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METHODS FOR ASSESSING THE SUSTAINABILITY OF INTEGRATED MUNICIPAL WASTE MANAGEMENT AND ENERGY SUPPLY SYSTEMS

Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in Auditorium 1382 at Lappeenranta University of Technology, Lappeenranta, Finland, on the 21th of August, 2009, at noon.

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Abstract

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The general striving to bring down the number of municipal landfills and to increase the re-use and recycling of waste-derived materials across the EU supports the debates concerning the feasibility and rationality of waste management systems. Substantial decrease in the volume and mass of landfill-disposed waste flows can be achieved by directing suitable waste fractions to energy recovery. Global fossil energy supplies are becoming more and more valuable and expensive energy sources for the mankind, and efforts to save fossil fuels have been made. Waste-derived fuels offer one potential partial solution to two different problems. First, waste that cannot be feasibly re-used or recycled is utilized in the energy conversion process according to EU's Waste Hierarchy. Second, fossil fuels can be saved for other purposes than energy, mainly as transport fuels.

This thesis presents the principles of assessing the most sustainable system solution for an integrated municipal waste management and energy system. The assessment process includes:

- formation of a SISMan (Simple Integrated System Management) model of an integrated system including mass, energy and financial flows, and
- formation of a MEFLO (Mass, Energy, Financial, Legislational, Other decision-support data) decision matrix according to the selected decision criteria, including essential and optional decision criteria.

The methods are described and theoretical examples of the utilization of the methods are presented in the thesis.

The assessment process involves the selection of different system alternatives (process alternatives for treatment of different waste fractions) and comparison between the alternatives. The first of the two novelty values of the utilization of the presented methods is the perspective selected for the formation of the SISMan model. Normally waste management and energy systems are operated separately according to the targets and principles set for each system. In the thesis the waste management and energy supply systems are considered as one larger integrated system with one primary target of serving the customers, i.e. citizens, as efficiently as possible in the spirit of sustainable development, including the following requirements:

- reasonable overall costs, including waste management costs and energy costs;
- minimum environmental burdens caused by the integrated waste management and energy system, taking into account the requirement above; and
- social acceptance of the selected waste treatment and energy production methods.

The integrated waste management and energy system is described by forming a SISMan model including three different flows of the system: energy, mass and financial flows. By defining the three types of flows for an integrated system, the selected factor results needed in the decision-making process of the selection of waste management treatment processes for different waste fractions can be calculated. The model and its results form a transparent description of the integrated system under discussion.

The MEFLO decision matrix has been formed from the results of the SISMan model, combined with additional data, including e.g. environmental restrictions and regional aspects. System alternatives which do not meet the requirements set by legislation can be deleted from the comparisons before any closer numerical considerations. The second novelty value of this thesis is the three-level ranking method for combining the factor results of the MEFLO decision matrix. As a result of the MEFLO decision matrix, a transparent ranking of different system alternatives, including selection of treatment processes for different waste fractions, is achieved.

SISMan and MEFLO are methods meant to be utilized in municipal decision-making processes concerning waste management and energy supply as simple, transparent and easy-to-understand tools. The methods can be utilized in the assessment of existing systems, and particularly in the planning processes of future regional integrated systems. The principles of SISMan and MEFLO can be utilized also in other environments, where synergies of integrating two (or more) systems can be obtained. The SISMan flow model and the MEFLO decision matrix can be formed with or without any applicable commercial or free-of-charge tool/software. SISMan and MEFLO are not bound to any libraries or data-bases including process information, such as different emission data libraries utilized in life cycle assessments.

Keywords: Energy-from-Waste, Waste-to-Energy, waste management, energy supply, decision-support

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Lappeenranta, August 2009

Mika Luoranen

”The hardest part is the weighting”

Contents

List of publications

Publication I
Luoranen, M., Horttanainen, M., 2008. Co-generation based energy recovery from municipal solid waste integrated with the existing energy supply system, Waste Management, 2008, vol. 28, nro. 1, p. 30-38, ISSN 0956-053X.

Publication II
Luoranen, M., Horttanainen, M., 2007a. Feasibility of energy recovery from municipal solid waste in an integrated municipal energy supply and waste management system, Waste Management & Research, 2007, vol. 25, nro. 5, p. 426-439, ISSN 0734-242X.

Publication III
Luoranen, M., Horttanainen, M., 2007b. MEFLO-method application for feasibility assessment of energy recovery from municipal solid waste in a small integrated municipal service system. Progress in Industrial Ecology – An International Journal, 2008, Vol. 5, No 1/2, pp. 124-148.

Publication IV
Luoranen, M., Soukka, R., Denafas, G., Horttanainen, M., 2009. Comparison of energy and material recovery of household waste management from the environmental point of view – Case Kaunas, Lithuania. Applied Thermal Engineering, Vol. 29, pp. 938-944.

The author of this thesis is the corresponding author in all the publications listed above.

Dr Soukka built the GaBi model presented in publication IV according to the author’s wishes and instructions.

Prof. Denafas provided and approved the information concerning Lithuania in publication IV.

Prof. Horttanainen has contributed to Publications I-IV, being the “model commentator” and the author’s discussion partner during the whole model formation and evolution process.

Nomenclature

Arabic letters

A	Alternative
C	Cost
E	Energy, Energy criteria
F	Financial criteria, decision factor
f	Fraction
i	Calculator index
I	Impact
j	Calculator index
k	Calculator index
L	Legislative criteria
L1	Level 1
L2	Level 2
L3	Level 3
m	Calculator index
M	Mass criteria
n	Number, normalized value
O	Other decision-support criteria
P1	Plant 1
P2	Plant 2
w	Weighting factor

Greek letters

Σ	Sum
η	Efficiency
Φ	Heat energy

Subscripts

EL	Electrical energy
EXP	Exploitable
max	Maximum
min	Minimum
NONREC	Non-recoverable
NET	Net amount
REC	Recoverable
REJ	Reject
SALE	Sold energy
SS	Source separation
SSL	Source separation loss
TOT	Total
TUE	Top-up electricity

Acronyms

APC	Air Pollution Control
BAT	Best Available Technology
bbl	Barrel of oil
CBA	Cost Benefit Analysis
CHP	Combined Heat and Power
DALY	Disability Adjusted Life Year; a measure of the gap in healthy years of life lived by a population as compared with a normative standard. More formally, DALY is a time-based measure which adds together years of life lost due to premature mortality with the equivalent number of years of life lived with disability or illness. (Lopez et al., 2006)
DH	District Heating
EfW	Energy-from-Waste
EFOM	Energy Flow Optimization Model
ER	Energy Recovery
ESS	Energy Supply System
EU	The European Union
EYR	Environmental Yield Ratio
GHG	Greenhouse Gas
HMA	Helsinki Metropolitan Area
IE	Industrial Ecology
IWM	Integrated Waste Management
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LF	Landfill
MC	Multi-Criteria technique
MCA	Multiple Criteria Analysis
MCDM	Multi-Criteria Decision Making
MEFLO	A ranking method
MR	Material recovery
MSW	Municipal Solid Waste
OECD	Organisation for Economic Co-operation and Development
PET	Polyethylene terephthalate
RDF	Refuse-Derived Fuel
REF	Recycled Fuel, Recovered Fuel
SISMan	Simple Integrated System Management; model / method
SLCC	Social Life Cycle Costs
SRF	Solid Recovered Fuel
SWM	Solid Waste Management
USD	US Dollar
WDF	Waste-Derived Fuel
WEEE	Waste from Electrical and Electronic Equipment
WH	Waste Hierarchy
WMS	Waste Management System

PART 1

1 *Introduction*

1.1 *Background*

The Waste Hierarchy (WH) of the European Union introduced in the Waste Directive (EEC, 1975) defines the measures that EU member states are obliged to take in order to protect human health and the environment, and to conserve natural resources. Prevention or reduction of waste production and its harmfulness is obviously the primary target in the plans that deal with future waste management issues. However, the amount of municipal wastes is still increasing (Mazzanti & Zoboli, 2008) in spite of the measures taken against this trend. Re-use and recycling are being adapted in different environments to reach savings in virgin materials of different processes.

The general striving to bring down the number of municipal landfills and to increase the re-use and recycling of waste-derived materials across the EU supports debates concerning the feasibility and rationality of waste management systems. The Landfill Directive (EC, 1999) sets the targets for biodegradable municipal waste going to landfills. By the 26th of April 2016, biodegradable municipal waste going to landfills must be reduced to 35 % of the total amount of biodegradable municipal solid waste (MSW) produced in 1995.

The disposal of combustible wastes has been banned in the Netherlands in 1995, in Denmark in 1997, in Germany in 2001, and in Sweden in 2002 (Defra, 2008). Substantial decrease in the volume and mass of landfill-disposed waste flows can be achieved by directing suitable waste fractions to energy recovery. Such materials are e.g. plastics that cannot be feasibly utilized in recycling processes, and other combustible materials containing “non-toxic impurities” that are not harmful to the environment, but may hinder the recycling of the materials.

Composting has been the most obvious treatment method for biowaste in Finland, but the markets for the compost product are not necessarily promising in all areas. In Finland there are areas where separately collected biowaste has been landfilled due to a low demand for the product (SYKE, 2008a; Huhtinen et al., 2007).

Anaerobic digestion is an attractive method, combining the advantages of composting with energy recovery as a “bonus”. For some reason, the advantages of this concept have not been taken into use widely in Finland so far. Only two anaerobic digestion plants treated municipal biowaste in Finland in 2007 (Huhtinen et al., 2007). However, there have recently been several projects preparing ground for anaerobic treatment investments.

There are also human health issues related to waste management. The utilization of biodegradable municipal wastes should be carried out so that the end-product (e.g. compost) is not harmful to people and the environment, and it can be properly used as a harmless and useful recovered material. Ashes from energy recovery processes are usually classified as landfill wastes, but can be used in some cases for different construction or other purposes (e.g. Cheeseman et al., 2005, Ferreira et al., 2003, Kamon et al., 2000, Lin et al. 2003, Lin et al., 2004).

The plans concerning energy recovery from waste have met resistance in Finland. The Finnish Association for Nature Conservation (2008) claims that energy recovery from waste is against the WH. However, the present combustion and flue gas treatment technologies can deal with the pollution components so that the legislative requirements are met, and the development continues. In areas where a suitable heat demand exists, it is feasible to produce electricity and heat in co-generation in a combined heat and power (CHP) plant with high efficiency. The heat load can be for example a district heating (DH) network or steam-needing industrial plant. In Finland DH is the most common way of household space heating. Almost half the building stock is connected to DH grids. In large cities the proportion of DH in space heating rises up to 90 %. Three quarters of the DH energy is produced in co-generation plants (Finnish Energy Industries, 2008a). Co-generation, or CHP, utilizes 80-90 % of the energy content of the fuel (Finnish Energy Industries, 2008b). The term “production” in connection with electric or heat energy refers in this thesis to processes which convert chemical energy of different fuels into utilizable energy forms, such as electricity and district heat. Electricity and heat are considered as products, hence the term production. In this context the term “energy consumption” is also used. It refers to the use of the energy products.

Despite the fact that according to Shafiee & Topal (2008b) there is no clear evidence of actual diminishing of the global fossil energy reserves, they are becoming more and more valuable and expensive energy sources for the mankind, and efforts to save fossil fuels have been made. Furthermore, the consumption of energy is increasing globally (US DOE, 2008). Waste that cannot be feasibly re-used or recycled can be utilized in energy production according to the WH. The fact that the prices of fossil fuels are increasing (Shafiee & Topal 2008a) has given an extra boost to the search of fuels that are cheap, available and have little environmental impacts. The oil prices moved strongly upward between 2002 and 2006 (Askari & Krichene 2008, Henriques & Sadorsky 2008), and the crude oil price has reached the 100 USD/bbl for the first time.

While the mankind is waiting for new technologies and methods (e.g. fusion power, fuel cells, geothermal energy, effective waste reducing technologies) to solve the problems of energy production and waste management in economically and environmentally acceptable ways, we should look around and utilize the technologies and methods that are available for us today.

Global warming caused by greenhouse gas emissions released in the atmosphere is generally considered as one of the most alarming environmental impacts related to both waste management and energy production globally. It is generally acknowledged that landfills and energy production from fossil fuels cause massive greenhouse gas emissions, which contribute to global warming (IPCC, 2007). By substituting fossil fuels by biofuels (e.g. wood, reed canary grass or bio-based share of MSW), greenhouse gas emissions can be decreased. Furthermore, by decreasing the amount of landfilled biodegradable fractions of municipal wastes, also greenhouse gas emissions from landfills are decreased.

The management of energy supply and delivery, as well as waste handling, have traditionally been areas of municipal operation in Finland and many other developed countries. However, the energy and waste management services have usually been separated from each other into independent branches of municipal service management. The goal of both systems is to provide services to “municipal customers”, who finance the operation of both systems. The Energy-from-Waste (EfW) process has been considered mostly as a waste management task, not so much an energy production option. However, the increase of the prices of fossil fuels is bound to force decision-makers to reconsider their point of view about how to arrange municipal, regional and national energy and waste management in the future. Integration of energy supply and waste management to an appropriate extent is certainly one of the issues to be discussed in many areas.

1.2 *Review of studies related to modeling and assessment of waste management and energy supply systems*

Most waste management models consider economic and environmental aspects of the system, but very few consider social aspects, according to Morrissey and Browne (2004). They categorize most waste management models into three categories:

- Cost Benefit Analysis (CBA)
- Life Cycle Analysis (LCA)
- Multi-Criteria technique (MC)

Finnveden et al. (2007) list several more methods and approaches which can be utilized for supporting waste management –related decisions:

- Environmental Impact Assessment (procedural method)
- Strategic Environmental Assessment (procedural method)
- Cost-effectiveness Analysis (analytical method)
- Life-cycle Costing (analytical method)
- Risk Assessment
- Material Flow Accounting
- Substance Flow Analysis
- Energy Analysis
- Exergy Analysis
- Entropy Analysis
- Environmental Management Systems (procedural method)
- Environmental Auditing

The above methods are also applicable in the assessment and design of energy supply systems.

In the following, the reviewed studies of municipal systems have been classified according to the system they study. The idea of this classification is to separate the studies concerning waste management system and energy supply system separately, and the studies concerning both waste management and energy systems, i.e. integrated waste and energy systems. Several methods have been utilized in the studies. The following classification has been used:

- municipal/regional solid waste management systems (Table 1-1): the studies include waste management processes (energy recovery processes are considered here as waste management processes);
- municipal/regional energy supply systems (Table 1-2): energy supply (heat and/or electricity generation and/or acquisition) has been included in the studies at some level;
- integrated municipal/regional waste management and energy supply systems (Table 1-3):

- also other energy generation processes than energy recovery from wastes have been included in the modeling process
- at least the energy recovery part of the waste management system has been connected with the energy supply model.

Numerous articles have been published about the modeling and assessment of waste management systems. The articles deal with various issues from several viewpoints. The publications show that there are several tools, i.e. softwares, available to be utilized in the modeling of waste management systems. A review including a short description of the methods used in some published articles concerning the modeling of municipal waste management systems is presented in Table 1-1.

Table 1-1. Review of municipal solid waste management system –related models.

Reference	Model/method	Model/method description
Abou Najm & El-Fadel (2004)		A linear programming optimization –based spreadsheet interface for optimizing waste management system costs.
Badran & El-Haggar (2006)	MPL software V.4.2	Mixed integer model for the MSW management of Port Said, Egypt. Used for calculating costs/profits.
Beigl & Salhofer (2004)		A scenario-based LCA and cost comparison of waste management alternatives. Used in comparison of recycling alternatives for household waste.
Bovea & Powell (2006)		A scenario-based LCA for solid waste management. Used in comparison of management alternatives for household waste.
Calvo et al. (2007)		Use of environmental indexes to determine the environmental threat posed by the landfills in Chile.
Chang & Chang (1998)		Integrating the idea of the cost-saving principle to energy and material recovery requirements in Taipei (Taiwan) metropolitan area.
Cherubini et al. (2008)		An LCA study of selected alternative scenarios aimed at minimizing the landfill disposal of MSW in Rome, Italy.
Dahlbo et al. (2007)	LCIA, SLCC	A comparison of five different waste management options for newsprint in Finland. The study combines LCA with economic analysis of social life cycle costs (SLCC).
Daskalopoulos et al. (1998)		A computer model for handling, treatment and disposal of MSW. The results of the model are mainly economical figures.

