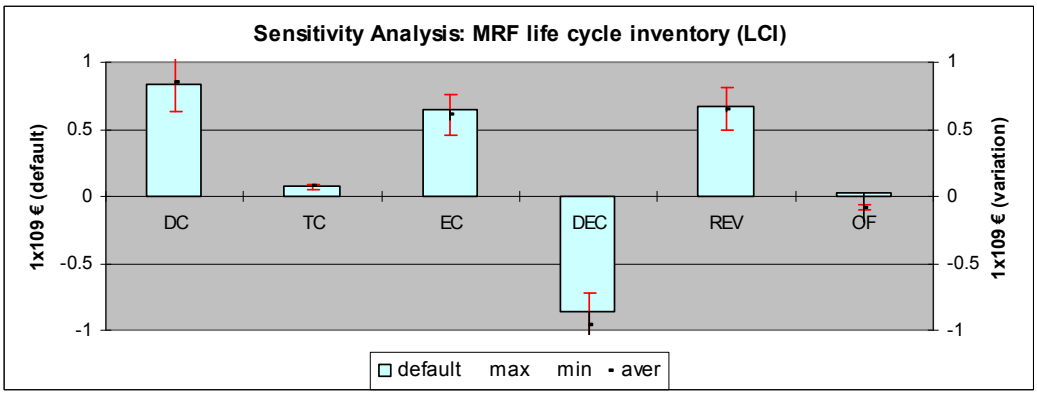


Figure 10-20 Sensitivity Analysis: MRF life cycle inventory

10.3.6 Life cycle inventory of displaced energy

The model accounts the amount of fugitive emissions to air and water due to displaced consumption and generation of energy. These fugitive emissions are associated to the power plant technology and on the fuel source that is used to generate the same amount of energy. The configuration of the German electricity configuration is given as a default. The configuration of the power plant technology is based on the electricity generation from coal, oil, natural gas, nuclear or hydro power stations. As a sensitive case of study, it is assumed that the power plant technology is based on the configuration of other countries belonging to the UCTE. Selected countries are Germany, Portugal, France, Denmark and Austria. These countries where randomly selected and their power plant technology configuration is taken from Table 2-6. In Figure 10-21, it is shown the result of this analysis. In this figure are plotted the parameter of the objective function as a function of the life cycle inventory of the power plant technology installed in the mentioned countries. The error lines are horizontally plotted in the max-min line considering ± 25% error from the average value. With exception of the displaced environmental cost (*DEC*) and the objective function (*OF*), the indicators are minimally affected. The disposal cost, transportation cost, environmental cost and revenue indicators have variations of approximately 6%, 7%, 1% and 3%, respectively. On the other hand, both the displaced environmental cost and the objective indicator variations of 24% and 110%, respectively. Thus, variations on the source of power technology have as well a considerable influence on the objective function indicator.

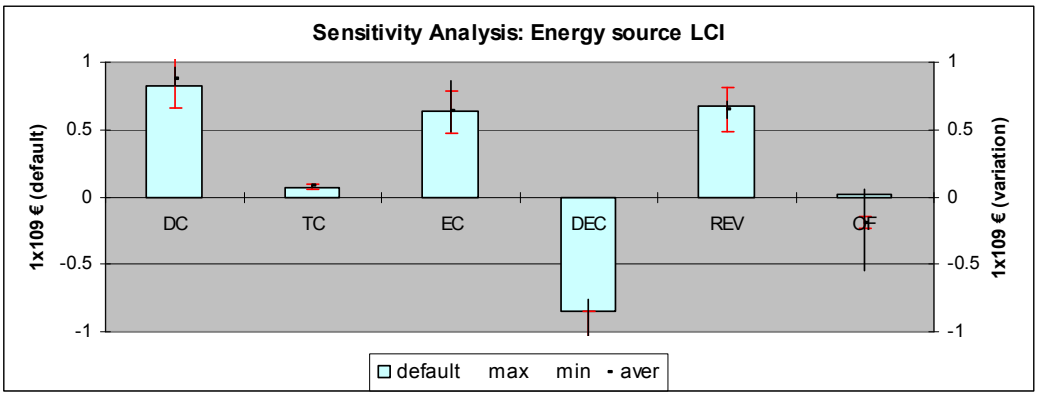


Figure 10-21 Sensitivity Analysis: Energy source life cycle inventory

11 CONCLUSIONS

Currently, it is not available in the market a quantitative assessment model that either fully recognises the multidimensionality of sustainability or incorporates the holistic integration between environmental, economical and social sustainability. Existing assessment models offer exclusively integrated solutions instead of sustainable ones, as it is required by current waste management strategic drivers. These models are based on the independent use of assessment tools such as life cycle assessment, cost-benefit assessment or multicriteria decision analysis. Independently, they can assess only one sustainable parameter but not the three at the same time. Therefore, decision maker do not count so far with an assessment model able to provide sustainable strategies.

As a result, in this document is suggested an assessment tool that can be used by decision makers as a decision aiding tool for the development of sustainable waste management strategies. However, it leaves the decision maker to take the final decision based on the information provided by the model. This assessment model, which is further referred as *SUWAMAS*, recognises the multidimensionality of sustainability and ensures the integration of environmental, economical and social issues in the pursuit of a sustainable waste management system. Additionally, it integrates a logistic module which ensures the proximity and self-sufficiency principles.

SUWAMAS is an integer non-linear mathematical programming model. The model finds the most effective sustainable strategy by minimising an objective function, which is subject to sustainable constraints. The objective function is a net social cost function. This function integrates the gross private cost, the environmental costs and the social costs savings derived from the sustainable management of waste and the recovery of energy and resources through the complete life cycle of the product system. The sustainable constraints include environmental, economical, social and logistical ones. These constraints are simultaneously solved by means of a life cycle assessment, cost-benefit analysis, multicriteria decision analysis and multi-commodity flow distribution, respectively. The sustainable constraints fulfil the community's legislation on waste and the integrate product policy approach. Every recovery and disposal facility fulfils as well the overall objectives and targets of the community's waste management operation framework in terms of its choice of technology and installed capacity.