Table 1-1. Continued.

Reference	**Model/method**	**Model/method description**
Diaz & Warith (2006)	WASTED	A software tool for evaluating the environmental effects of municipal solid waste management decisions.
Dornburg et al. (2006)		A tool for optimizing a biomass and waste treatment system to save fossil primary energy.
Döberl et al. (2002)		A cost-benefit analysis and cost effectiveness analysis-based methodology to evaluate the long-term costs and effects of different waste management scenarios in Austria.
Eriksson et al. (2005)	ORWARE	A comparison of combinations of waste fraction treatment methods to landfilling in three Swedish municipalities, covering the use of energy resources, environmental impacts and financial and environmental costs.
Eriksson et al. (2002)	ORWARE	A computer-based model for the calculation of substance flows, environmental impacts, and costs of waste management.
Huang, et al. (2001)		An interval-parameter fuzzy-stochastic programming model for municipal solid waste management. Used for minimizing system costs over the planning horizon.
Kirkeby et al. (2006)	EASEWASTE	An LCA model for evaluating the overall consumption and environmental impacts of municipal solid waste management systems.
Korhonen et al. (2004)		A study constructing indicators for analyzing different waste management scenarios from the point of view industrial ecology (IE).
Marchettini et al. (2007)		An evaluation of the collection, treatment and disposal options of MSW through two indicators: environmental yield ratio (EYR) and Net eMergy.
Minciardi et al. (2007)		A non-linear, multi-objective decision-making model of MSW management, including minimization of four objectives related to economic costs, unrecycled waste sanitary landfill disposal and incinerator emissions.
Reich (2005)	ORWARE	An economics assessment of municipal waste management systems, consisting of elements of life cycle costing (LCC) and LCA.
Rodríguez-Iglesias et al. (2003)	IWM-1	An LCA-based Integrated Waste Management (IWM-1) model to predict the overall environmental burdens and economical impacts of MSW management systems.
Tanskanen (2000a, 2000b)	HMA	A Helsinki Metropolitan area (HMA) model for analyzing on-site collection systems of waste materials separated at the source for recovery.

Table 1-1. Continued.

Reference	**Model/method**	**Model/method description**
Vego et al. (2007)	PROMETHEE, GAIA	Study of the efficiency of providing a waste management system for four counties. Ecological, economic, social and functional criteria included.
Wilson (2002a, 2002b)		A Life Cycle Inventory (LCI) model for evaluating environmental burdens caused by municipal waste management.
Özeler et al. (2006)		Development and comparison of different solid waste management (SWM) system options for Ankara city, utilizing LCA.

Studies concerning the modeling of industrial energy processes are more numerous than publications related to municipal energy production. However, also municipal systems have been modeled from different points of view (Table 1-2).

Table 1-2. Review of municipal energy supply system –related models.

Reference	**Model/method**	**Model/method description**
Alanne & Saari (2006)		A comparison of distributed and centralized energy production from the point of sustainability. Political, economic, social and technological dimensions of regional energy systems are considered.
Bernal-Agustín et al. (2007)		A simulator for calculating the day-ahead electricity market of Spain.
Cherni et al. (2007)	SURE	A multi-criteria decision-support system to assist in calculating the most appropriate set of energy options for providing sufficient power to fulfill local demand in developing countries.
Chicco & Mancarella (2008)		A model for studying the effects of trigeneration compared to separate electricity, heat and cooling energy production. The comparison is based on the trigeneration CO_2 emission reduction –indicator.
Curran et al. (2005)		Workshop resulting in a basic model presenting system boundaries for energy supply systems from the point of view of life cycle inventory data.
Poulin et al. (2008)		A model of a customer electricity demand profile suited for technico-economic studies of large populations.
Thatcher (2007)		A method for constructing regional electricity demand data sets for load duration curve predictions.
Tveit et al. (2006)		A framework for investigating cost-efficient integration of industrial and municipal energy systems.

A strong connection between municipal waste management and energy systems has been acknowledged in several studies. Especially in Sweden there has been interest in studies concerning integrated waste and energy management.

Eriksson et al. (2003) have presented the results of a study including both the waste management and energy system of the city of Jönköping in Sweden. One of the conclusions of the study is that also the local energy company should be involved in the considerations concerning future waste management system options, as energy recovery from MSW affects also the local energy system.

Finnveden et al. (2005) state that waste management systems should be considered together with policies on energy systems. On the basis of a large set of studies, they conclude that the WH is valid as a rule of thumb according to the LCA study concerning different strategies for the treatment of solid waste in Sweden. The focus was mainly on energy use and climate change. The functional unit of the study was treatment of the amount of the included waste fractions collected in Sweden during one year.

Also Holmgren (2006) highlights the relation between energy and waste management in her dissertation. Holmgren studied energy recovery from wastes and its effects on local district heating systems in Sweden from the economic and environmental point of view, and concluded that it can be difficult to design policy instruments for waste incineration due to some conflicting goals for waste management and energy systems. In some cases waste incineration can make CHP production in district heating networks less viable, and this may cause conflicts in matching the goals of waste and energy management.

McDougall et al. (2001) have introduced the IWM-II model, which is based on the principle of Integrated Waste Management (IWM). Energy recovery from waste materials is included in the system. The approach is holistic, and therefore useful in strategic planning of waste management systems. According to McDougall et al. (2001, 15) “IWM systems combine waste streams, waste collection, treatment and disposal methods, with the objective of achieving environmental benefits, economic optimization and societal acceptability. This will lead to a practical waste management system for any specific region.” A sustainable waste and energy management system is in this context a system which is (according to the definition of sustainable waste management by McDougall et al.):

- environmentally effective,
- economically affordable, and
- socially acceptable.

Other studies dealing with the idea of integrating municipal waste management and energy supply are presented in Table 1-3. The perspectives of these studies vary. Generally, it can be concluded that the studied publications do not cover the overall impacts of municipal integrated systems including both waste management and energy supply in its entirety. On the other hand, this is mainly due to the selection of system the boundaries of the studies, not necessarily due to possible deficiencies of the methods and tools. The research concerning integration of these systems has been typically restricted to the impacts of substitution of fossil fuels by waste-derived fuels in energy production. However, both energy supply and waste management in urban areas have contentual commonalities that enable a feasible integration process. The term “feasible” is used in this context to describe a system alternative that is acceptable for environmental, economical and other possible reasons.

Table 1-3. Review of models involving municipal solid waste management and energy supply systems.

Reference	**Model/method**	**Model/method description**
Assefa et al. (2005)	ORWARE	A scenario-based computer tool for LCA of waste management alternatives.
Caputo et al. (2004)		Economic comparison of energy production from refuse-derived fuel (RDF) in only electric power production and CHP.
Cormio et al. (2003)	EFOM	A linear programming optimization method based on the energy flow optimization model (EFOM) to reduce environmental impacts and economical efforts, applied in a case in Southern Italy.
Eriksson et al. (2007)	ORWARE	An LCA tool used in environmental comparison of waste and other fuels in district heating production.
Knutsson et al. (2006)	HEATSPOT	A simulation tool for calculating the responses of Swedish district heating systems to changes (fuel prices, policy measures). The outcomes of the model (changes in energy production and consumption and costs after changes) are given at national level. Waste is considered as one of the fuel options.
Korhonen & Savolainen (2001)		Considerations from the perspective of utilizing the possibilities involved in regional material (waste) flows, energy flows and CHP production.
Sahlin et al. (2002)	HEATSPOT	A study of the impacts of increasing waste incineration on district heating production in Sweden.
Snäkin & Korhonen (2002)		Study of utilizing the concept of IE at regional level (North Karelia region of Finland). Utilization of wood fuels, peat and municipal and household waste and CHP are considered.

There are several methods available for the modeling of waste management and energy systems, including freeware and commercial softwares, as presented above. The outcomes and interpretations of the models are crucially dependent on the initial boundaries and data used in the calculations. Thus, it is important to concentrate on the purposes and principles according to which the actual models should be formed. This includes understanding the original purpose/aim of the processes to be modeled. Softwares are merely tools for calculating the necessary results for decision-making processes.

1.3 *Motives for the research of municipal integrated waste management and energy supply systems, and objectives of the study*

The primary goal of this study is to contribute to the field of municipal/regional system planning by utilizing the idea of IWM and taking it further by combining it to municipal energy system model and forming a larger integrated model including both the waste management and energy management of a region. The integration includes high-efficiency energy production, i.e. co-generation, and waste management, according to the principles of sustainable development. A further goal of this study is to point out the advantages and bottlenecks of integrating municipal energy supply and waste management systems.

The co-operation of municipalities and industry is a complex area containing different political, economical and social aspects. This study has been carried out keeping these different angles in mind. However, the main emphasis is on regional thinking, due to the nature of the municipal energy supply system and waste management system. In regional thinking, the overall effects of the integrated system are those which count. For example, environmental effects are considered as a sum of effects of both the energy and waste management sector. The energy sector covers in this context the acquisition of electricity and heat entirely, not just the acquisition of electricity and heat through energy recovery from wastes.

The author believes that this holistic point of view brings out useful knowledge that can be utilized in future municipal system design processes that involve integration of energy production and waste management.

The principles according to which a municipal service system including waste management and energy supply can be modeled and its feasibility assessed, are presented. The assessment is performed by forming a SISMan (Simple Integrated System Management) model of the integrated system, and utilizing the results of the SISMan model in the MEFLO (Mass, Energy, Financial, Legislational, Other decision-support data) ranking method. The SISMan and MEFLO methods have been developed during the study. The target group of the SISMan modeling and the MEFLO ranking method are primarily the designers of system models for municipal decision-makers.

1.4 *Structure of the thesis*

This thesis is divided into two parts (Fig. 1-1). In the first part, the objectives and scope of this study, as well as a review of the characteristics of energy supply and waste management systems are presented. In the second part, the principles, methods of formation, use and interpretation of the results of the SISMan model and the MEFLO ranking method are presented and discussed.

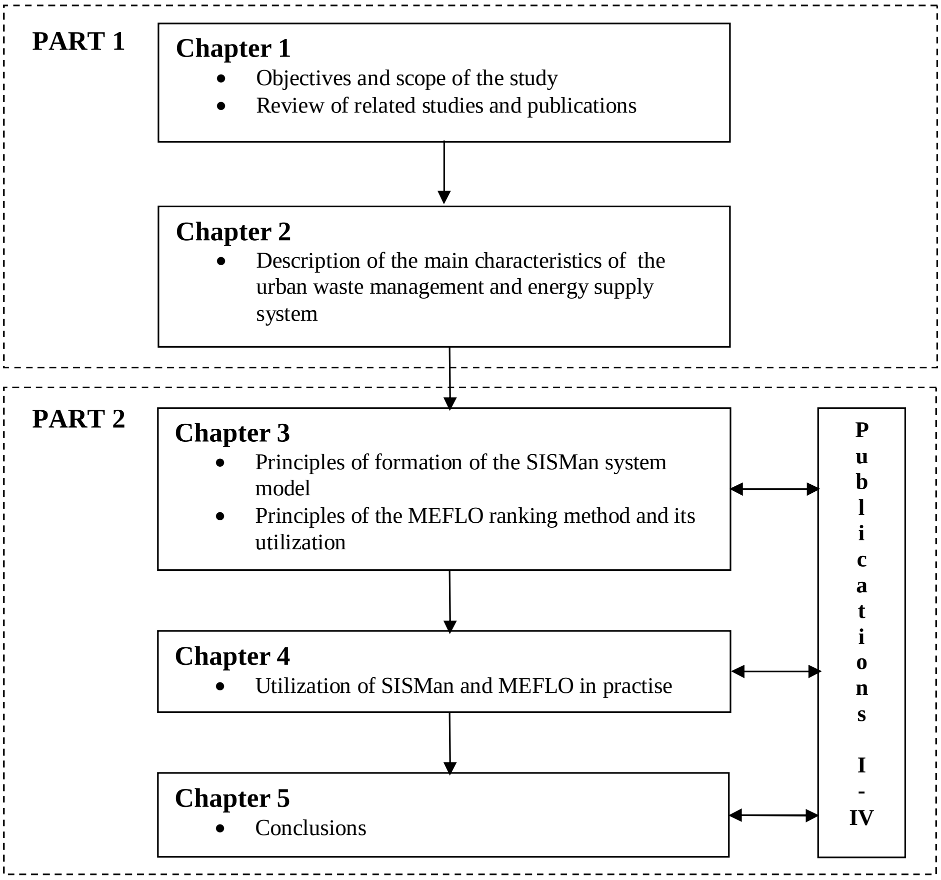

Fig. 1-1. Structure of the study.

Publications I-IV describe the evolution from SISMan 0-model to the present day SISMan model and its utilization according to the MEFLO method. The evolution process is presented in Fig. 1-2.

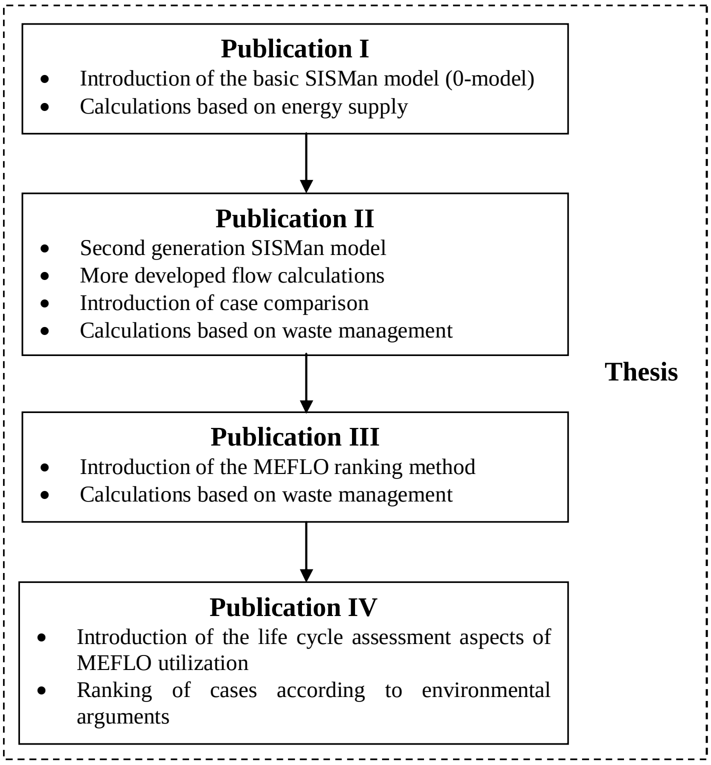

Fig. 1-2. Evolution of SISMan and MEFLO.

Both the SISMan model and the MEFLO method are under continuous development. New technologies and increasing knowledge in environmental effects of different waste treatment and energy production processes help in the development of the system models and their utilization.

2 *Review of the characteristics of Finnish waste management and energy supply systems*

2.1 *Characteristics of Finnish solid waste management system*

According to the Finnish Waste Act (Finlex, 2008) the holder is responsible for the recovery or disposal of waste and the costs caused by it. However, municipalities are principally responsible for the management of MSW. MSW involves in this context household waste and waste of comparable nature, composition and quantity arising from industrial, service or other operations, other than hazardous waste. Municipalities are also responsible for MSW transport, recovery and disposal, as well as for related information sharing and counselling. (SYKE, 2008a)

Municipalities are not responsible for wastes which are under producer responsibility. Producer responsibility involves the responsibility of product manufacturing and importing companies to take care of the costs of waste management of their products when they are no longer used. Product responsibility is applied to the producers and importers of the following products (Finlex, 2008):

- passenger cars, vans and other similar vehicles;
- tyres of motor vehicles and other vehicles and equipment;
- electrical and electronic equipment;
- batteries and vehicles involving accumulators (since September 26, 2008);
- newspapers, magazines, office paper and other similar paper products; and
- packaging (note that professional packagers of products and importers of packaged products are regarded as producers).

Furthermore, municipalities are not responsible for waste arising from industry, commercial enterprises and private service operations. (SYKE, 2008a)

In recent years co-operation between Finnish municipalities in waste management has been increasing significantly. In practice, many municipalities have transferred most of the waste management operations to waste management companies under their command. Approximately 40 collective waste management companies have been founded, representing 4.8 million citizens (approximately 90 % of the total population) (SYKE, 2008a; Population Registration Centre, 2008).

MSW transport is organized by the municipality either as an independent operation or employing another corporation or private undertaking. This method is called a municipal waste transport scheme. MSW transport can also be organized by mutual agreement between the waste holder and the transporter. The latter is called a contractual waste transport scheme. Municipalities define which scheme is applied. (Finlex, 2008)

The environmental costs of the Finnish public were 1200 M€ in 2006. Waste management was responsible of 163.5 M€, and waste water treatment fro 530.5 M€ of the total costs (Statistics Finland, 2008a). Municipal waste management is financed by collecting a municipal waste charge to cover at least the costs of setting up, running, closure and after-care of disposal sites (Finlex, 2008). Municipalities have the right to collect charges to cover other waste management-related costs, such as waste transport, hazardous waste management, counseling, and related authority duties. The waste charge has to correspond to the level of service provided and encourage reduction of the quantity and harmfulness of waste, and recovery of waste (SYKE, 2008a).

The total amount of MSW generated in Finland in 2006 was approximately 486 kg/person annually, which is considerably less than the average MSW generation rate in the EU. Approximately 60 % of MSW comes from households, and the rest comes from small enterprises, the public sector and services. (SYKE, 2008b)

In Finland, approximately 20 kg/person more of MSW than the average of the EU ends up in landfills annually, i.e. 250 kg/person/a (Huhtinen et al., 2007). The MSW generation rate is generally relatively constant throughout the year, compared for instance to the use of heating energy in the northern hemisphere. However, in summer the generation of MSW can be shifted from one area to another. In Finland there are many municipalities with a lot of leisure-time buildings owned by people from other municipalities. During holiday seasons the MSW generation can be multiplied from the normal situation in these communities.

The composition of Finnish MSW in 2006 is presented in Table 2-1. As can be seen in the table, the recovery rates (material or energy) for some separately collected fractions (biowaste, metals, glass, plastics, wood, paper and cardboard, and WEEE, i.e. Waste from Electrical and Electronic Equipment) are already quite high. However, the overall recovery rate of approximately 39 % is still well below the target of approximately 80 % set in Finland by the year 2016 (Huhtinen et al., 2007). Furthermore, the recovery rates do not express whether a treatment method utilized for a certain fraction is the most feasible one from the environmental and economical point of view.

Table 2-1. Municipal solid waste in Finland in 2006 (source: Statistics Finland, 2008b).

MSW classification	**Total amount**	**Recovery as:**				**Landfill disposal**		**Incineration***	
		material		**energy**					
	[10^{3}t]	[10^{3}t]	[% weight]	[10^{3}t]	[% weight]	[10^{3}t]	[% weight]	[10^{3}t]	[% weight]
Mixed waste	1 585	40	2.5 %	51	3.2 %	1 445	91.2 %	49	3.1 %
Separately collected	980	798	81.4 %	118	12.0 %	59	6.0 %	5	0.5 %
Paper and cardboard	422	417	98.8 %			5	1.2 %		
Biowaste	197	162	82.2 %			35	17.8 %		
Glass	136	134	98.5 %			1	0.7 %		
Metals	32	32	100.0 %						
Wood	31	1	3.2 %	26	83.9 %	2	6.5 %	3	9.7 %
Plastics	28	5	17.9 %	23	82.1 %				
WEEE	39	39	100.0 %						
Others	95	8	8.4 %	69	72.6 %	16	16.8 %	2	2.1 %
Total	2 565	838	32.7 %	169	6.6 %	1 504	58.6 %	54	2.1 %

* in incinerator and hazardous waste treatment plant

In 2006, approximately 0.84 Mt of the total 2.6 Mt generated was recovered as materials. About half of the recovered material was paper and cardboard. The 75% collection and recycling target that had been set for the producers was clearly surpassed in 2007 (Paperinkeräys, 2007).

Material recovery of biowaste was 0.16 Mt in 2006. Mroueh et al. (2007) have estimated that in 2005 more than the separately collected amount of biowaste ended up in landfills among mixed waste. It is probably reasonable to assume that the situation continued during 2006. In

Finland the separately collected MSW-based biowaste is commonly processed in tunnel or drum reactors. Open-air windrows are used in the post-maturation process of the compost.

The compost product has had low demand in Finland. Thus, part of the compost has been disposed in landfills. Furthermore, some operational problems have occurred in composting plants, e.g. longer than planned maturation periods and local odour nuisance. Thus, less than expected investments in composting plants have been made. Anaerobic digestion has had only a marginal role in the treatment of MSW-based biowaste in Finland, only two digestion plants were in operation by 2007. (Huhtinen et al., 2007)

Approximately 0.13 Mt glass waste was recovered as material in 2006. Nearly 99 % of the separately collected glass waste was utilized as material. 77 % of the glass packaging was recovered as materials (PYR, 2008).

Approximately 0.22 Mt of MSW was recovered in the energy production. Over a half of this amount consisted of mixed MSW or separately collected energy waste (SYKE, 2008b).

Landfill disposal had been decreasing in Finland for several years, until during 2005 and 2006 a slight increase occurred. In 2004, landfill disposal was 1.4 Mt and in 2006 1.5 Mt. A great majority of this was mixed MSW, but also 0.35 Mt of separately collected biowaste was landfilled. (SYKE, 2008b)

Finland has a well working deposit system for recycling of alcohol and beverage bottles and cans. In 2007, 94 % of the bottles and cans related to the deposit system were returned to collection points located in commercial enterprises. The recycling rates were 97 % for glass and plastic bottles, 89 % for aluminum cans, and 82 % for disposable plastic bottles. The Finnish recovery rates are top class in the world. For example, the average recycling rate for aluminum cans in Western Europe was approximately 58 % and in the United States 45 % in 2006. In Sweden, the recycling rate for deposit PET bottles and aluminum cans is approximately 85 %. In Finland, disposable, recyclable as raw material, bottles became tax free from the beginning of 2008. The target recycling rate for the deposit PET bottles has been set to 80 % by the Council of State. (SYKE, 2008c)

The total greenhouse gas (GHG) emission of Finland was 80.3 $MtCO_2$-eq. (equivalent metric tonnes of CO_2) in 2006. The average allowed GHG emission according to the Kyoto protocol is approximately 71.0 $MtCO_2$-eq./a in 2008-2012. Waste management was responsible for 2.5 $MtCO_2$-eq. GHG emissions in 2006 (Statistics Finland, 2008c). Dahlbo et al. (2000) have estimated that 94 % of the GHG emissions of waste management are caused by landfills. The rest of the GHG emissions come from the collection and transportation of waste, and for a minor part from other waste treatment methods.

According to the basic scenario presented in the Finnish National waste plan (Huhtinen et al., 2007), at least 48 % (by weight), consisting of recycling of 28 % and biological treatment of 20 %, of generated MSW, approximately 2.1 Mt/a, will be recovered as material and 31 % as energy in 2016. The recycled material will consist mainly of paper and cardboard, as has been the case so far in Finland. Also metals, glass, WEEE, scrap-tires and plastics are recycled. Landfill disposal would be 21 % of the mass, the total amount of landfills being 30-40. Furthermore, the target value for MSW generation rate is 400 kg/person/a.

2.2 *Characteristics of the Finnish energy supply system*

In Finland, industry accounts for a higher proportion of total energy consumption than in any other OECD country. Another specific feature of the Finnish energy system is its high overall efficiency in energy production, since about one third of electricity is produced at CHP plants. These CHP plants are connected to the district heating systems of communities, or they supply process heat and steam to industrial installations. In major cities, the share of district heating used for household heating energy is typically 70-90 %. (VTT Energy, 2003)

The utilization of CHP decreases the total amount of required primary energy supply by approximately 11 %, compared to the use of primary energy in separately produced electricity and heat. CHP decreases the use of fossil fuels even more, because most of the CHP plants are decentralized and near local energy resources. (Finnish Energy Industries, 2008c)

The total electricity production in Finland was 77.8 TWh in 2007. CHP accounted for 34 % and nuclear power for 29 %, condensing power production for 18 %, hydropower production 18 % and wind power 2 % of the total electricity production. (Statistics Finland, 2008d)

District heat production was 33.5 TWh and industrial heat production 61.7 TWh in 2007. 76 % of district heat and 80 % of industrial heat was produced with CHP in 2007. District heat was produced mainly with natural gas and hard coal. 62 % of the total district heat was produced with fossil fuels, 14 % with renewable fuels and 21 % with peat. (Statistics Finland, 2008d)

Due to the cold climate, the heating of residential and service buildings in Finland accounts for a relatively high percentage of the total primary energy consumption, i.e. about 22 %. Almost all big towns in Finland use CHP for district heating. (VTT Energy, 2003)

The shares of the total fuel consumption in the production of electric and heat energy in 2007 were 23 % for waste liquors, 22 % for coal, 18 % for natural gas and 15 % for peat. Fossil fuels accounted for 45 % of the total energy, and the share of renewable fuels was 36 %. The use of recycled fuels increased from 2006, as large combustion plants acquired environmental permits meeting the requirements set in the Waste Incineration Directive. (Statistics Finland, 2008d)

The decrease in the total fuel consumption in 2007 was due to good water resource situation in the Nordic countries. Hence, more hydropower was imported to Finland to compensate for domestic electricity production. (Statistics Finland, 2008d)

The energy sector accounts for a major part of the GHG emissions of Finland. In 2006, energy production was responsible for 32.9 Mt CO2-eq. GHG emissions of the total 80.3 Mt CO2-eq.. A relatively large range of variation is typical for the Finnish GHG emissions. Between 1990 and 2006, the average variation was in the range of 5 MtCO_2-eq., mainly due to the variation in the emissions of the energy sector. (Statistics Finland, 2008e)

The heat demand in the municipal district heating grids depends on the weather conditions. In this study the features of the Finnish climate are used as the reference. A combined heat and power production -based system has been selected as an example of a municipal energy supply system, due to its high efficiency and relevance in the Scandinavian climate. CHP is considered as the best available technology (BAT) in areas where heat demand exists.

Space heating is needed during autumn, winter and spring. In district heated buildings, the district heat is used also for domestic hot water and sometimes for air-conditioning purposes. The fluctuation of heat energy demand causes challenges for the design and operation of municipal heating networks. The fluctuation in heat demand can be divided into three categories:

- Annual heat demand fluctuations: space heating energy demand takes place in autumn, winter and spring. During the summer season the heat demand consists of heating domestic hot water.
- Weekly heat demand fluctuations: the heat demand is lower during weekends.
- Daily (hourly) heat demand fluctuations: a morning peak caused by the use of domestic hot water, and an evening peak caused mainly by the use of domestic hot water.

Furthermore, changes in the weather conditions cause fluctuations in the heat demand.

In Fig. 2-1, a hypothetical annual fluctuation of municipal energy demand is presented. District heating systems are normally designed so that approximately 50 % of the peak load, i.e. instantaneous heat demand during the coldest hours of winter, can be produced in the main CHP plant. In larger networks heat can be produced in several CHP plants. The excess heat energy needed during peaks is produced in smaller peak-load production units, which are heat-only plants.

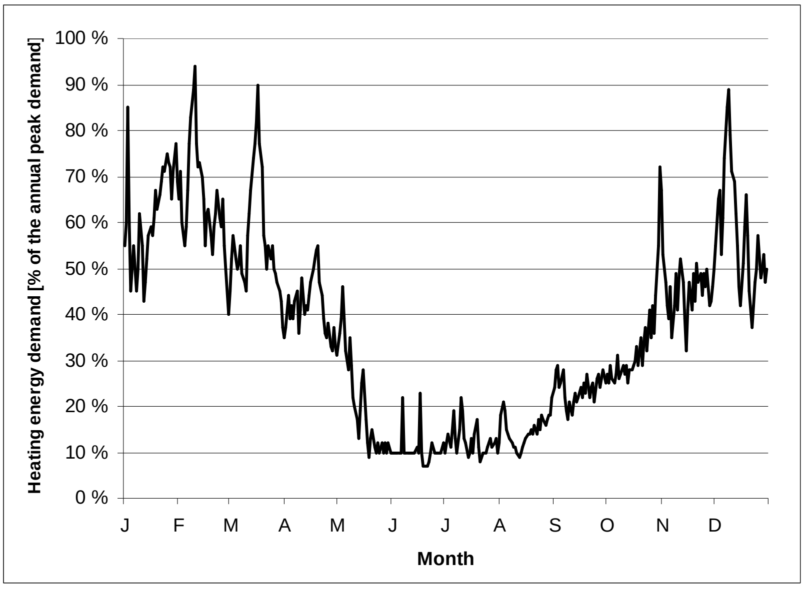

Fig. 2-1. Example of annual fluctuation of heat demand in the Finnish environment (adapted from ETY, 1989).

Electricity demand is much more constant annually than heat demand. However, same kind of peaks can be identified also in the electricity demand:

- Annual electricity demand fluctuations: the electricity demand is somewhat higher during the winter season due to electricity used in heating. During summer the electricity demand may decrease due to the holiday season.
- Weekly electricity demand fluctuations: the electricity demand is lower during weekends.
- Daily (hourly) heat demand fluctuations: peaks in the morning, mid-day and evening due to start-up of air-conditioning systems and use of domestic hot water heated with electrical energy.

In practice, electricity is needed in space heating in spite of district heating being the main space heating form. There are always areas or buildings that are not connected to the district heating grid for various reasons. For example, in scarcely populated areas the investments in district heating grids are often too high to be carried out by the municipality. Furthermore, the district heating grids do not always cover the highly populated areas entirely. This may be due to the strategic planning of a municipality, or lack of financial resources.

CHP production has a high overall annual efficiency, which in Finland is often 85-90 %. This is much higher than the 40-45 % efficiency of a condensing power plant generating only electricity. Separate power and heating plants need approximately 40 % more fuel than a corresponding CHP plant. (VTT Energy, 2003)

In municipal district heating systems the heat demand of the grid (customers) is the main design factor of the CHP plant(s). The plant is designed to meet a certain heat load (for example 50 % of the expected peak load). Electricity is produced according to the power-to-heat ratio (characteristic for the selected technology) of the CHP plant. Normally, electricity is purchased from outside to compensate for the electricity demand of the electricity grid (customers). Compiling the electricity demand from several sources (own production first, then compensating top-up energy) is not easy. Market circumstances can create situations where the production of electricity in an own CHP plant is more expensive than the electricity available in the electricity market. Such a situation is created in Finland for example when there is cheap hydropower-based electricity available, mainly exported from Norway.

PART 2

3 *Methods*

3.1 *Basic frame formation*

The procedure of the SISMan model formation for studying the characteristics of integrated municipal service systems based on the structure of Finnish waste management and energy supply systems is presented below. The aim of the routine is to find the most viable, i.e. economically and environmentally acceptable, system solution for a region from the point of view of the different interest groups involved in municipal system solutions:

- the inhabitants, who finance both the waste management and energy supply system;
- the waste management company;
- the energy company; and
- other possible interest groups, such as companies dealing with REF (recycled fuel, recovered fuel) production, recycling processes, waste transport etc.

One of the main principles in building the model structure has been the requirement that the waste management system solution for the area under study has to be realistic. The proposed system option has to be based on proven technologies, i.e. processes which are used widely in similar circumstances, or otherwise proven reliable. This leads indisputably to the conclusion that the final system proposal has to be selected from a group of pre-selected alternatives. In other words, the selection process has to be based on a case comparison of different system alternatives. The results have to be transparent, i.e. easy to trace to the original process models, and easy to interpret. The idea is that the proposed decision-support method will not favor any technology or policy related to waste management and energy production.

Although it is probably not possible to find a solution which realizes all the expectations of the interest groups simultaneously, it is possible to find a solution which realizes the original purpose of the waste management and energy service systems most efficiently, which is to serve the citizens of the municipalities. In this respect, it is possible to define “a minimum overall impact system” which causes optimum financial and environmental effects. This can be done by selecting a set of system alternatives and performing a comprehensive comparison involving economical and environmental aspects. Usually this leads to a compromise between the cheapest and environmentally superior alternative.