SUWAMAS does not follow the waste hierarchy approach of the EU waste policy. Instead, *SUWAMAS* follows the integrated product policy approach. This approach agrees with the 6th Environmental Action Programme and with the EU's Sustainable Development Strategy, which are based *inter alia* on the life cycle thinking principle. Thus, *SUWAMAS* assesses the waste management infrastructure from a holistic point of view and do not give a rank or give preference values for the existing waste management operations. The holistic combination of waste management operations seeks to reduce the life cycle environmental impacts of products from the mining of raw material to its final disposal. As a result, the model considers the optimal material flow distribution within the system as a function of the choice of technology of the waste management operation and the composition of the generated waste. The optimal combination of waste management operations ensures the efficient reduction of the cumulative life cycle environmental impacts of product systems combined with the benefit of public participation in policy-making to identify eco-efficient solutions.

The sustainable waste management concept or strategy is defined in terms of the flow distribution of generated primary and secondary waste. The proposed material flow

distribution integrates environmental, economical and social issues in the pursuit of a sustainable waste management system that is *economically efficient, socially equitable and responsible and environmentally sound*. As a result, the proposed material flow distribution is efficient, acceptable and cost-effective. The implementation of the proposed sustainable strategies provides the following benefits:

- It guarantees sustainable consumption and production patterns by minimising and avoiding the amount of secondary waste generated from the recovery and disposal waste management operations (prevention principle). This action determinates how resources are used and shifts to more sustainable production and consumption patterns.
- It ensures the most environmentally effective material flow distribution by minimising the amount of waste going to disposal and consequently the amount of generated fugitive emissions to air, water and land derived from its management through the complete life cycle of the product system. Additionally, it enhances the reuse of recovered material, which has a lowest impact to the environment and to the economy in comparison to its similar manufactured from virgin resources (substitution principle). This action avoids the generation of environmental impacts derived from the extraction of primary raw materials, its conversion to consumer products and from its final disposal (precautionary principle, life cycle thinking).
- It provides the most economically affordable waste distribution flow with the highest benefit derived from the recovery of resources and with the lowest recovery/disposal cost. It internalises external environmental costs (externalities) derived from the generation of direct and displaced fugitive emissions through the entire life cycle of the product system. Therefore, generated and displaced fugitive emission pay the full costs of their impact (polluter pays principle, life cycle thinking).
- It ensures the most socially acceptable concept with the highest social benefit. In the one hand, the material flow distribution reflects the preferences of the different stakeholders for the installed waste management operations (public participation principle). On the other hand, it ensures equitable opportunities and distribution of goods across the community by guaranteed *inter alia* the maximisation of not only more but also better jobs within the waste management infrastructure (social equity principle).
- It guarantees the most logistically optimised waste distribution flow with the shortest disposal routes between generation and treatment sources and the required number and location of the waste management operations (proximity and self-sufficiency principles).

The sensitivity analysis showed that proposed waste management concepts or strategies are reliable. In the one hand, it showed that calculated life cycle inventories agree with the ones generated by other LCA studies. Existing differences are in accordance with the study goals, scope, assumptions and methodology choices. On the other hand, it make clear that the proposed material flow distribution is dependant not only on the selected allocation methods, assumptions and life cycle inventories but also on the quality of the input data. For example, the results of the model are influenced by the selection of the characterisation method or by the selection of the local power generating system. The first one is used for the assessment of external costs, while the second one is required for the estimation of displaced energy and resources. Both data sources can provide a high level of uncertainty in the final result. These values should be used with caution. Thus, it is recommended to use site-specific data and to keep the uncertainty of collected background and foreground information as low as possible in order to minimise the uncertainty of the results.

Finally, *SUWAMAS* is a reliable and robust assessment tool, which can be used for the development of sustainable waste management concepts or strategies for existing and new waste management infrastructures. These sustainable concepts are considered within the overall context of sustainable development by recognising and incorporating the multidimensionality of sustainability in every steps of the decision making process. As a result, *SUWAMAS* ensure the integration of environmental, economical and social issues in the pursuit of a sustainable waste management system that is *economically efficient, socially equitable and responsible and environmentally sound*.

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ANNEXES

Annex Table 1. Physical composition of the primary waste *i* as a function of the waste category *w*

Waste category (w) vs. Primary waste (i)		1	2	3	4	5	6	7	8	9	10
W	Units	%	%	%	%	%	%	%	%	%	%
1	Fe-metal packages	1.156	6.010	4.600	1.300	2.750	9.600	-	3.400	-	-
2	NFe-metal packages	0.533	-	0.400	-	0.250	-	-	-	-	-
3	Mixed metal	0.711	-	-	-	-	-	-	-	-	-
4	Waste Paper	7.822	39.040	0.700	34.500	4.430	20.400	-	47.500	-	5.200
5	Glass	4.444	2.410	0.500	1.700	-	3.900	-	2.100	-	0.500
6	Waste Textiles	2.844	-	48.000	0.600	-	1.800	-	0.600	-	-
7	Waste Wood	1.244	-	7.500	-	-	-	-	-	-	0.900
8	WEEE	0.800	-	32.200	-	-	-	-	-	-	-
9	Plastic packages	5.422	9.830	0.100	23.700	1.200	5.100	-	8.100	-	-
10	Polystyrene	0.089	-	-	-	-	-	-	-	-	-
11	Mixed plastic	1.422	-	1.400	-	3.150	-	-	-	-	-
12	Composite packages	1.956	-	-	-	-	-	-	-	-	-
13	Mixed composites	2.667	-	-	-	-	-	-	-	-	-
14	Biowaste	20.444	31.320	-	23.300	18.500	9.000	-	19.500	-	12.700
15	Green waste	2.044	-	0.900	2.600	20.000	6.200	-	6.600	-	78.800
16	Sewage sludge	-	-	-	-	-	-	100.000	-	-	-
17	Shoes	0.889	-	-	-	-	-	-	-	-	-
18	Vacuum cleaner dirt	0.622	-	-	-	-	-	-	-	-	-
19	Inert	2.489	-	-	-	-	-	-	-	-	-
20	Refurbishment waste	1.422	6.440	0.300	4.700	-	39.500	-	1.500	-	-
21	Hazardous waste	0.356	0.330	0.200	6.600	-	4.400	-	10.700	100.000	-
22	Leather	0.089	-	-	-	-	-	-	-	-	-
23	Rubber	0.178	-	-	-	-	-	-	-	-	-
24	Diapers & Hygienic paper	14.490	-	-	-	-	-	-	-	-	-
25	Fine fraction	10.844	-	-	-	-	-	-	-	-	-
26	Middle fraction	14.222	-	-	-	-	-	-	-	-	-
27	Mixed waste	0.799	4.620	3.200	1.000	49.720	0.100	-	-	-	1.900

Continue…

Waste category (w) vs. Primary waste (i)		11	12	13	14	15	16	17	18	19	20
W	Units	%	%	%	%	%	%	%	%	%	%
1	Fe-metal packages	-	-	0.100	13.000	50.000	-	47.900	47.900	-	-
2	NFe-metal packages	-	-	0.020	2.000	50.000	-	12.700	12.700	-	-
3	Mixed metal	-	-	-	-	-	-	-	-	-	-
4	Waste Paper	0.600	100.000	0.400	2.000	-	-	-	-	-	-
5	Glass	0.100	-	99.390	-	-	-	5.400	5.400	-	-
6	Waste Textiles	-	-	-	-	-	-	-	-	100.000	-
7	Waste Wood	5.000	-	-	-	-	100.000	2.600	2.600	-	-
8	WEEE	-	-	-	-	-	-	-	-	-	-
9	Plastic packages	0.200	-	-	26.000	-	-	-	-	-	-
10	Polystyrene	-	-	-	-	-	-	-	-	-	-
11	Mixed plastic	-	-	0.050	-	-	-	20.600	20.600	-	-
12	Composite packages	-	-	-	7.000	-	-	-	-	-	-
13	Mixed composites	-	-	-	-	-	-	-	-	-	-
14	Biowaste	-	-	-	-	-	-	-	-	-	-
15	Green waste	86.700	-	-	-	-	-	-	-	-	-
16	Sewage sludge	-	-	-	-	-	-	-	-	-	-
17	Shoes	-	-	-	-	-	-	-	-	-	-
18	Vacuum cleaner dirt	-	-	-	-	-	-	-	-	-	-
19	Inert	-	-	0.040	-	-	-	9.900	9.900	-	-
20	Refurbishment waste	-	-	-	-	-	-	-	-	-	-
21	Hazardous waste	-	-	-	-	-	-	-	-	-	-
22	Leather	-	-	-	-	-	-	-	-	-	-
23	Rubber	-	-	-	-	-	-	0.900	0.900	-	-
24	Diapers & Hygienic paper	-	-	-	-	-	-	-	-	-	-
25	Fine fraction	5.300	-	-	-	-	-	-	-	-	-
26	Middle fraction	-	-	-	-	-	-	-	-	-	-
27	Mixed waste	2.100	-	-	50.000	-	-	-	-	-	100.000

Sources: (BayLfU 2003), (CIWMB 1999), (EPA-I 2001), (MUNLV 2005), (Niessen 2002), AEA Technology (AEAT/ENV/R/1626)

Annex Table 2. Physical Properties of waste categories *w*

Physical Properties (MPPw,pp)		1	2	3	4	5	6	7	8	9	10	11
	Variable	**WPDL**	**WPDH**	**LFD**	**HFD**	**DOC**	**DDOC**	**DDOC**	**DDOC**	**BCF**	**LHV**	**BWF**
W	Units	frac.	frac.	frac.	frac.	frac.	frac.	frac.	frac.	frac.	MJ/kg	
1	Fe-metal packages	0.680	0.320	0.125	0.875	0.000	0.000	0.000	0.000	0.000	0.00	0
2	NFe-metal packages	0.680	0.320	0.385	0.615	0.000	0.000	0.000	0.000	0.000	0.00	0
3	Mixed metal	0.680	0.320	0.255	0.745	0.000	0.000	0.000	0.000	0.000	0.00	0
4	Waste Paper	0.330	0.670	0.818	0.182	0.400	0.550	0.270	0.700	1.000	15.70	1
5	Glass	0.800	0.200	0.056	0.944	0.000	0.000	0.000	0.000	0.000	0.00	0
6	Waste Textiles	0.050	0.950	0.783	0.217	0.400	0.770	0.120	0.200	0.800	17.34	1
7	Waste Wood	0.290	0.710	0.368	0.632	0.300	0.550	0.015	0.500	1.000	17.51	1
8	WEEE	0.000	1.000	0.590	0.410	0.010	0.550	0.010	0.000	0.000	16.87	1
9	Plastic packages	0.070	0.930	0.940	0.060	0.280	0.350	0.010	0.000	0.000	30.74	1
10	Polystyrene	0.800	0.200	0.510	0.490	0.280	0.350	0.010	0.000	0.000	38.04	1
11	Mixed plastic	0.300	0.700	0.510	0.490	0.280	0.350	0.010	0.000	0.000	25.70	1
12	Composite packages	0.070	0.930	0.510	0.490	0.500	0.550	0.180	0.500	0.800	16.59	1
13	Mixed composites	0.070	0.930	0.510	0.490	0.500	0.550	0.180	0.500	0.800	19.91	1
14	Biowaste	0.770	0.230	0.443	0.557	0.150	0.770	0.270	0.850	1.000	17.36	1
15	Green waste	0.805	0.195	0.860	0.140	0.170	0.550	0.270	0.300	1.000	13.83	1
16	Sewage sludge	1.000	0.000	1.000	0.000	0.500	0.550	0.600	0.300	1.000	16.40	1
17	Shoes	0.037	0.963	0.000	1.000	0.280	0.550	0.270	0.200	0.500	23.94	1
18	Vacuum cleaner dirt	0.300	0.700	0.000	1.000	0.000	0.000		0.300	0.000	14.93	1
19	Inert	0.890	0.110	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.00	0
20	Refurbishment waste	0.200	0.800	0.506	0.494	0.280	0.550		0.200	0.000	18.81	1
21	Hazardous waste	0.600	0.400	0.000	1.000	0.010	0.550	0.010	0.000	0.000	31.91	1
22	Leather	0.050	0.950	0.400	0.600	0.200	0.550	0.270	0.200	0.500	26.98	1
23	Rubber	0.050	0.950	0.333	0.667	0.010	0.550	0.010	0.000	0.000	37.12	1
24	Diapers & Hygienic paper	0.000	1.000	0.000	1.000	0.500	0.550	0.180	0.500	0.500	19.24	1
25	Fine fraction	1.000	0.000	1.000	0.000	0.090	0.600		0.300	0.500	12.26	1
26	Middle fraction	1.000	0.000	0.400	0.600	0.600	0.550		0.600	0.500	17.02	1
27	Mixed waste	0.526	0.474	0.760	0.240	0.150	0.660		0.600	0.611	16.46	1