In Fig. 3-1, three basic methods for waste management are presented in relation to resource efficiency. Resource efficiency means in this context the efficiency of use of energy and natural resources during the whole life cycle of products or services from the use of natural resources to disposal or recovery of materials or energy.

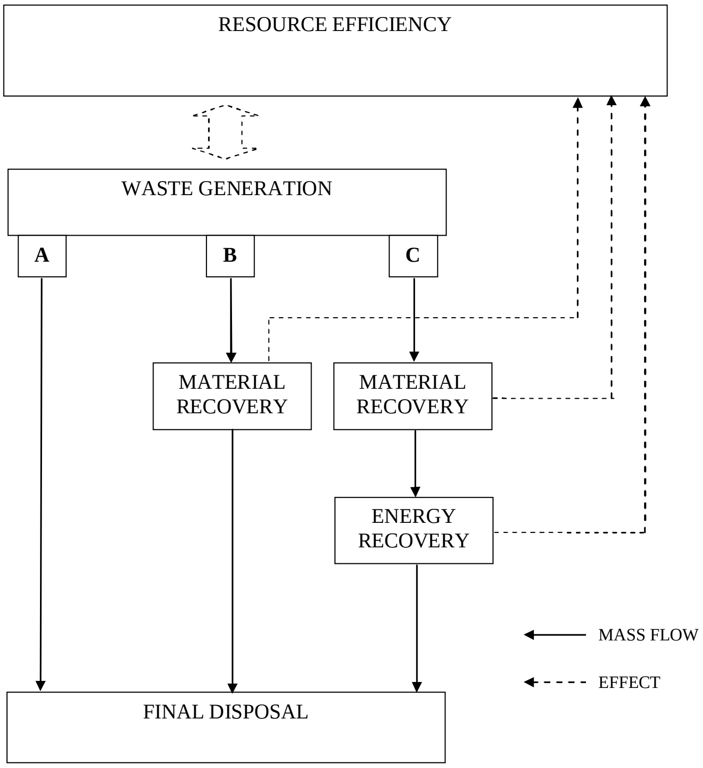

Fig. 3-1. Interrelationship between resource efficiency and three waste management options.

Alternative A represents the past system, where all the generated waste ended up in landfills. This alternative is no longer in use in developed countries. In alternative A, there is no feedback effect to resource efficiency.

In system B, material recovery is added to the original landfill-based system. The resource efficiency of the waste management system increases due to the savings in the virgin material use in products, and due to the decreased amount of landfill waste. Non-recyclable materials are directed to landfills. In alternative B, energy savings due to recycling of materials back to product manufacturing can be achieved. However, this is not always the case.

In alternative C, energy recovery is added to system B. This increases the resource efficiency of the system further, because there are non-recyclable materials which can be utilized for energy production purposes. In alternative C, an energy supply system that utilizes the waste-derived energy is integrated with the waste management system. In addition to alternative B, by bringing the energy recovery option into the consideration, a more complete comparison of the benefits and drawbacks of realistic system options can be made to support the final decision-making. The material recovery process can be also a 0-process, i.e. material recovery is not present in the system.

The alternatives in Fig. 3-1 can be described as different phases of system development. Alternative A represents inefficient history (i.e. all utilizable resources of waste streams are lost), B is a transition-phase system (i.e. some utilizable resources are still lost), and system C represents an efficient municipal system (i.e. all utilizable waste resources are recovered), including integration to other systems.

3.2 *Formation of the SISMan model for energy supply and waste management systems*

The starting point in the formation of a SISMan model is defining the system to be modeled. At this stage it is necessary to simplify the operation of the system as much as possible. A holistic approach is used. According to McDougall et al. (2001, 23) it has three main advantages:

1. It gives an overall picture of the system. Such a view is essential for strategic planning.
2. The overall burden of the waste management system is the only rational approach, otherwise reductions in environmental burdens of one part of the process may result in greater environmental burdens elsewhere.
3. Economically, by looking at the whole system it is possible to determine whether the whole system operates efficiently and whether it could run at break-even or at a profit.

The waste management model is outlined in this context to concern a system involving material recovery options (i.e. recycling processes for different waste fractions and composting of biowaste), energy recovery from municipal solid waste, and landfill disposal. Anaerobic digestion and energy production from landfill gas are not considered in this context. These choices have been made in order to make the presentation of the principles of forming an integrated model as simple and easy-to-follow as possible. However, anaerobic digestion and landfill gas utilization can be easily included in the model. The energy system of the integrated model includes production of heat and electricity, as well as purchasing of top-up electricity.

The term SISMan has been selected to describe both the method and the model formed according to the method. The SISMan model includes the processes and flows of the system. The analogy is much the same as presented by McDougall et al. (2001, 15) for integrated waste management. The key features of IWM are:

- an overall approach;
- use of a range of collection and treatment methods;
- handling all materials in the waste stream;
- environmentally effective;
- economically affordable; and
- socially acceptable.

The features listed above are also features of the SISMan concept. The main difference is that in this context the model is expanded to cover the whole energy supply system.

In the SISMan concept, top-down strategy is utilized in model forming. In top-down thinking, first an overall picture of the system is formed, and after that more detailed descriptions of the processes included the system can be formed. A top-down view points out the areas of utilizable synergies between different municipal service systems (crossing areas in Fig. 3-2). The three basic municipal service systems, i.e. water supply, waste management and energy supply, are necessities which a municipality has to be able to secure for its inhabitants. The water supply system (includes the production and supply of domestic drinking water and waste water treatment) is connected to the waste management system normally through the treatment of the sludges from the waste water treatment plant, and to the energy supply system through the consumption of electrical and heat energy, and possibly production of energy, e.g. in the case of utilization of anaerobic digestion of sewage sludge. In this context, the water supply system is not included in the consideration. However, e.g. thermal treatment of sewage sludge can easily be added to the basic model.

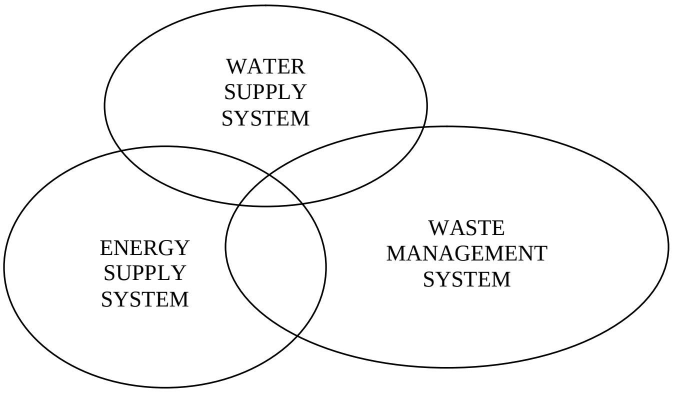

Fig. 3-2. An example of a top-down view of municipal service systems.

The formation of the SISMan model for an integrated municipal solid waste management and energy supply system is carried out first by forming individual sub-models of both systems and then combining them. A top-down approach model of such an integrated system is presented in Fig. 3-3. In the schematic presentation of the integrated system, both systems are framed with dashed lines. The arrows between the different processes describe interaction (mass, energy and impacts) between the processes and the two service systems. Financial flows of the system have been left out in this context for the sake of simplicity.

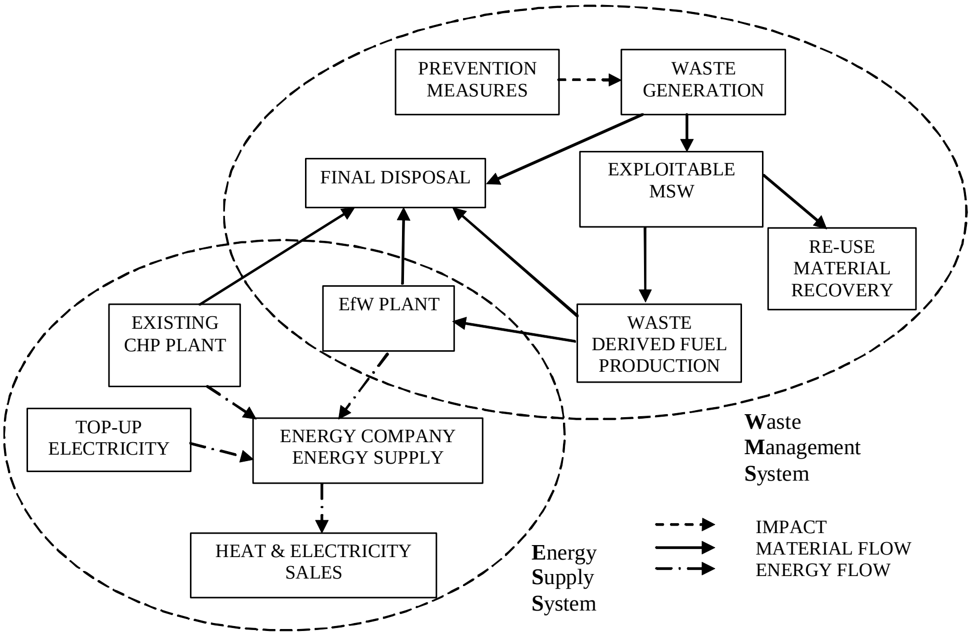

Fig. 3-3. Integrated system model for municipal waste management and energy supply (Publication III).

The integrated system presented in Fig. 3-3 is based on a hypothetical case, which involves integration of a waste management system (existing, new or upgraded) to an existing energy supply system. This is the case in many developed countries when waste management is developed to meet the more and more stringent requirements set for waste management efficiency.

This kind of a base model can be used as a base option in decision-making procedures involving new systems, and in assessment processes concerning existing systems. For example, the base model could provide municipal decision-makers with a minimum waste treatment cost to be billed from customers according to the system structure. This minimum cost could be compared with the actually billed cost to check if the target of financial efficiency has been reached. The model could be also used by the authorities in studies concerning the effects of the level of different taxation (e.g. landfill tax, CO_2-trade) on the costs of recycling, energy recovery and landfill disposal.

It is important to be aware of the fact that a SISMan model is always a case-specific model determined by different characteristics typical to the specific environment, such as spatial, technological, cultural and political aspects. The quality of the information has effects on the forming of the model. Information concerning the quality of MSW is perhaps the most important factor in the model forming process. This is emphasized by e.g. McDougall et al. (2001) by stating that the best system for any given region will be determined locally. Hence, a totally general SISMan model does not exist.

The simplified SISMan model of municipal waste management and energy supply system includes the following assumptions:

- The two systems are assumed to operate as one integrated service system providing waste management and energy services for customers (i.e. citizens of the area).
- The waste management company and energy company have agreed on the following principles:
    - The prices of district heat and electricity will not be raised because of the investments in energy recovery system, i.e. WDF (waste-derived fuel) manufacturing and energy recovery plant. Price variations would complicate the interpretation of the results.
    - The WDF production plant is owned and operated by the waste management company. The investment is amortized by waste management –related payments, i.e. REF and/or waste management fee.
    - The EfW plant is owned and operated by the energy company. The energy company will use the savings from energy recovery, i.e. savings in fuel prices, to amortize the EfW plant investment. The rest of the amortization is paid by raising the waste management fee, if necessary.
- The waste generation rate is constant (after prevention measures) annually. Decrease of the total waste amount is not considered a responsibility or possibility of the waste management system, as waste is assumed to be already generated. Source separation is utilized. Only household waste is considered in this context.
- The energy demand, i.e. electricity and heat, is considered as annual total energies. The annual energy demand for heat and electricity is constant. The existing energy production plant is designed to meet the heat demand of the grid. Top-up electricity from electricity exchange is used to cover the gap between own electricity production and the demand.
- CHP is utilized in energy production, as it has higher efficiency than separate electricity and district heating production.
- The waste management company and the energy company are considered as non-profit units in order to maintain transparency. The purpose is to determine a certain minimum level of costs calculated for the system.
- The effects of transportation of waste and fuels are assumed equal in every system alternative. Hence, transportation can be left out of the consideration in the preliminary comparison when the differences between impacts caused by different system alternatives are under comparison. Transportation can be added as a sub-model later, when the relevant characteristics, e.g. the transportation distances in each system alternative, can be more accurately known.

The basic principle in forming and utilizing a SISMan model for an integrated system can be described as follows:

- formation of a basic flowchart including all “possible flow alternatives” for each material, energy and financial stream;
- formation of cases where different flow-routes are included in different cases; and
- calculation of flows in different cases, comparison of the results of different cases.

Basically, the SISMan model should be formed so that it can provide the decision-makers with all the results that can be calculated. In other words, all material, energy and financial flows required for the decision-making process will be provided by the SISMan model. The rest of the information used in municipal, or analogous, decision-making processes will not be included in the SISMan model and its equations.

3.2.1 *Mass flow model*

MSW is divided into different waste fractions which are easy or relatively easy to separate from each other according to their characteristics. The fractions should be as homogenous as possible. The number of fractions and fraction data depend on the source separation method selected for the area under study. The fractions are given the status of recoverable or non-recoverable according to their characteristics.

The mass flows of the integrated system model are presented in Fig. 3-4. The total waste amount is determined as:

$$\sum f_{MSW} = \sum_{i} f_i \qquad (i = 1, \ldots, n_f) \qquad (3.1)$$

where Σf_{MSW} is the total sum of municipal solid waste fractions [t/a, kg/person/a etc.], f_i is the amount of fraction i [t/a, kg/person/a etc.], and n_f is the number of fractions.

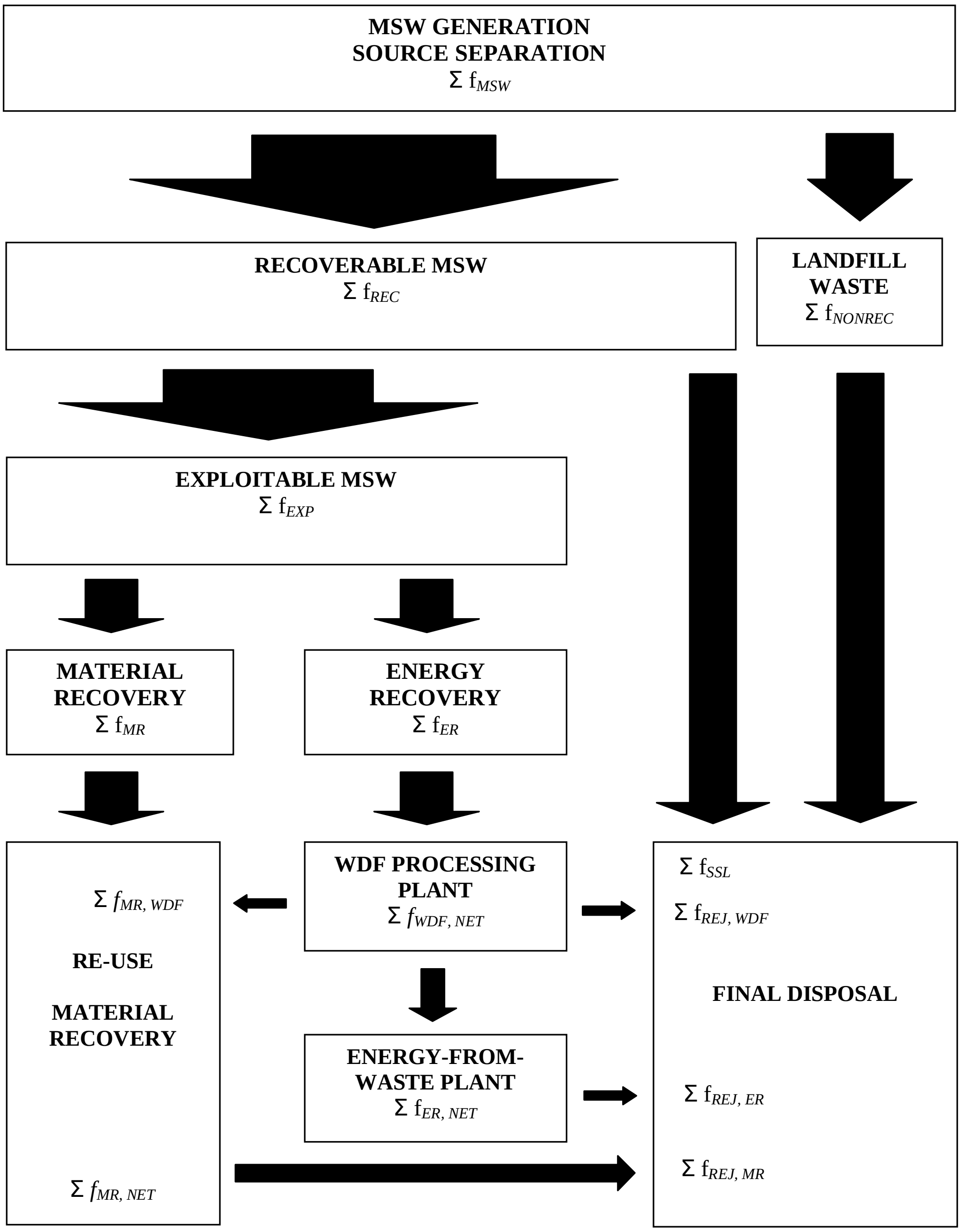

Fig. 3-4. Mass flows of the system.