Sources:
[1, 2]: (MUNLV 1998); [3,4]: (Perry 1999), (Bilitewski 1991); [5]: (IPCC 2000), Ecoinvent (Doka 2003), (AGO 1997), (AGO 2004); [6]: (IPCC 2000]; [7]: Ecoinvent (Doka 2003); [8]: (MUNLV 1998); [9]: (Doka 2003), (BayLfU 2003); [10]: (Doka 2003), (BayLfU 2003), (Niessen 2002).

Annex Table 3. Chemical properties of waste categories *w*

Chemical Properties (MCCw,cc)		1	2	3	4	5	6	7	8
	Variable	**C**	**H**	**O**	**N**	**S**	**Cl**	**Inert**	**H2O**
W	Units	frac	frac	frac	frac	frac	frac	frac	frac
	Molecular weight	12	1	16	14	32	35.455	1	18
1	Fe-metal packages	0.0454	0.0063	0.0428	0.0005	0.0001	0.0000	0.9049	0.0300
2	NFe-metal packages	0.0454	0.0063	0.0428	0.0005	0.0001	0.0000	0.9049	0.0300
3	Mixed metal	0.0454	0.0063	0.0428	0.0005	0.0001	0.0000	0.9049	0.0300
4	Waste Paper	0.4366	0.0569	0.4486	0.0009	0.0021	0.0016	0.0533	0.0520
5	Glass	0.0052	0.0007	0.0036	0.0003	0.0000	0.0006	0.9896	0.0200
6	Waste Textiles	0.4613	0.0640	0.4180	0.0218	0.0020	0.0012	0.0317	0.2000
7	Waste Wood	0.4827	0.0600	0.4237	0.0030	0.0011	0.0007	0.0289	0.2000
8	WEEE	0.4440	0.0262	0.1046	0.0183	0.0012	0.0358	0.3700	0.0070
9	Plastic packages	0.6715	0.0971	0.1581	0.0046	0.0007	0.0008	0.0671	0.1000
10	Polystyrene	0.8710	0.0845	0.0396	0.0021	0.0002	0.0000	0.0026	0.0020
11	Mixed plastic	0.5772	0.0801	0.1834	0.0097	0.0029	0.0348	0.1120	0.0200
12	Composite packages	0.4514	0.0615	0.4534	0.0018	0.0008	0.0035	0.0276	0.0471
13	Mixed composites	0.4790	0.0629	0.2515	0.0200	0.0035	0.0131	0.1700	0.0767
14	Biowaste	0.4864	0.0656	0.3723	0.0167	0.0002	0.0086	0.0503	0.7829
15	Green waste	0.4031	0.0564	0.3900	0.0200	0.0005	0.0000	0.1300	0.6200
16	Sewage sludge	0.3702	0.0463	0.0035	0.0498	0.0329	0.0000	0.4973	0.6300
17	Shoes	0.5194	0.0692	0.0757	0.0049	0.0131	0.0240	0.2937	0.0115
18	Vacuum cleaner dirt	0.3525	0.0467	0.1983	0.0618	0.0114	0.0124	0.3169	0.0547
19	Inert	0.0190	0.0037	0.0149	0.0006	0.0104	0.0014	0.9500	0.0209
20	Refurbishment waste	0.5054	0.0614	0.4142	0.0010	0.0010	0.0090	0.0079	0.0770
21	Hazardous waste	0.6690	0.0960	0.0520	0.0200	0.0000	0.0000	0.1630	0.0500
22	Leather	0.5857	0.0781	0.1123	0.0976	0.0039	0.0239	0.0986	0.1000
23	Rubber	0.7765	0.1035	0.0000	0.0000	0.0200	0.0000	0.1000	0.0120
24	Diapers & Hygienic paper	0.4660	0.0849	0.3395	0.0148	0.0008	0.0039	0.0900	0.6140
25	Fine fraction	0.3447	0.0473	0.3496	0.0014	0.0020	0.0067	0.2483	0.2000
26	Middle fraction	0.4462	0.0638	0.2852	0.0327	0.0052	0.0083	0.1587	0.7200
27	Mixed waste	0.4154	0.0575	0.2762	0.0297	0.0025	0.0000	0.2187	0.3000