In an ideal system, the total waste can be classified as recoverable (i.e. recoverable as material or energy) or landfill waste (i.e. non-recoverable or inert waste fractions). The total MSW amount is divided into the following streams:

$$\Sigma f_i = \Sigma f_{REC} + \Sigma f_{NONREC} \tag{3.2}$$

where Σf_{REC} is the recoverable MSW streams [t/a, kg/person/a etc.] and Σf_{NONREC} is the non-recoverable MSW fractions, basically landfill waste [t/a, kg/person/a etc.].

In an ideal SISMan model (i.e. free of losses) it is assumed that one flow is directed entirely to one treatment process (i.e. material or energy recovery, or landfill disposal). In the real world this is not the case. Due to source separation losses, i.e. losses that occur in the source (e.g. households, industry, trade), the actual amount of recovered material flows is smaller than in the theoretical case of equation 3.2. This leads to a situation where parts of recoverable waste end up in the landfill waste stream. This can be due to unsuccessful source separation, or differences in source separation policies between different areas or types of households. Due to incomplete source separation, material streams to landfill increase, and the total recovery rate decreases. The theoretically maximum recoverable waste flow is:

$$\Sigma f_{REC} = \Sigma f_{EXP} + \Sigma f_{SSL} \tag{3.3}$$

where Σf_{EXP} is the exploitable MSW streams [t/a, kg/person/a etc.] and Σf_{SSL} is the source separation loss [t/a, kg/person/a etc.].

The term exploitable MSW has been chosen to represent incomplete source separation. Parts of recoverable waste streams are lost in the landfill stream. Exploitable waste (recovered recoverable waste fractions) is defined as:

$$\Sigma f_{EXP} = \Sigma f_{MR} + \Sigma f_{ER} \tag{3.4}$$

where Σf_{MR} is the waste streams directed to material recovery processes [t/a, kg/person/a etc.], and Σf_{ER} is the waste streams directed to the energy recovery process [t/a, kg/person/a etc.].

Source separation efficiency defines the share of the fraction that is correctly separated, i.e. separated into right bins:

$$\eta_{SS,i} = \frac{f_{EXP,i}}{f_{REC,i}} \tag{3.5}$$

where $\eta_{SS,\ i}$ is the source separation efficiency of fraction i [-], $f_{EXP,i}$ is the recovered , i.e. exploitable, part of fraction i [t/a, kg/person/a etc.], and $f_{REC,i}$ is the theoretically or technically recoverable fraction [t/a, kg/person/a etc.].

The amount of exploitable waste can now be calculated as:

$$\Sigma f_{EXP} = \sum_i \eta_{SS,i} \cdot f_{REC,i} \qquad (i = 1, \ldots, n_f) \tag{3.6}$$

The rest of the fraction is transported to landfill with mixed waste. In a regional system model, source separation efficiency can also represent the differences between different areas (or districts) inside the waste management system. Different areas can utilize different source separation policies. This can lead to a situation where a certain fraction is collected as recoverable fraction from one area, and from another area the same fraction is collected with other various fractions and transported to landfill.

The total waste amount can now be divided into three streams:

- exploitable MSW, i.e. recoverable fractions received to recovery;
- landfill waste, i.e. non-recoverable fractions; and
- source separation loss, i.e. the non-recovered part of recoverable fractions.

Rejects in the material recovery processes are disposed to landfill. The net material recovery is defined as:

$$\sum f_{MR,NET} = \sum f_{MR} + \sum f_{MR,WDF} - \sum f_{REJ,MR} \tag{3.7}$$

where $\Sigma f_{MR,NET}$ is the net amount of recovered materials [t/a, kg/person/a etc.], $\Sigma f_{MR,WDF}$ is the recoverable materials extracted from the WDF manufacturing process [t/a, kg/person/a etc.] and $\Sigma f_{REJ,MR}$ is the rejects to landfill from the material recovery processes [t/a, kg/person/a etc.].

Waste-derived fuel (e.g. REF, RDF or SRF) is produced in a specific manufacturing plant including all necessary equipment to produce fuel of required quality. The net amount of produced WDF is:

$$\sum f_{WDF,NET} = \sum f_{ER} - \sum f_{REJ,WDF} - \sum f_{MR,WDF} \tag{3.8}$$

where $\Sigma f_{WDF,NET}$ is the net amount of produced waste-derived fuel [t/a, kg/person/a etc.], and $\Sigma f_{REJ,WDF}$ is the rejects to landfill from the WDF manufacturing process [t/a, kg/person/a etc.].

The net amount of waste recovered in the energy recovery process is:

$$\sum f_{ER,NET} = \sum f_{WDF,NET} - \sum f_{REJ,ER} \tag{3.9}$$

where $\Sigma f_{ER,NET}$ is amount of waste flows utilized as energy [t/a, kg/person/a etc.] and $\Sigma f_{REJ,ER}$ is rejects to landfill from the EfW plant [t/a, kg/person/a etc.].

The material stream to landfill is:

$$\sum f_{LF} = \sum f_{NONREC} + \sum f_{SSL} + \sum f_{REJ,MR} + \sum f_{REJ,WDF} + \sum f_{REJ,ER} \tag{3.10}$$

where Σf_{LF} is the waste flows to landfill [t/a, kg/person/a etc.].

From Eq. 3.1-3.9:

$$\sum f_{MSW} = \sum f_{MR,NET} + \sum f_{REJ,MR} + \sum f_{WDF,NET} + \sum f_{REJ,WDF} + \sum f_{NONREC} + \sum f_{SSL} \tag{3.11}$$

3.2.2 *Energy flow model*

The energy flows of the integrated system are presented in Fig. 3-5. In the original situation, i.e. reference state, the energy company produces heat in a CHP plant (P1) to meet the annual demand of the heating grid, in this context the district heating grid. Electricity is produced in P1 according to the power-to-heat ratio of the plant. The gap between own electricity production and electricity demand is purchased from electricity exchange.

In the evolutionary state, an investment in an EfW (P2) plant has been made. The heat demand will be produced in P2 and P1 plants so that P2 operates in a constant annual heat and electricity load, and P1 operates as a control plant which produces the gap between the heat demand and heat production of P2. As in the reference state, electricity is produced in P1 according to the power-to-heat ratio characteristic to the technology, and the gap is purchased from electricity exchange. In practice, the load of an EfW plant varies during the year due to maintenance shutdowns. There can be also fluctuations in the load during the operational periods of the plant. However, the main principle is to operate P2 with as constant load as possible during each longer period. This will usually minimize the annual emissions from the plant, as the transition phases from one load to another are more difficult to control than a steady load run. Typically the greatest flue gas emissions are produced during the start-up and shut-down phases.

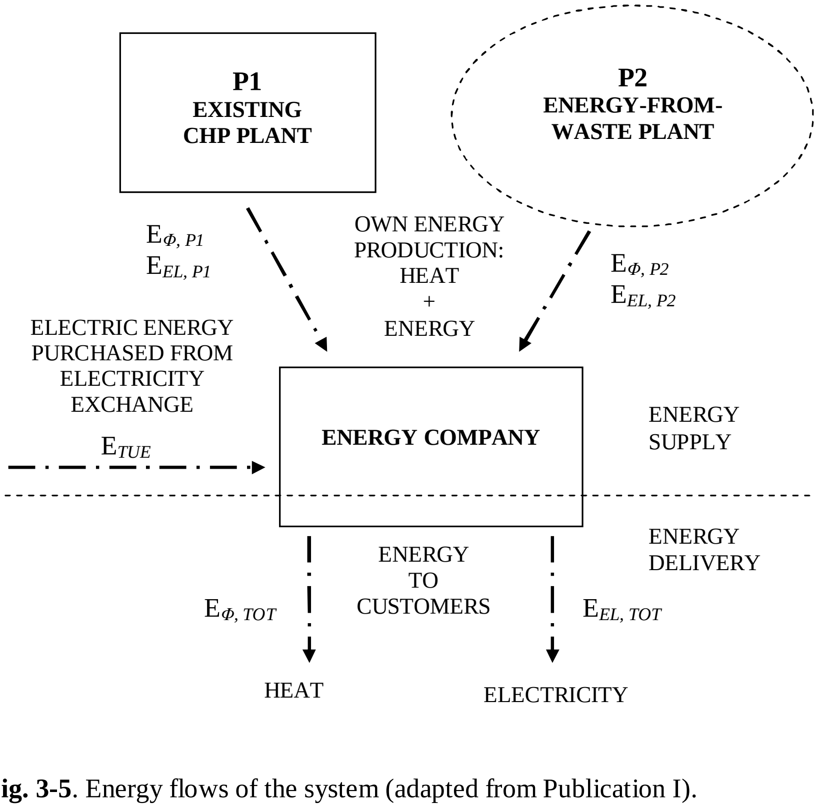

Fig. 3-5. Energy flows of the system (adapted from Publication I).

The energy supply streams of the system are:

$$E_{TOT} = E_{EL,TOT} + E_{\Phi,TOT} \tag{3.12}$$

where E_{TOT} is the total energy supply [GWh/a], $E_{EL,TOT}$ is the total electricity supply [GWh/a], and $E_{\Phi,TOT}$ is the total heat energy supply [GWh/a].

The electricity supply is:

$$E_{EL,TOT} = E_{EL,P1} + E_{EL,P2} + E_{TUE} \tag{3.13}$$

where $E_{EL,P1}$ is the electricity produced in the existing plant P1 [GWh/a], $E_{EL,P2}$ is the electricity produced in the planned EfW plant P2 [GWh/a], and E_{TUE} is electricity bought from electricity exchange [GWh/a].

The heat supply is:

$$E_{\Phi,TOT} = E_{\Phi,P1} + E_{\Phi,P2} \tag{3.14}$$

where $E_{\Phi,P1}$ is the heat produced in P1 [GWh/a], and $E_{\Phi,P2}$ is the heat produced in P2 [GWh/a].

In this context it is assumed that the energy transportation losses for heat and electricity are included in the definitions of process efficiencies of P1 and P2. Hence, the energy delivery (sales) of the system is:

$$E_{SALE} = E_{TOT} \tag{3.15}$$

$$E_{EL,SALE} = E_{EL,TOT} \tag{3.16}$$

$$E_{\Phi,SALE} = E_{\Phi,TOT} \tag{3.17}$$

where E_{SALE} is the total sold energy including electricity and heat [GWh/a], $E_{EL,SALE}$ is the total sold electricity including own production and purchased electricity [GWh/a], and $E_{\Phi,SALE}$ is the total sold heat energy including district heat and process heat [GWh/a].

3.2.3 *Financial flow model*

The financial flows of the system are presented in Fig. 3-6. The customers of the energy company and the waste management company finance the operation of the integrated system, i.e. the area inside the largest dashed line. The waste management fees are directed to cover the costs of

- landfill disposal of non-recoverable waste, source separation losses, rejects from WDF manufacturing and material recovery processes;
- material recovery processes, i.e. recycling and composting; and
- WDF manufacturing.

The energy bill covers

- the heat production costs of P1 and P2;
- the electricity production costs of P1 and P2; and
- the electricity purchasing costs from electricity exchange.

The investment costs of the WDF production plant and P2 are divided between the waste management system and energy system. First, possible savings in the energy supply costs are used in amortizing the investments. If the savings are not big enough to amortize the investments in the required payback time, the rest of the cost is covered by raising the WDF price. The raise is transferred further to be billed in the waste management fee.

Depending on the environment and circumstances the model has been built for, the money flows can stay inside the integrated system (i.e. the process is owned and operated by the energy company or the waste management company) or leave the system (i.e. the process is owned and/or operated by an external service provider).

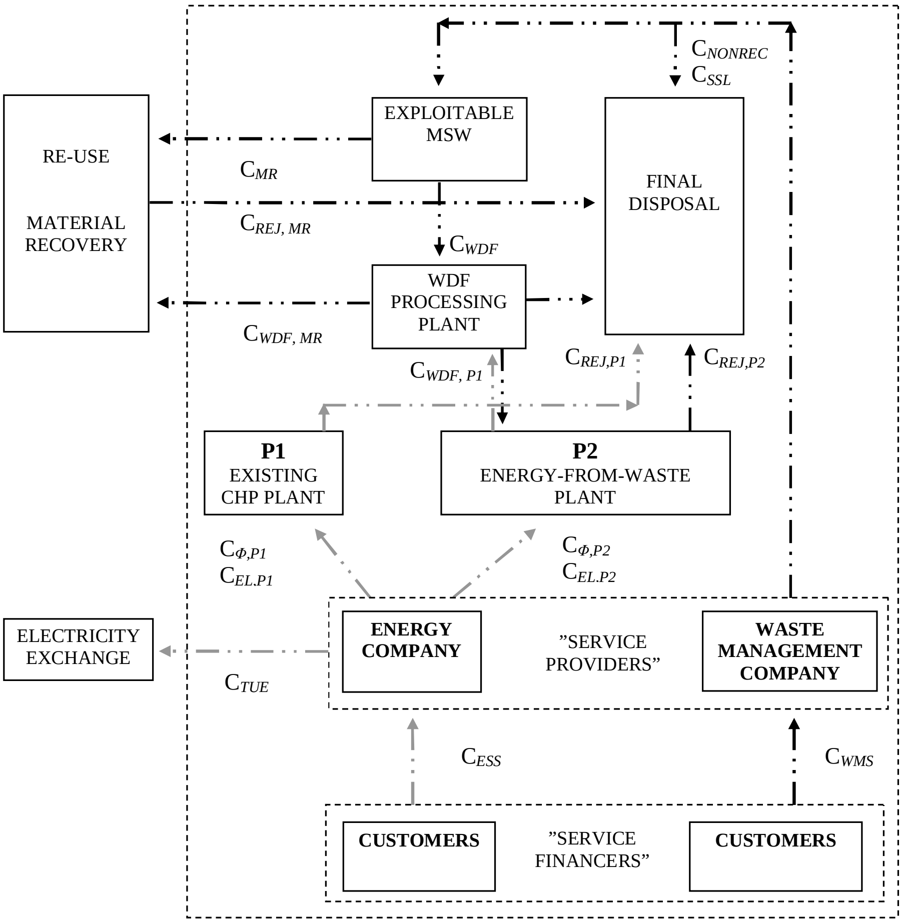

Fig. 3-6. Financial flows of the system (adapted from Publication III).

The money flows of the system are presented in this context from the customers' point of view. The costs are divided according to the processes they are related to: landfill disposal, material recovery processes, the WDF manufacturing process, energy production in P2, energy production in P1 and electricity acquisition from outside the system. All the processes can be interpreted as services. The costs include the investments and the operational and maintenance costs of the individual processes. In other words, the process costs are the costs attached to the customer's waste management and energy bills to cover the operations and services needed to provide the waste management service and energy supply for the customer. When considering the processes as services, they can be treated in the same way in the calculations regardless of whether they are provided from outside the system or from within the system. This gives more flexibility in the formation of different municipal service systems.