Continue…

Chemical Properties (MCCw,cc)		9	10	11	12	13	14	15	16	17	18	19	20
	Variable	**Cd**	**Tl**	**Hg**	**Sb**	**As**	**Pb**	**Cr**	**Co**	**Cu**	**Mn**	**Ni**	**V**
W	Units	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
	Molecular weight	1	1	1	1	1	1	1	1	1	1	1	1
1	Fe-metal packages	43.10	0.00	5.60	88.20	7.00	344.30	158.80	0.00	99.00	3,459.00	160.40	0.00
2	NFe-metal packages	1.70	0.00	0.20	25.80	7,215.00	95.50	172.00	0.00	645.00	3,059.00	34.10	0.00
3	Mixed metal	9.10	0.00	5.40	74.50	9,480.00	609.60	289.10	0.00	744,800	1,056.00	38.90	0.00
4	Waste Paper	2.30	0.00	0.06	0.00	8.60	14.00	30.00	0.00	54.00	82.00	9.70	0.00
5	Glass	2.60	0.00	0.01	0.00	50.10	429.00	372.00	0.00	14.00	131.00	16.40	0.00
6	Waste Textiles	2.40	0.00	0.66	0.00	8.30	100.00	118.00	0.00	57.00	57.00	11.70	0.00
7	Waste Wood	2.80	0.00	0.51	0.00	7.70	36.00	13.00	0.00	34.00	106.00	6.60	0.00
8	WEEE	228.80	0.00	1,688.00	0.00	11.00	2,713.00	728.00	0.00	20,459.00	506.00	1,543.80	0.00
9	Plastic packages	3.10	0.00	0.08	0.00	7.00	129.00	89.00	0.00	90.00	111.00	20.10	0.00
10	Polystyrene	4.70	0.00	0.10	44.00	0.20	25.00	7.10	0.00	9.00	3.60	5.70	0.00
11	Mixed plastic	76.20	0.00	0.80	0.00	25.50	473.00	334.00	0.00	101.00	82.00	18.20	0.00
12	Composite packages	3.00	0.00	0.05	0.00	7.70	11.00	28.00	0.00	102.00	63.00	13.30	0.00
13	Mixed composites	26.60	0.00	0.64	0.00	28.70	638.00	2,750.00	0.00	834.00	155.00	148.30	0.00
14	Biowaste	2.80	0.00	0.04	0.00	8.30	15.00	20.00	0.00	33.00	76.00	7.60	0.00
15	Green waste	6.00	0.00	1.40	52.20	7.30	153.60	101.00	0.00	690.00	498.40	23.60	0.00
16	Sewage sludge	1.04	0.12	1.04	0.12	1.47	57.97	45.56	6.01	209.30	197.00	0.20	0.12
17	Shoes	12.90	0.00	0.18	0.00	7.70	324.00	5,992.00	0.00	57.00	42.00	13.40	0.00
18	Vacuum cleaner dirt	3.90	0.00	0.71	0.00	6.50	154.00	183.00	0.00	119.00	230.00	27.70	0.00
19	Inert	32.60	0.00	0.03	0.00	12.30	1,402.00	197.00	0.00	51.00	532.00	36.00	0.00
20	Refurbishment waste	24.50	0.00	0.29	0.00	5.00	322.00	88.00	0.00	75.00	82.00	21.80	0.00
21	Hazardous waste	1,940.00	0.00	242.00	60.00	1.00	143.00	74.00	0.00	12,000.00	180,000	726.00	0.00
22	Leather	18.50	0.00	1.63	0.00	6.80	180.00	7,885.00	0.00	192.00	49.00	30.90	0.00
23	Rubber	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	Diapers & Hygienic paper	2.50	0.00	0.10	0.00	6.70	11.00	21.00	0.00	24.00	51.00	9.10	0.00
25	Fine fraction	2.40	0.00	0.39	0.00	27.70	131.00	279.00	0.00	223.00	1,476.00	26.50	0.00
26	Middle fraction	4.30	0.00	0.11	0.00	10.90	83.00	90.00	0.00	139.00	266.00	16.80	0.00
27	Mixed waste	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Sources: Ecoinvent (Doka 2003), (BayLfU 2003), (Niessen 2002)

Annex Table 4. Displaced fugitive emissions to air and water from the production of diverse goods

Fugitive Emissions to: Air	**kg-mg*/ kg**	**Fe**	**Aluminium**	**Paper**	**Glass**	**PET**	**HDPE**	**PVC**	**LDPE**	**PP**
Carbon dioxide	CO_2	1.334E+00	9.573E+00	2.074E+00	8.748E-01	2.494E+00	1.760E+00	1.963E+00	1.948E+00	1.860E+00
Methane	CH_4	3.148E-03	1.603E-02	2.508E-03	1.303E-03	5.859E-03	5.700E-03	8.561E-03	5.791E-03	6.059E-03
Nitrous oxide	N_2O	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Hydrofluorocarbons	HFCs	1.085E-13	1.232E-13	7.702E-14	2.193E-14	2.198E-13	1.192E-16	1.204E-15	1.125E-16	1.006E-16
Perfluorocarbons	PFCs	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Sulphur hexafluoride	SF_6	1.364E-07	1.329E-06	1.388E-07	2.710E-08	1.122E-07	3.946E-11	7.594E-10	2.473E-11	4.099E-11
Sulphur dioxide	SO_2	5.336E-03	3.857E-02	4.393E-03	5.029E-03	7.812E-03	1.370E-02	9.680E-03	8.262E-03	1.290E-02
Nitrogen dioxide	NO_2	5.548E-03	2.188E-02	4.492E-03	3.633E-03	7.172E-03	9.911E-03	9.748E-03	9.619E-03	9.590E-03
Ammonia	NH_3	7.599E-05	2.722E-04	6.945E-05	8.061E-05	3.400E-05	1.784E-07	1.496E-04	1.228E-07	1.638E-07
Hydrogen chloride	HCl	8.915E-05	3.639E-04	4.720E-05	7.468E-05	9.078E-05	4.788E-05	1.428E-04	5.593E-05	3.309E-05
Hydrogen sulphide	H_2S	1.221E-05	1.584E-05	4.012E-05	3.293E-06	6.635E-06	1.901E-06	2.066E-06	9.725E-07	1.495E-06
NMVOC	NMVOC	6.834E-04	2.817E-03	7.834E-04	4.216E-04	2.552E-03	5.932E-03	2.293E-03	6.771E-03	2.352E-03
Dioxins and furans	PCDD/F	7.045E-09	6.531E-10	1.188E-10	5.300E-11	1.884E-10	6.771E-12	9.887E-12	1.402E-12	9.657E-12
PAH	PAH	8.489E-07	8.871E-05	1.806E-07	4.055E-08	1.378E-07	5.374E-10	3.334E-09	1.735E-10	7.136E-10
Carbon monoxide	CO	2.490E-02	9.797E-02	2.353E-03	6.705E-04	2.277E-03	8.487E-04	1.438E-03	1.095E-03	7.594E-04
Particulates, < 2.5 µm	$PM_{2.5}$	1.243E-03	5.463E-03	6.980E-04	5.107E-04	5.669E-04	7.254E-04	8.536E-04	5.080E-04	3.750E-04
Particulates,	PM	4.371E-03	9.702E-03	6.712E-04	1.083E-03	6.777E-04	1.263E-03	1.517E-03	8.906E-04	6.584E-04
Particulates, >10 µm	PM_{10}	5.715E-03	1.503E-02	1.169E-03	1.316E-03	1.103E-03	9.496E-04	1.162E-03	6.714E-04	4.982E-04
Cadmium	Cd*	7.882E-02	1.656E-01	5.563E-02	8.237E-02	1.386E-01	5.527E-05	2.202E-03	3.854E-05	5.492E-05
Thallium	Tl*	2.592E-04	1.848E-03	5.119E-04	4.361E-04	1.746E-03	2.861E-05	1.016E-04	3.289E-05	2.021E-05
Mercury	Hg*	2.334E+00	3.266E-01	7.655E-02	2.255E-02	3.822E-01	3.442E-01	5.033E-01	3.341E-01	3.912E-01
Antimony	Sb*	1.054E-02	6.453E-02	1.270E-02	7.075E-02	2.583E-02	9.686E-06	2.591E-04	8.331E-06	8.584E-06
Arsenic	As*	7.469E-02	5.172E-01	1.018E-01	9.925E-02	2.582E-01	1.428E-04	4.629E-03	7.234E-05	1.679E-04
Lead	Pb*	4.809E+00	2.105E+00	8.787E-01	1.031E+00	1.530E+00	3.895E-03	1.182E-01	1.245E-03	5.187E-03
Chromium	Cr*	1.535E+00	1.321E+00	8.869E-01	3.284E-01	4.070E+00	6.806E-04	1.522E-01	3.932E-04	7.039E-04
Cobalt	Co*	6.431E-02	3.165E-01	8.360E-02	9.013E-02	1.771E-01	1.799E-04	1.050E-03	5.676E-05	2.388E-04
Copper	Cu*	6.274E-01	1.283E+01	5.602E-01	2.525E-01	1.307E+00	9.825E-04	4.387E-02	4.830E-04	1.156E-03
Manganese	Mn*	2.916E-01	4.523E-01	7.707E-01	1.693E-01	1.723E-01	7.950E-04	2.253E-03	1.752E-04	1.125E-03
Nickel	Ni*	1.570E+00	4.913E+00	1.019E+00	3.167E-01	2.260E+00	7.582E-04	1.866E-01	3.194E-04	9.271E-04
Vanadium	V*	1.587E+00	7.260E+00	2.949E+00	5.836E-01	7.022E+00	8.159E-04	1.872E-02	4.741E-04	8.474E-04
Fugitive Emissions to: Water	**kg / kg**									
Biological Oxygen Demand	BOD_5	1.213E-02	2.170E-02	2.202E-03	1.931E-03	4.776E-03	4.739E-04	1.393E-03	4.802E-04	2.618E-04
Chemical Oxygen Demand	COD	1.417E-02	3.437E-02	1.047E-02	2.350E-03	1.065E-01	1.164E-03	4.598E-03	1.544E-03	8.461E-04
Nitrogen Total	N-tot	1.133E-05	6.355E-05	1.231E-04	1.743E-05	1.618E-05	7.567E-06	1.297E-05	1.984E-06	4.607E-06
Phosphorus total	P-tot	8.957E-07	6.502E-07	1.276E-05	1.835E-06	6.011E-07	4.644E-07	3.820E-05	1.960E-06	1.492E-06

Continue..

Fugitive Emissions to: Air	**kg-mg*/ kg**	**PS**	**PU**	**Wood Chips**	**Ammonium Nitrate**
Carbon dioxide	CO_2	2.569E+00	4.049E+00	3.369E-02	2.694E+00
Methane	CH_4	8.995E-03	1.525E-02	4.067E-05	5.494E-03
Nitrous oxide	N_2O	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Hydrofluorocarbons	HFCs	8.260E-17	2.753E-14	9.565E-16	3.665E-14
Perfluorocarbons	PFCs	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Sulphur hexafluoride	SF_6	2.078E-11	3.687E-08	1.282E-09	4.108E-08
Sulphur dioxide	SO_2	9.462E-03	1.548E-02	7.165E-05	5.137E-03
Nitrogen dioxide	NO_2	1.131E-02	1.702E-02	7.831E-04	1.517E-02
Ammonia	NH_3	1.709E-07	2.192E-04	1.057E-06	6.239E-03
Hydrogen chloride	HCl	2.582E-05	1.900E-04	6.377E-07	4.935E-05
Hydrogen sulphide	H_2S	4.755E-07	2.123E-06	5.375E-08	2.156E-05
NMVOC	NMVOC	2.631E-03	3.663E-03	2.111E-04	1.132E-03
Dioxins and furans	PCDD/F	7.050E-13	7.136E-11	1.982E-11	2.607E-10
PAH	PAH	1.101E-10	2.559E-08	4.180E-08	3.792E-07
Carbon monoxide	CO	1.626E-03	2.769E-03	6.041E-04	2.070E-03
Particulates, < 2.5 µm	$PM_{2.5}$	3.812E-04	2.517E-03	8.089E-05	1.424E-03
Particulates,	PM	6.680E-04	4.317E-03	2.233E-05	8.823E-04
Particulates, >10 µm	PM_{10}	5.030E-04	3.415E-03	3.013E-05	1.401E-03
Cadmium	Cd*	3.126E-05	1.971E-02	1.464E-03	5.369E-01
Thallium	Tl*	2.347E-05	2.194E-04	1.080E-05	4.607E-04
Mercury	Hg*	6.160E-02	3.985E-01	1.614E-03	7.185E-02
Antimony	Sb*	6.392E-06	7.489E-03	3.536E-04	3.537E-02
Arsenic	As*	5.193E-05	6.251E-02	3.372E-03	4.962E-01
Lead	Pb*	1.048E-03	3.438E-01	5.857E-02	2.488E+00
Chromium	Cr*	3.793E-04	1.195E+00	6.120E-02	7.694E+00
Cobalt	Co*	3.794E-05	3.119E-02	1.969E-03	1.011E+00
Copper	Cu*	3.603E-04	2.554E-01	2.800E-02	2.156E+00
Manganese	Mn*	9.171E-05	4.783E-02	4.483E-03	2.066E-01
Nickel	Ni*	2.480E-04	2.459E-01	1.622E-02	9.615E+00
Vanadium	V*	4.472E-04	4.152E-01	1.873E-02	3.473E+01
Fugitive Emissions to: Water	**kg / kg**				
Biological Oxygen Demand	BOD_5	3.167E-04	2.634E-03	1.565E-04	6.100E-03
Chemical Oxygen Demand	COD	1.157E-03	8.626E-03	1.712E-04	6.590E-03
Nitrogen Total	N-tot	6.873E-06	1.874E-03	1.968E-07	4.383E-04
Phosphorus total	P-tot	2.692E-07	3.025E-04	2.664E-08	1.987E-07