The overall waste management cost is the sum of the process costs involved:

$$C_{WMS} = C_{NONREC} + C_{SSL} + C_{MR} + C_{WDF} + C_{WDF,MR} - \left(C_{REJ,MR} + C_{REJ,P1} + C_{REJ,P2}\right) \qquad (3.18)$$

where C_{WMS} is the "break even cost" of the waste management system [€/a/person or €/t_{MSW}], C_{NONREC} is the costs of disposal of non-recoverable landfill waste [€/a/person or €/t_{MSW}], C_{SSL} is the costs of landfill disposal of source separation loss [€/a/person or €/t_{MSW}], C_{MR} is the costs of material recycling, i.e. fees billed by material recovery processors [€/a/person or €/t_{MSW}], C_{WDF} is the costs of WDF manufacturing including landfill payments of rejects from the WDF process and the gate fee to or from P1 [€/a/person or €/t_{MSW}], $C_{WDF,MR}$ is the costs of recoverable materials from WDF manufacturing to material recovery [€/a/person or €/t_{MSW}], $C_{REJ,MR}$ is the landfill fees for rejects from material recovery processes (from an outside service provider) [€/a/person or €/t_{MSW}], $C_{REJ,P1}$ is the landfill fees for disposal of rejects from plant P1 (ashes + APC wastes) [€/a/person or €/t_{MSW}], and $C_{REJ,P2}$ is the landfill fees for disposal of rejects from the EfW process, i.e. ashes and APC wastes [€/a/person or €/t_{MSW}].

Some rejects have a decreasing effect on C_{WMS} in equation 3.17. This is due to the principle of considering the processes as services. For example, the cost of energy production (Equation 3.19) in P1 includes the costs caused by the final disposal of the ashes and APC waste. Disposal of the ashes transfers money from the energy system to the waste management system. Hence, the cost decreases the overall waste management cost. The same analogy is applied for the rejects from material recovery and the rejects from P2. The fuel costs of P1 are included in the energy prices.

C_{WMS} can be interpreted as the minimum operating cost of the integrated system from the waste management point of view. In practice, additional costs (e.g. reservations for future investments etc.) can be added to this cost before billing the customer.

The energy supply system-related costs of the integrated system are:

$$C_{ESS} = C_{TUE} + C_{EL} + C_{\Phi} \qquad (3.19)$$

where C_{ESS} is the costs due to energy supply, including acquisition and production [€/a/person or €/MWh], C_{TUE} the is costs of purchasing electricity from electricity exchange [€/a/person or €/MWh_{TUE}], C_{EL} the is costs of electricity production in P1 and P2 [€/a/person or €/MWh_{EL}], and C_{Φ} is the costs of heat production in P1 and P2 [€/a/person or €/MWh_{Φ}].

Let us assume that “an average customer” of the energy company is also a customer of the waste management company. From the customer’s point of view it is important that the overall cost of purchasing a service, including electricity, heat and waste management is minimized. The overall service cost is defined as:

$$C_{TOT} = C_{ESS} + C_{WMS} \tag{3.20}$$

where C_{TOT} is the total cost of energy supply and waste management [€/a/person], C_{ESS} is the energy cost [€/a/person], and $\mathrm{C}_{\mathrm{WMS}}$ is the waste management cost [€/a/person].

The economical efficiency of an integrated service system can be assessed by comparing the overall service cost of the existing system, i.e. the sum of energy and waste management bills, and the calculated overall service cost from the model.

3.3 *MEFLO-rating*

According to Ekvall et al. (2007), a combination of tools for environmental systems analysis can provide a more holistic picture of a system than LCA. Emphasizing this aspect, a proposal for a more comprehensive method called MEFLO for modeling municipal waste management and energy system is presented below. The MEFLO method can be interpreted as a Multi-Criteria Decision Making (MCDM) method according to the classification presented by Zhou et al. (2006).

The MEFLO rating method can be described as the instructions on how to use the results of the SISMan model and to provide decision-makers transparent information about the integrated system alternatives chosen for the comparison process. Furthermore, during the MEFLO-rating additional information is included in the process to confirm that the targets set for the operation of the system are met. The targets can be binding or trend setting, depending on the case.

The relevance of MEFLO and SISMan is presented in Fig. 3-7. The original task is to find the most feasible system solution for an integrated waste management and energy supply system utilizing energy recovery from solid waste. Two kinds of information about the system are provided to support the decision-making process:

- the results of techno-economical calculations provided by the SISMan calculation model; and
- interpretation of the calculated results and additional data provided by the MEFLO process.

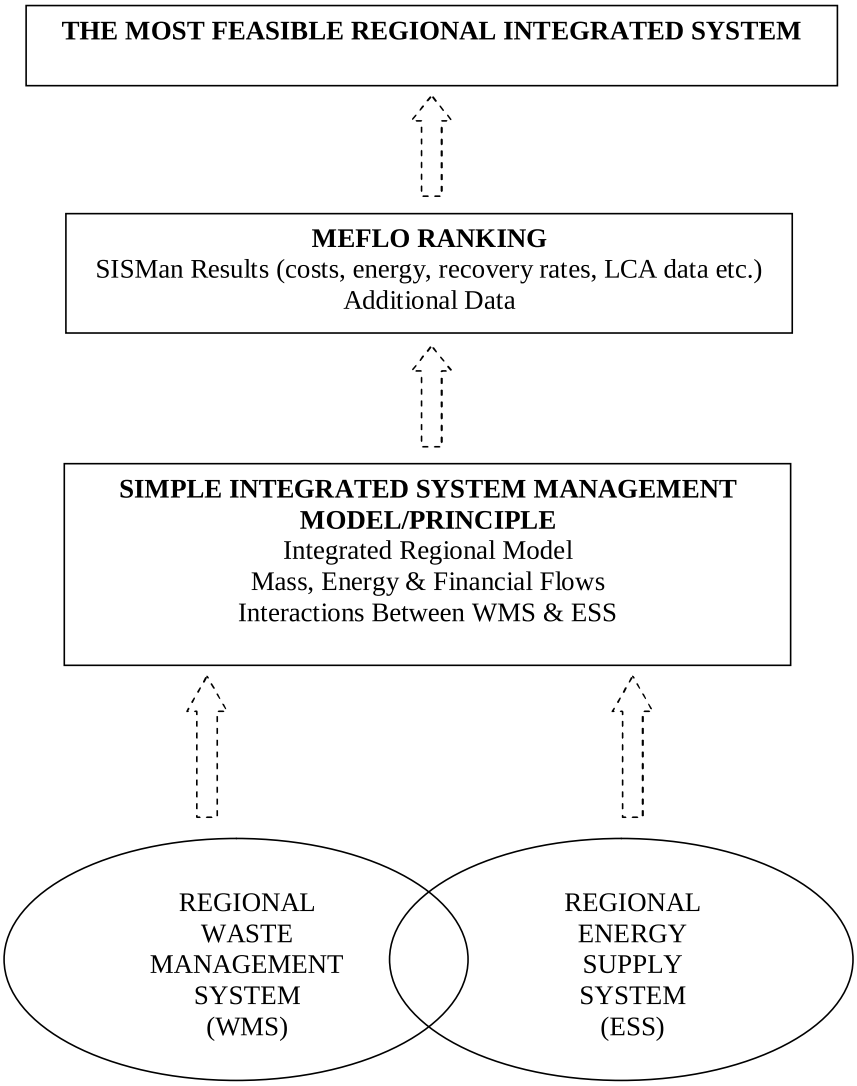

Fig. 3-7. Relationship between the SISMan model and MEFLO.

As the result of the MEFLO process, the most feasible system solution is determined according to the following:

- technical ranking of the system alternatives;
- economical ranking of the system alternatives;
- efficiency ranking (according to e.g. recovery rates) of the system alternatives;
- environmental ranking (according to e.g. emissions or doses) of the system alternatives; and
- political ranking of the system alternatives.

In the MEFLO method, the decision-support data is divided into five categories or modules. The relevance of the MEFLO assessment modules is discussed in the following.

3.3.1 *Mass criteria*

The mass criteria are the basis for all of the considerations related to waste management systems. The whole waste management is based on dealing with different mass flows of different characteristics. The costs are calculated for the mass flows. The mass flows connect the system model to the reality by giving the model a scale. For waste management systems, the mass flows determine the size of the system, i.e. how many inhabitants are involved in the system. The cultural characteristics and the economic structure of the area have an effect on the mass flows. Furthermore, the waste generation rate and composition is different in developing countries than in developed countries.

The results of the mass criteria –module of the MEFLO-rating can be expressed as scalar units.

3.3.2 *Energy criteria*

The significance of energy criteria in a system model contributes to the efficiency of the system. The energy demand has to be fulfilled as efficiently as possible. In the case of energy production, this usually means cheap energy production from non-fossil fuels, if possible.

The results of the energy criteria –module of the MEFLO-rating can be expressed as scalar units.

3.3.3 *Financial criteria*

Financial criteria are usually needed in decision-making processes as balancing factors. For example, from the technical point of view a system solution can be superior compared to the other alternatives, but the investment of such a system could prove impossible for a municipality, or other instance involved, to carry out. In practice financial data is usually crucial in decision-making processes, since technically superior solutions tend to be the most expensive investments. Financial considerations usually lead to a compromise between the technically best (and most expensive) solution and other technically feasible (and less expensive) options.

The results of the financial criteria –module of the MEFLO-rating can be expressed as scalar units.

3.3.4 *Legislative criteria*

The operation of different systems is often regulated by requirements which do not necessarily come up in normal techno-economical analyses of systems. Especially the results of financial considerations may lure decision-makers to choose the cheapest alternative. In this respect, a certain base-line must be defined for the system in order to ensure the quality standards of the winning option. Legislative criteria define the requirements and limits that are binding to a system, such as:

- flue gas emissions from combustion processes;

- restrictions of the composition of disposed waste; and
- requirements for the efficiency of the energy production processes.

The legislative criteria include also other non-binding target values that may have been set to the operation of systems involved, such as:

- material, energy and/or total recovery rate of MSW;
- bioenergy utilization rate in the area;
- minimization of environmental effects, e.g.:
    - toxic effects
    - global warming
    - acidification
    - eutrophication
    - use of natural resources.

The results of the legislative criteria –module of the MEFLO-rating can be expressed as scalar units. However, the units are not necessarily directly comparable.

LCA is becoming a more and more important evaluation criterion in system planning. The revised LCA standard (ISO, 2006a) directs system assessment towards life cycle impact assessment (LCIA), which utilizes comparison of environmental impacts classified in impact categories. In this study, the results of LCIA studies are included under the Legislative criteria section, as they broaden the perspective defined by the more strict environmental and technical requirements included in the legislation. LCA is one of the most commonly used tools for the assessment of the environmental impact of different treatment options (see Ekvall et al., 2007). For further information concerning the utilization of LCA in waste management system -related studies, the reader is referred to e.g. Finnveden et al. (2005).

3.3.5 *Other decision-support criteria*

In the decision-making processes, also such factors exist that cannot be determined in an unambiguous relation to the other properties of the system. These factors are related to the history, politics and personal preferences of the decision-makers. Such factors are for example:

- the political environment of the decision-making group (regional policy, public opinion);
- historical influences of the decision-makers;
- strategic plans for the region which the decision concerns;
- economical development (global and regional);
- employment; and
- other factors.

Such factors are often called social aspects. Morrissey & Browne (2004) have recognized e.g. the following social aspects in their review:

- public acceptance;
- public participation in planning and implementation; and

- consumer behaviour.

Furthermore, Hung et al. (2007) include social justice, social welfare, social acceptance, land demand and technology maturity in the category of social factors in their study concerning food waste management methods. The social aspects are hard to quantify, yet they may have significant effects on the outcome of system studies involving regional systems.

For some factors, e.g. public acceptance of the alternatives, the ranking has to be carried out by rating the alternatives from best to worst. This can be done by e.g. pairwise comparison. According to Zhou & Schoenung (2007), this method is usually used when the problem solving resources, i.e. people, time and money, are limited. Furthermore, social impacts are often local, hence the relative importance of the factors can be seen as case-specific. In other words, generic weighting (for definition, see: Zhou & Schoenung, 2007) cannot be utilized in such cases.

The above mentioned criteria can turn the clear ranking order based on the results of modules M, E, F, and L (Mass, Energy, Financial, Legislative) basically upside down.

The results of the other decision criteria –module of the MEFLO-rating cannot necessarily be expressed as scalar units.

3.4 *Formation of the MEFLO decision matrix*

Basically, the stages of modeling a system presented above can be carried out despite of what kind of criteria are used in the final decision-making process. The results of the SISMan calculation model are essential background information for the actual decision-making procedure. The decision-making process requires formation of a decision matrix compiled from all the important factors needed to bring out the essential features of different system alternatives for comparison. This involves the economic, environmental and social aspects of the system, as e.g. Morrissey & Browne (2004) state in their review of MSW models. The selection of relevant factors in order to reach the desired result, which is the most feasible system alternative, is a very important stage of the process. A typical decision matrix can include the following information:

- financial information:
  - waste management costs [€/t_{MSW}, €/person·a]
  - investment costs [M€, €/a]
  - maintenance costs [€/a]
  - energy supply costs [M€/a, €/MWh];
- energy information:
  - waste-derived energy production [GWh/a]
  - substitution of fossil fuels [GWh/a, kg CO_2-eq.];
- system performance related factors:
  - waste recovery rates [%]
  - process efficiencies [%];
- environmental factors:
  - emissions to environment of different substances [t/a]
  - environmental impacts [DALY/emission, kg CO_2-eq./emission]; and
- social factors:

  - public acceptance of the technologies and policies applied
  - strategic regional targets, e.g. employment.

The decision matrix contains different types of information in different units. The decision matrix information can be classified under three different categories:

- numerical results having same units;
- numerical results having different units; and
- information with no clear units.

The numerical results of SISMan calculations having the same unit can easily be combined as one. However, some figures are not comparable although the basic units are. For example, emissions calculated as SO_2, e.g. kg_{SO2}/a cannot be summed directly with emissions of CO_2 (kg_{CO2}/a). A typical example of a combined result is the annual cost of the system, which can be compiled from the annual costs of different sub-processes.

The results of different units are more difficult to compare. For example, the relation between fossil energy substitution and recovery rate of municipal waste is not easy to understand.

Social factors are usually the most difficult to compare with the characteristics expressed as numerical values. Furthermore, these factors cannot usually be given any specific values. Comparison of this kind of decision-making -related characteristics is often carried out by classifying the cases from better to worse. This kind of classification is crucially dependent on the classifier’s personal perspective. System alternatives can be ranked by combining the decision-makers’ opinions. The combining can be carried out by a survey of the decision-makers’ personal preferences of specific characteristics included in the decision matrix.

The properties/characteristics which are important in the decision process are defined at the early stages of the SISMan modelling and MEFLO evaluation/ranking process. In general, the decision matrix can contain both essential decision-support data, such as requirements set for e.g. investment costs and system emissions, and optional data, which may consist of LCA results and regional-specific data requiring subjective considerations. This kind of classification makes it possible to compare the influence of the essential and the optional factors in the final decision.

Both the model designer and the decision-makers should take part in the formation of the decision matrix. This approach is supported also by Finnveden et al. (2007) when they state that the questions which are to be answered by the models should be determined by the model designer/analyst and decision-makers. The essential part of the decision matrix consisting of mainly technical and environmental factors can be compiled by the designer simultaneously with the SISMan model formation. The set of optional decision factors including environmental data (i.e. LCA-related factors) can also be compiled by the model designer. Optional factors which take the regional circumstances into account are defined by the decision-makers.

An example of a decision matrix for an integrated waste management and energy supply system is presented in Table 3-1.

Table 3-1. Example of a MEFLO decision matrix for an integrated waste management and energy supply system.

Decision matrix factor	Factor unit	Best ranking
Essential decision factors		
Economical decision factors		
Waste management cost	€/t_{MSW}	lowest cost
Total investment costs	M€	lowest cost
Technical decision factors		
Energy consumption	GWh/a	lowest overall energy consumption
Realization of BAT	-	highest realization
Optional decision factors		
Life Cycle -based decision factors		
Climate change	DALYs/kg emission*	lowest impact / emission
	kg CO_2-eq./kg emitted**	lowest impact / emission
	kg CO_2-eq./kg emitted***	lowest impact / emission
Stratospheric ozone depletion	DALYs/kg emission*	lowest impact / emission
	kg CFC-11-eq./kg emitted**	lowest impact / emission
	kg CFC-11-eq./kg emitted***	lowest impact / emission
Human toxicity,	DALYs/kg emission*	lowest impact / emission
including workplace and indoor pollutants	m3 air/g emitted to air, water or soil**	lowest impact / emission
	m3 water/g emitted to air, water or soil**	lowest impact / emission
	m3 soil/g emitted to air, water or soil**	lowest impact / emission
Ionising radiation	DALYs/kg emission*	lowest impact / emission
Photo oxidant formation	DALYs/kg emission*	lowest impact / emission
	kg ethylene-eq./kg emitted***	lowest impact / emission
	kg formed ozone/kg emitted***	lowest impact / emission
Acidification	PDF/m^3/a*	lowest impact / emission
	m^2 unprotected ecosystem/g emitted**	lowest impact / emission
	kg SO^2-eq.***	lowest impact / emission
Eutrophication	(PDF/m^3/a)/kg emission*	lowest impact / emission
	m^3 water/g emitted to air water or soil**	lowest impact / emission
	kg 1,4-DCB-eq. emitted to fresh water, sea water or industrial soil/kg emitted***	lowest impact / emission
Ecotoxicity	(PDF/m^3/a)/kg emission*	lowest impact / emission
	m^3 water/g emitted to air water or soil**	lowest impact / emission
	kg 1,4-DCB-eq. emitted to fresh water, sea water or industrial soil/kg emitted***	lowest impact / emission
Regional targets		
Employment	jobs	highest employment rate
MSW recovery rate	%	highest recovery rate
Social factors		
Public acceptance	-	highest acceptance
Public participation	-	highest participation

LCIA Methods:
* Eco-Indicator 99
** EDIP 2003
*** (Dutch) LCA Handbook

3.5 *Interpretation of the MEFLO decision matrix*

Combining all the factors as one conclusive ranking requires weighting all the factors related to each other. According to ISO (2006b), the weighting steps of LCA are based on value choices and are not scientifically based. Furthermore, Seppälä (2003, 39) states that impact category weights are based on the mixing of scientific, ideological, political and ethnical points of views. Hence, decisions made according to large data sets including different information in various units are more or less subjective from the point of the decision-maker. Furthermore, different individuals, organizations and societies may have different preferences, and therefore reach different weighting results based on the same data (ISO, 2006b).

In this context, the results of each impact category are combined as one final result of the used method by characterisation, normalization and weighting the partial results, which are commonly utilized in MCDM and LCIA. This is done in order to be able to rank the system alternatives in an effective and transparent manner. According to Seppälä (2003, 24), the typical aggregation rule applied in LCIA to calculate the total impact value caused by a product system I(a) is:

$$I(a) = \sum_i w_i \frac{I(a)_i}{N_i} \qquad (i = 1, \ldots, n) \qquad (3.21)$$

where w_i is the impact category weight, $I_i(a)$ is the indicator result of impact category i caused by product system a, N_i is the normalization value of impact category I, and n is the number of impact categories.

According to Seppälä (2003, 19), in Multi-Attribute Value Theory it is customary to normalize the impact category results onto the [0,1] range. The most preferred impact levels are fixed to zero and the least preferred are fixed to one. Seppälä points out that this type of normalization step differs from the normalization of LCIA, in which the impact category indicator results are expressed relative to a well-defined reference system. In this context such reference systems cannot be defined for e.g. economical factors and public acceptance. Hence, case-specific normalization is applied.

Normalizing the factor results onto a fixed scale by setting the best value either to 0 or 1 and the worst value to 1 or 0 can be contradictory. The scale of the factor results is the same for every factor. The advantage of this scaling is that there is not a single normalized factor result which dominates the final scoring of the system alternative. The disadvantage of a fixed scale is the fact that the difference between the best and the worst case is always the same, no matter how great the difference between the unnormalized factor results is. This aspect is also emphasized by Chung and Poon (1996), who state that although the magnitude of differences is preserved, small differences are exaggerated and large discrepancies are understated in relation to the overall picture. However, they also state that this kind of normalization prevents a situation where a single merit may offset a large number of small demerits.

The normalization method applied to rank system alternatives in the MEFLO decision matrix has been modified from the one presented by Seppälä (2003). The variation of the relative differences between the lowest and highest numerical values under comparison has been taken into consideration by setting the least preferable numerical value to 1 and calculating the rest of the normalized values relative to that value. This approach preserves the relative differences during the normalization process. Now the most preferable value is normalized to zero only if the impact of that option is zero. Otherwise, the normalized value is greater than zero and in the range of [0,1].

The decision matrix can involve two different ranking rules. For example, when environmental impacts are considered, the best ranking is given to the alternative which has the lowest value. However, when e.g. the recovery rate of waste is under comparison, the best ranking is given to the alternative which has the highest value. If the most preferred impact level is the minimum of the calculated values, equation 3.22 is used:

$$I^{n}_{i,j} = \frac{I_{i,j}}{I_{\max,j}} \tag{3.22}$$

where $I^{n}_{i,j}$ is the normalized factor result for system i according to impact category j, $I_{i,j}$ is the factor result for system i according to factor j, and $I_{max,j}$ is the highest value of $I_{i,j}$.

If the most preferred impact level is the maximum of the calculated values, equation 3.23 is used:

$$I^{n}_{i,j} = 1 - \frac{I_{i,j} - I_{\min,j}}{I_{\max,j}} \tag{3.23}$$

This normalization method requires that the numerical values to be normalized are preferably greater than or equal to zero. Also, less than or equal to zero is an acceptable range. In this case the negative values can be transformed into positive by changing the ranking rule from min to max or vice versa. However, if the numerical values vary from negative to positive values, which may occur when e.g. relative changes between the alternatives are presented, the normalization has to be carried out differently. The most preferable alternative is set to zero, whether it “deserves” or not this value after normalization. This leads to a different kind of relative scaling than proposed above. Combining the results of two different normalization methods can be controversial. Hence, it is recommended here that the factor results are calculated so that the numerical values to be normalized are greater than or equal to zero.

A special recommendation is given here for the decision factors which involve a fixed scale for the factor results and the ranking rule according to which the higher the factor result is the better. Such a factor is e.g. the MSW recovery rate, which is restricted to the scale of [0…100 %], or [0, 1]. In some situations, i.e. when the lowest score is greater than 0 and the highest score is 1, Equation 3.23 does not produce a correct normalized value to the highest score. In situations where the highest score is the maximum of the scale and the ranking rule is the greater the better, the highest score should always get normalized value of 1. Hence, it is recommended that in such cases the ranking rule is changed to the lower the better, and $I_{i,j}$ is substituted by term $I_{max,j}$ - $I_{i,j}$. Equation 3.22 is then applied to calculate the normalized factor results.

After the factor results have been calculated and normalized, a preliminary ranking can be performed. This level 0 ranking shows the ranking of the alternatives according to each factor.

According to Hämäläinen & Alaja (2008), decision-makers may have difficulties even in identifying their own objectives. Thus, the weighting of the different properties of the system alternatives becomes an even more problematic task. Furthermore, the transparency of the comparison can suffer if different impact category results, such as environmental impacts and costs, are directly combined as one result in order to rank the system alternatives. Hence, a procedure which separates different factors into groups maintaining the transparency of the ranking process is introduced. The ranking of the cases has been divided here into three stages (Fig. 3-8):

- Level 1: ranking inside each decision factor group, e.g. ranking according to the economical properties;
- Level 2: ranking inside the main categories, e.g. ranking according to the environmental and the economical factor groups; and
- Level 3: final ranking between the main categories, i.e. ranking according to the essential and the optional properties groups.

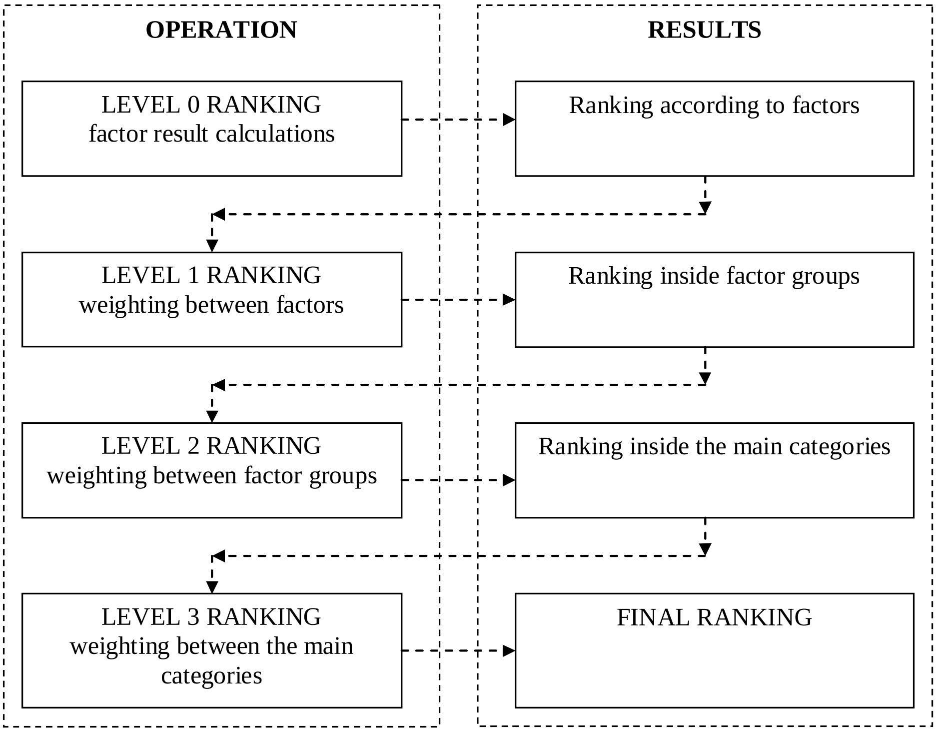

Fig. 3-8. Three-level ranking of MEFLO cases.

The three-level ranking is presented in this context for the first time, as far as the author knows, and can be interpreted as one of the two main contributions of this study to system assessment, the other contribution being the expanded concept of municipal integrated waste management and energy supply system described above.

Level 1 ranking yields the rankings inside each factor group. Level 1 ranking can be interpreted similarly to the ranking which has normally been performed in related LCIA studies. For example, Dahlbo et al. (2007) have ranked five different cases according to the Eco-indicator 99 model and social life cycle costs (SLCC) results. In this case, the Eco-indicator 99 results would be interpreted as one factor group and the SLCC results could be included in the group of economical factors.

Level 1 ranking is achieved by first summing up the normalized factor results (in LCIA indicator results) and normalizing the sum:

$$I(L1)_{i,k} = \sum_j w(L1)_j \cdot I^n_{i,j} \qquad (j = 1, \ldots, n_j) \qquad (3.24)$$

where $I(L1)_{i,k}$ is the impact caused by system i according to factor group k, $w(L1)_j$ is the factor j weight (level 1 weight), and n_j is the number of factors in factor group k.

The normalized factor group results for system i according to factor group k are calculated from equation:

$$I(L1)^n_{i,k} = \frac{I(L1)_{i,k}}{I(L1)_{\max,k}} \qquad (3.25)$$

where $I(L1)^n_{i,k}$ is the normalized impact caused by system i according to factor group k, and $I(L1)_{max,k}$ is the highest impact value in factor group k.

Level 1 ranking is carried out by giving the minimum sum the best ranking. Furthermore, positions of the sums in the range [0,1] give a rough idea of whether the alternatives are close or apart from each other according to the criteria.

Level 2 results are calculated by the same analogy as level 1 ranking:

$$I(L2)_{i,m} = \sum_k w(L2)_k \cdot I(L1)^n_{i,k} \qquad (k = 1, \ldots, n_k) \qquad (3.26)$$

where $I(L2)_{i,m}$ is the impact caused by system i according to main category m, $w(L2)_k$ is the factor group k weight (level 2 weight), and n_k is the number of factor groups in main category m.

The normalization of main category results for the rest of the alternatives is written as:

$$I(L2)^n_{i,m} = \frac{I(L2)_{i,m}}{I(L2)_{\max,m}} \qquad (3.27)$$

where $I(L2)^n_{i,m}$ is the normalized factor group result for system i according to main category m, and $I(L2)_{max, m}$ is the highest impact value in main category m.

Level 2 ranking is carried out using the same analogy as in level 1 ranking. As the result of level 2 ranking, the alternatives are given rankings according to the essential factors and the optional factors.

Level 3 is the final stage, where the results of the essential and the optional categories are combined:

$$I(L3)_i = \sum_m w(L3)_m \cdot I(L2)^n_{i,m} \qquad (m = 1, \ldots, n_m) \qquad (3.28)$$

where $I(L3)_i$ is the total impact caused by system i according to the selected factors, $w(L3)_m$ is the main category m weight (level 3 weight), and n_m is the number of main categories.

The normalized final impacts for the rest of the cases are determined as:

$$I(L3)^n_i = \frac{I(L3)_i}{I(L3)_{\max}} \qquad (3.29)$$

where $I(L3)^n_i$ is the normalized final result for system i, and $I(L3)_{max}$ is the highest impact value among the systems under comparison. The final ranking is given using the same analogy as in levels 1 and 2.

The weights inside each factor group are relative to the weights of the same factor group. In other words, Level 1 weights $w(L1)_j$, determine the importance of each factor related to the other factors in the same factor group. Equally, Level 2 weights $w(L2)_k$ determine the importance of results of a factor group related to the other factor groups inside the same main category. Level 3 weights $w(L3)_m$ determine the importance of the results between the main categories. The grouping of the weighting in three stages contributes to the understanding of the related importance of different factors. For most decision-makers it is probably more difficult to describe the relative weights between e.g. total investment cost and acidification impact than to give weights inside a factor group which includes factors of similar nature, such as total investment cost and waste management fee. Furthermore, the results of different studies involving the same system can be integrated. For example, if an LCIA study including weights between the selected impact categories has been performed for the system alternatives, the results can be utilized in the MEFLO decision matrix, assuming that the circumstances have not changed. In this case Level 1 weights would have already been determined for the selected environmental impacts.

According to Finnveden et al. (2002), case-specific normalization requires case-specific weighting. The weights between the factors, factor groups and main categories can be determined by several different methods. The weighting methods and approaches can be classified into five main groups (Finnveden et al. 2002, 185):

- proxy weighting methods;
- technology abatement weighting methods;
- monetisation weighting methods;
- panel weighting methods; and
- distance to target weighting methods; authorized targets or standards.

In this context, panel weighting have been chosen as the method of specifying the weights for the calculation of the final results. Panel approaches have one thing in common (Finnveden et al. 2002, 188): it is assumed that the relative importance of damages, impact categories, or interventions (weighting factors) can be derived from an individual or a group of people by elicitation. Elicitation is the process of gathering judgements concerning the problem through specially designed methods of verbal and/or written communication. However, there are several differences between panel methods, e.g.:

- the size of the panel and the type of panellists;
- the elicitation situation;
- the question format;
- presentation of background information;
- the response modes; and
- the type of aggregation.

The weighting involves value choices. Hence, different individuals and groups may produce significantly different weights. Finnveden et al. (2002) state that there is no single panel composition that fulfils all requirements. Furthermore, elicitation situations, question formats and the background information bias panelists' responses. The different temporal and spatial dimensions of environmental problems complicate the weighting task for the panelists, and it is unclear whether they really understand the scope of estimated damages or impacts.

4 Results and discussion

The use of the SISMan and MEFLO methods to study the feasibility of utilizing energy recovery from municipal solid waste in a district heated municipal system is discussed in the following sections. The purpose is to give a general example of using SISMan and MEFLO as decision-making support methods. Furthermore, the advantages and restrictions of using SISMan and MEFLO and the relevance of the methods are discussed.