Source: Adapted from (Althaus 2004), (Hischier 2004), (Werner 2003), (Nemecek 2004), (UBA 2000)

Annex Table 5. Displaced fugitive emissions to air and water due to recovered energy

Fugitive Emissions to: Air		Coal kg/ kWh	Oil kg/ kWh	Nat. Gas kg/ kWh	Nuclear kg/ kWh	Hydro kg/ kWh		Electricity[1] kg/ kWh	Diesel kg/kg	Fuel oil kg/MJ	Nat. Gas kg/MJ
Carbon dioxide	CO_2	9.8875E-01	8.5786E-01	6.0107E-01	8.2053E-03	4.2130E-03		5.210E-01	3.500E+00	8.824E-02	6.397E-02
Methane	CH_4	3.1896E-03	4.6928E-04	1.5007E-03	1.6049E-05	3.8612E-06		1.606E-03	9.100E-04	4.852E-05	1.602E-04
Nitrous oxide	N_2O	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00		0.000E+00	0.000E+00	0.000E+00	0.000E+00
Hydrofluorocarbons	HFCs	1.5323E-14	2.7468E-15	3.9434E-16	3.7543E-16	2.4712E-16		7.550E-15	0.000E+00	0.000E+00	0.000E+00
Perfluorocarbons	PFCs	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00		0.000E+00	0.000E+00	0.000E+00	0.000E+00
Sulphur hexafluoride	SF_6	2.1113E-09	3.2350E-09	6.1010E-10	3.2663E-10	9.5005E-11		1.240E-09	0.000E+00	0.000E+00	0.000E+00
Sulphur dioxide	SO_2	3.2500E-03	6.6125E-03	2.1870E-04	3.7838E-05	5.0177E-06		1.721E-03	3.100E-03	5.029E-04	2.538E-05
Nitrogen dioxide	NO_2	2.2623E-03	2.8204E-03	7.1986E-04	3.9425E-05	3.1003E-05		1.191E-03	3.300E-02	1.492E-04	4.462E-05
Ammonia	NH_3	3.8956E-05	2.8901E-06	2.4472E-07	5.9977E-06	1.4095E-07		2.102E-05	2.000E-05	2.199E-07	3.754E-08
Hydrogen chloride	HCl	6.2214E-05	2.1643E-06	2.1852E-07	7.1634E-07	8.2635E-08		3.002E-05	1.000E-06	1.646E-06	5.406E-08
Hydrogen sulphide	H_2S	5.8969E-08	6.8058E-08	7.1138E-06	2.1862E-08	4.9999E-09		3.587E-07	0.000E+00	6.746E-09	7.513E-07
NMVOC	NMVOC	8.0264E-05	2.8014E-04	1.5422E-04	7.0006E-06	4.3323E-06		5.441E-05	-7.400E-07	2.996E-05	1.632E-05
Dioxins and furans	PCDD/F	8.2592E-11	1.8562E-11	1.1241E-11	2.6704E-12	2.2337E-12		4.150E-11	6.500E-14	1.923E-12	1.293E-12
PAH	PAH	3.1062E-08	2.7489E-08	7.8547E-08	1.2238E-09	8.3359E-10		1.949E-08	8.000E-09	1.641E-09	1.029E-08
Carbon monoxide	CO	2.6937E-04	3.2680E-04	2.2545E-04	2.3038E-05	1.6623E-05		1.559E-04	8.900E-03	2.744E-05	1.623E-05
Particulates, < 2.5 μm	$PM_{2.5}$	2.0542E-04	1.4495E-04	1.4502E-05	6.2662E-06	1.6782E-05	→	1.053E-04	0.000E+00	3.989E-05	1.358E-06
Particulates,	PM	1.0783E-04	1.8613E-04	1.0307E-05	6.9538E-06	8.4693E-05		6.406E-05	0.000E+00	7.898E-06	1.181E-06
Particulates, >10 μm	PM_{10}	1.3174E-03	2.2531E-04	1.3873E-05	1.5537E-05	1.0436E-04		6.466E-04	1.900E-03	1.519E-05	1.894E-06
Cadmium	Cd	3.6647E-09	4.4250E-08	5.5058E-10	9.1370E-10	6.1981E-11		3.109E-09	6.200E-08	3.396E-08	7.406E-11
Thallium	Tl	8.1720E-11	1.6914E-11	5.2356E-12	9.4000E-12	2.5160E-11		4.487E-11	0.000E+00	1.603E-12	5.518E-13
Mercury	Hg	4.3409E-08	6.7474E-09	2.6741E-09	5.8435E-10	4.1804E-10		2.123E-08	0.000E+00	7.320E-10	3.222E-10
Antimony	Sb	3.5611E-09	5.1500E-10	1.6584E-10	2.0328E-10	1.3524E-11		1.798E-09	0.000E+00	6.581E-11	2.594E-11
Arsenic	As	3.9075E-08	8.1363E-08	1.3869E-09	2.3880E-09	2.7183E-10		2.145E-08	2.500E-08	1.389E-08	2.050E-10
Lead	Pb	1.3550E-07	4.1908E-07	1.1338E-08	1.0837E-08	2.8390E-09		7.880E-08	0.000E+00	6.144E-08	1.475E-09
Chromium	Cr	4.5010E-08	1.5507E-07	4.8749E-09	1.1393E-07	2.2302E-08		7.128E-08	0.000E+00	1.892E-08	1.157E-09
Cobalt	Co	1.2016E-08	4.0007E-07	5.0828E-10	2.1191E-09	4.2478E-10		1.542E-08	0.000E+00	3.404E-08	9.785E-11
Copper	Cu	5.5584E-08	5.5616E-07	6.6813E-09	1.1156E-08	1.9839E-09		4.356E-08	0.000E+00	5.265E-08	9.126E-10
Manganese	Mn	5.6577E-08	1.2774E-07	2.2876E-09	2.6339E-09	6.9124E-10		3.098E-08	0.000E+00	6.062E-10	2.983E-10
Nickel	Ni	2.3161E-07	3.2274E-06	6.4230E-09	1.2071E-08	1.3354E-09		1.866E-07	2.500E-06	6.657E-07	1.043E-09
Vanadium	V	1.1501E-07	1.1417E-05	7.5695E-09	2.7405E-08	1.5405E-09		3.172E-07	0.000E+00	2.626E-06	1.619E-09
Fugitive Emissions to: Water											
Biological Oxygen Demand	BOD_5	1.7210E-04	3.5471E-03	5.9248E-05	1.6690E-05	8.1395E-06		1.699E-04	0.000E+00	3.788E-04	6.707E-06
Chemical Oxygen Demand	COD	1.9916E-04	3.6004E-03	7.1717E-05	2.1061E-05	9.5743E-06		1.863E-04	0.000E+00	3.841E-04	8.076E-06
Nitrogen Total	N-tot	7.4629E-07	7.8946E-05	9.5806E-08	2.8019E-07	2.3754E-08		2.209E-06	0.000E+00	4.585E-07	1.739E-08
Phosphorus total	P-tot	6.4774E-09	2.5042E-07	4.1150E-09	1.1420E-08	4.1550E-10		1.330E-08	0.000E+00	4.585E-07	1.739E-08

[1] Fugitive emissions derived from the generation of electricity are calculated considering generic UCTE values and German power plant technology: Coal (47.7%), Oil (2.2%), Natural Gas (4.5%), Nuclear (39.3%) and Hydro (6.3%). Adapted from Ecoinvent Data v1.1 (2004) and (UBA 2000).

CURRICULUM VITAE

Eduardo Márquez Oropeza

I. PERSONAL DETAILS

Nationality	Mexican - German
Marital Status	Married
Date of Birth	31 May 1975
Place of Birth	Mexico City, Mexico

II. EDUCATION

09/03-05/06 **Universität Dortmund (Germany)**
Bio- and Chemical Engineering Faculty
Dr.-Ing. candidate
- Dissertation: "*SUWAMAS*, a decision support model for sustainable waste management systems"

09/99-08/00 **University of Manchester (England)**
The Manchester School of Engineering
MSc. in Environmental Engineering
- Thesis: "Wastewater best available techniques for the petroleum refining industry. A review of practices in Mexico and the UK"
- Best top 5% in academic performance

09/94-02/99 **Instituto Politécnico Nacional (Mexico)**
ESIQIE
BEng. in Chemical Industrial Engineering
- Thesis: "Eco-efficient assessment for a new tail gas control system for a sulphur removal unit at the refinery of Cadereyta, PEMEX"
- Best top 5% in academic performance
- Best National Chemical Engineering Thesis 2000, IMIQ

09/91-08/94 **Instituto Politécnico Nacional (Mexico)**
High School CECyt no.9

09/88-08/91 **Secondary School no. 78 "Rep. del Paraguay" (Mexico)**

09/86-08/88 **Elementary School "Maestro Miguel Ángel A. Quintana" (Mexico)**

09/81-08/86 **Bilingual Elementary School "Instituto Ovalle Monday" (Mexico)**

III. WORK EXPERIENCE

09/03-03/06 **Fraunhofer Institute – UMSICHT (Germany)**
Scientific Guest

02/01-08/02 **UQUIFA Mexico (Mexico)**
Head of the Environmental Department

04/98-08/99 **Instituto Mexicano del Petróleo (Mexico)**
Project Engineer

IV. CONFERENCES & MEETINGS

11/2005 ISWA 2005. International Solid Waste Association. Buenos Aires, Argentina. Invited as speaker.
10/2005 IEG Annual Meeting. Rome, Italy. Invited as special guest and speaker.
04/2005 The 20th International Conference on Solid Waste Technology and Management. Philadelphia, PA, USA. Invited as speaker.
04/2005 AchemAmerica 2005. Mexico City, Mexico. Invited as speaker.

V. AFFILIATIONS

2004-now International Solid Waste Association, ISWA.
2003-now DAAD Alumni Organisation
1998-2000 Mexican Chemical Engineers Institute, IMIQ.

VI. PERSONAL SKILLS AND COMPETENCES

IT Skills High level of competency in office and engineering based programs:
MS-Word, MS-Excel, VBA, MS-PowerPoint, MS-Vision, MS-Project, MS-Outlook, MS-Access, Tsweet, ISC-3, Umberto, SimaPro, Lindo API, Lingo.

Languages
English: Excellent proficiency level
German: Good proficiency level
French: Basic proficiency level
Spanish: Native Speaker

09/02-09/03 Goethe Institute / Volkshochschule Göttingen e.V.
Göttingen, Germany
- Intensive German Course as a Foreign Language
- Certificate (Deutsche Sprachprüfung für den Hochschulzugang ausländischer Studienbewerberinnen und Studienbewerber, DSH).

Hobbies Practice sports, reading, concerts, travelling and cultural events.

Sports Member of the Handball Fortuna Sport Club. (2004-now)
Captain of the Mexican Handball National Team (1996-1998)
Captain of the IPN´s Handball and Baseball Teams (1994-1998)

VII. SCHOLARSHIPS

2003-2006 CONACYT. PhD research program at the University of Dortmund
2003 DAAD. Intensive German Course at the Goethe Institute, Göttingen
1999-2000 CONACYT. MSc program at the University of Manchester
1997-1998 TELMEX. Academic excellence Bachelor program
1995-1999 IPN. Academic excellence Bachelor program
1994-1995 IMP. Academic excellence program