4.1 Examples of using SISMan and MEFLO in system design and assessment

4.1.1 Example of the formation of a SISMan model and cases

The SISMan model of integrated waste management and energy supply system is presented in Fig. 4-1. In the figure, municipal solid waste is divided into seven fractions:

- fractions utilizable as material or energy:
  - biowaste
  - paper
  - cardboard
  - plastics;
- fractions utilizable as material:
  - glass
  - metals; and
- landfill waste (non-recoverable waste).

The basic SISMan model of the system includes all possible flow alternatives (i.e. directions) for mass, energy and money. The mass and energy flows are alternative, i.e. the flows are either mass or energy flows, not both. A financial flow is attached to each mass and energy flow. The direction of financial flows can be opposite to the mass and energy flows. The cases have been formed by changing the directions of the flows from one process to another. Every case is a steady model including constant material, energy and money flows. One fraction is directed primarily to one treatment process (material recovery, energy recovery or landfill). The flows in Fig. 4-1 are mass flows, except for the flows leaving the energy recovery box (i.e. electricity and district heat), which are energy flows.

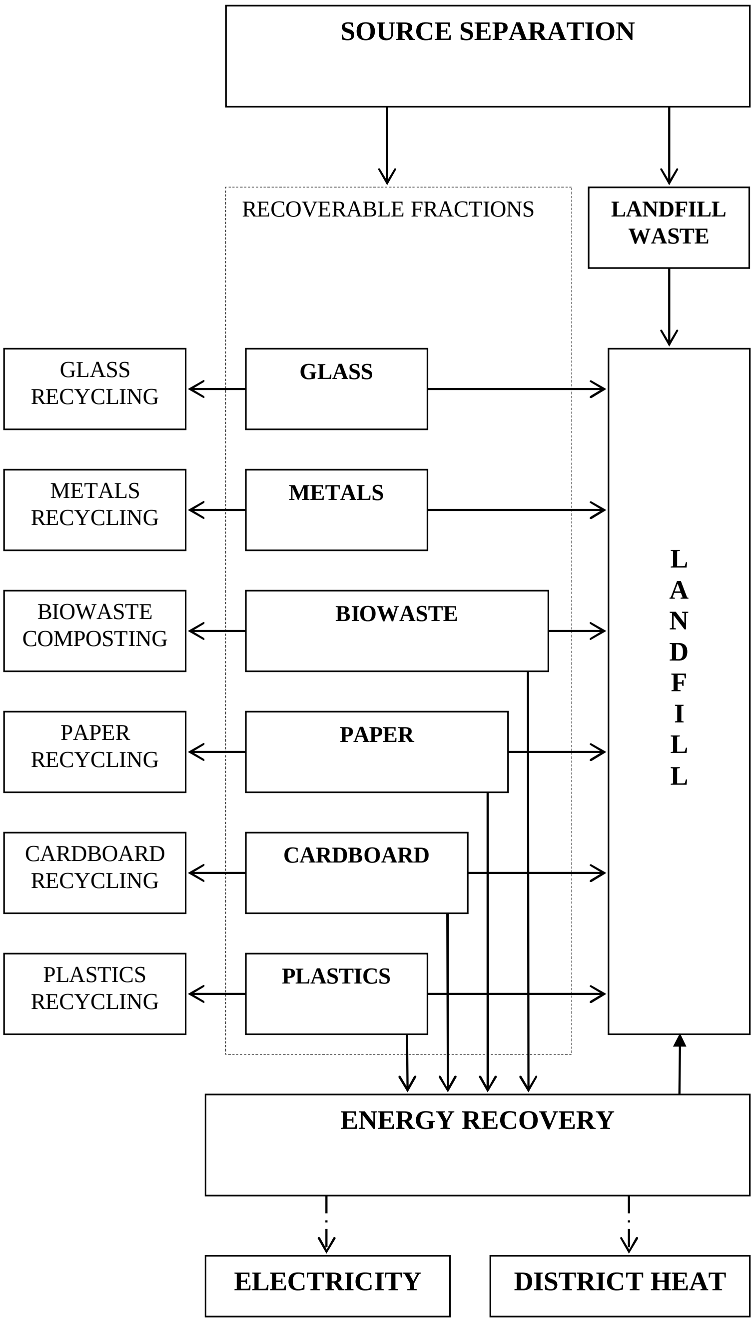

Fig. 4-1. System model.

There is no energy to be gained from glass and metals. Hence, they are directed to recycling processes in all the cases. The landfill waste fraction consists of non-recyclable and non-combustible waste, i.e. non-recoverable fractions. Hence, landfill disposal is the only option for these fractions. The four remaining fractions are utilizable both as matter and as energy.

The arrows from each recoverable fraction box to landfill present the source separation losses of the fractions.

The energy supply system model considers the energy supply structure for heat and electricity separately. In order to determine possible substitution of fossil energy resources, the structure of energy supply has to be determined. The energy supply part of the integrated system is presented in Fig. 4-2. The flows in Fig. 4-2 are energy flows. As in Fig. 4-1, money flows are attached to the presented energy flows. The analogy has been utilized in Publications I-IV. District heat energy equal to the total heat demand is produced in P1 and P2. The renewable heat energy produced from MSW in P2 substitutes fossil heat energy produced originally in P1, and contributes to fossil resource saving. In Finland, 60 % of the energy content of waste-derived fuels is considered renewable in the calculation of the subsidiary for electricity production from renewable sources (Vesanto et al., 2007). Furthermore, savings can be achieved due to savings in fuel costs. If P1 uses renewable biofuel, e.g. wood or straw, no savings in CO_2 emissions can be achieved. In fact, the emissions are probably somewhat higher due to the lower efficiency of electricity production of P2 and the fossil fuels included in the waste-derived fuel. Thus, savings in fuel costs would be desirable in order to justify energy recovery from MSW from the point of view of energy supply.

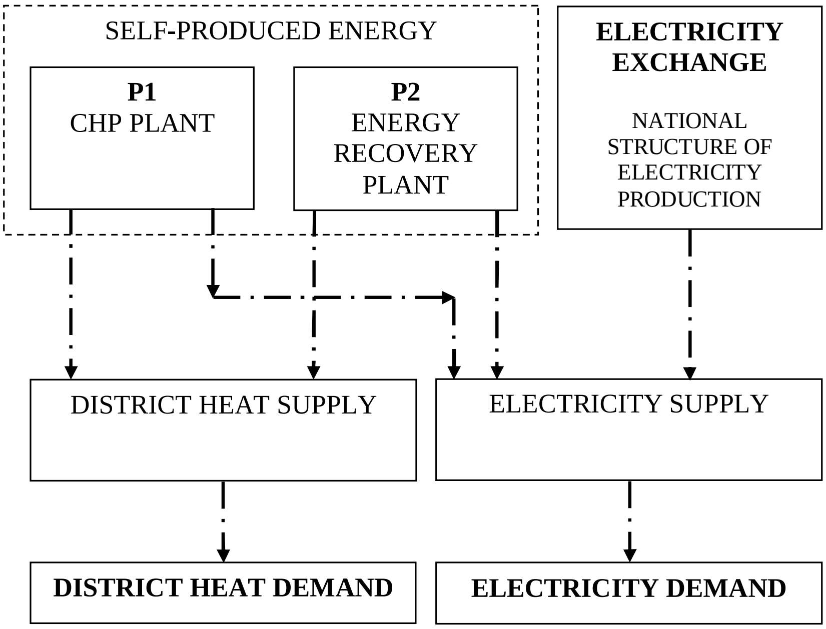

Fig. 4-2. Energy supply system model.

The electricity supply comes from two origins, from the energy company’s own production plants P1 and P2 and from outside the integrated system, i.e. electricity exchange. When top-up electricity is purchased from the exchange, it can be difficult to determine which part of the electricity is from fossil origins and which from renewable sources. National average values can be used in determining the electricity production structure of the purchased top-up electricity.

In practice, due to the lower efficiency of electricity production in P2 compared to P1 (because of lower steam temperatures in P2), less electricity is produced in P1 and P2 compared to the original situation, i.e. reference state. This means that more top-up electricity must be purchased from the exchange to meet the demand. In some cases this can mean that even more fossil fuels are needed to meet the electricity demand. However, when energy recovery from waste materials is considered, the primary target should be to reach the minimum possible environmental effects of the integrated system with reasonable costs. Thus, a small increase in fossil fuel consumption does not necessarily result in a higher overall environmental burden.

The formation of cases is based on the characteristics of the waste fractions. In order to make a comparison of different fraction treatment methods, there have to be fractions which are utilizable both as material and energy. The maximum number of cases is determined by the number of available treatment methods for each fraction. Competing options can be for example recycling and incineration of plastics, or three different recycling processes for office paper.

In this context it is assumed that no materials that can be recovered as materials end up to be combusted due to incomplete source separation. For further information concerning the significance of separation efficiency in municipal waste management systems the reader is referred to Tanskanen (2000a, 2000b).

The cases have been formed simply by choosing between material or energy recovery of a fraction. The formation of two cases is presented in Fig. 4-3, based on the treatment options for biowaste. Case A includes composting of the biowaste fraction, case B stands for grate combustion of the fraction. Several cases can be formed for a municipal solid waste management system with a similar analogy.

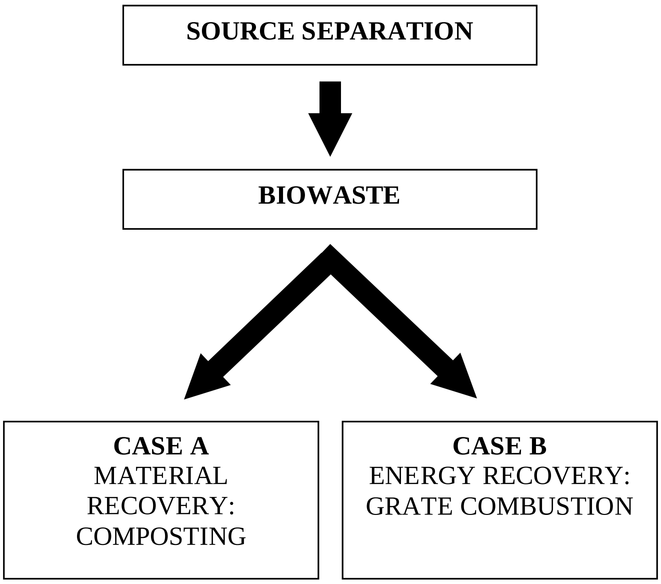

Fig. 4-3. Forming of cases in the SISMan model.

Five selected cases of system alternatives formed on the basis of the model in Fig. 4-1 are presented in Table 4-1. The total number of combinations that can be formed by selecting between ER and MR for the four fractions is sixteen. In this context, the number of cases has been limited to five in order to study differences between the impacts of material and energy recovery of selected waste fractions. Although Case 5 does not include energy recovery, it can be compared with the other cases to study whether there is any sense of introducing energy recovery to the region.

Table 4-1. System alternatives formed from Fig. 4-2.

Fraction	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Glass	MR	MR	MR	MR	MR
Metals	MR	MR	MR	MR	MR
Biowaste	ER	MR	MR	MR	MR
Paper	ER	ER	MR	MR	MR
Cardboard	ER	ER	ER	MR	MR
Plastics	ER	ER	ER	ER	MR
Landfill waste	LF	LF	LF	LF	LF

MR = Material Recovery
ER = Energy Recovery
LF = Landfill

The feasibility of each system alternative can be studied by comparing the cases with two main comparison methods:

- comparison between cases: two or more cases are compared, the case that has the higher/lower effect/value is the more recommendable treatment method for the fraction; and
- simultaneous comparison of selected cases: the highest/lowest effect/value is the most recommendable system option.

In the case comparison, the treatment options (two or more) for one fraction are compared to each other at a time. The treatment methods for other fractions are constant. For example, if the global warming potential (CO_2-equivalent) is the determining factor, and there are three options for biowaste treatment (landfill, composting and incineration), a three-case comparison can be formed. This simplification involves the assumption that the required investments, mostly on the energy recovery system, do not change significantly.

An example of case-pair comparison for the cases of Table 4-1 is presented in Table 4-2. A similar comparison has been performed in Publication IV for the city of Kaunas.

Table 4-2. Comparison of case pairs.

Compared cases	**Result of the comparison**
Case 1 vs. Case 2	feasibility of ER compared to MR for biowaste
Case 2 vs. Case 3	feasibility of ER compared to MR for paper
Case 3 vs. Case 4	feasibility of ER compared to MR for cardboard
Case 4 vs. Case 5	feasibility of ER compared to MR for plastics

In simultaneous comparison, all the cases are included in the comparison. For example, if the waste management cost is chosen to be compared, the cost is calculated for every case and then compared. The lowest cost is the most feasible one. Simultaneous comparison is a more flexible comparison method than case-pair comparison, since it is not restricted to comparing one fraction treatment method at a time.

The proposed comparison methods may not give any “absolute level of discharge” –kind of results, but they will give a ranking order between the cases for each selected category. This approach is necessary in strategic system considerations, as also McDougall et al. (2001) have stated.

4.1.2 *Examples of formation and interpretation of the MEFLO decision matrix*

An example of the MEFLO decision matrix is presented in Table 4-3 and Table 4-4. In Table 4-3 the decision factors and the factor results selected to contribute to the decision-making process are presented. The purpose is to find the most preferable system alternative from cases 1-5 according to the selected factors. It should be noted that cases 1-5 in Table 4-3 and Table 4-4 are not the cases presented in Table 4-1. The simultaneous comparison method is applied. The decision matrix has been compiled mainly from the results of publication II and publication IV. The results of publication II have been calculated with a self-composed spreadsheet application, and the results of publication IV with the commercial LCA application Gabi. The factors have been divided in two essential and three optional factor groups in order to make the weighting problem more understandable to the decision-makers. The factor results are presented here by the case number used in the original studies. However, cases 1-5 in Publications II and IV do not involve equal system properties such as waste amounts, energy demand or system classifications. Furthermore, the weights $w(L1)_j$, $w(L2)_k$ and $w(L3)_m$ presented in Table 4-4 are not related to any real study. Hence, any conclusions concerning the ranking of cases 1-5 of the decision matrix (Table 4-4) according to this example should be avoided.

Table 4-3. Example of the MEFLO decision matrix – factor results.

Decision factors	**Unit**	**Factor results**				
		Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Essential decision factors (Level 2)						
Essential factor group 1 (Level 1)						
Waste management fee*	€/t_{MSW}	19.9	110.8	54.2	70.2	50.9
Total annual system costs*	M€/a	1.987	11.077	5.417	7.018	5.092
Investment costs*	M€	38.9	9.7	13.8	7.1	18.8
Essential factor group 2 (Level 1)						
Unrecovered MSW (calculated from the total recovery rate)*	-	0.20	0.83	0.23	0.36	0.31
Unrecovered MSW as material (calculated from the material recovery rate)*	-	1.00	0.99	0.45	0.46	0.63
Unrecovered MSW as energy (calculated from the energy recovery rate)*	-	0.20	0.84	0.78	0.90	0.68
Optional decision factors (Level 2)						
Optional factor group 1 (Level 1)						
Abiotic Depletion (ADP)**	kg Sb-Equiv.	2.97	2.36	3.34	2.74	3.42
Acidification Potential (AP)**	kg SO2-Equiv.	3.48	1.32	3.50	1.34	1.98
Eutrophication Potential (EP)**	kg Phosphate-Equiv.	0.62	0.17	0.62	0.16	0.24
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)**	kg DCB-Equiv.	3.84	6.04	3.88	6.08	6.27
Global Warming Potential (GWP 100 years)**	kg CO2-Equiv.	541.01	429.00	585.29	473.28	451.76
Human Toxicity Potential (HTP inf.)**	kg DCB-Equiv.	29.41	26.60	31.13	28.32	87.27
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)**	kg DCB-Equiv.	45651.30	46176.50	37119.46	37644.65	47669.91
Ozone Layer Depletion Potential (ODP, steady state)**	kg R11-Equiv.	0.00	0.00	0.00	0.00	0.00
Photochem. Ozone Creation Potential (POCP)**	kg Ethene-Equiv.	0.15	0.13	0.15	0.13	0.38
Radioactive Radiation (RAD)**	DALY	0.00	0.00	0.00	0.00	0.00
Terrestric Ecotoxicity Potential (TETP inf.)**	kg DCB-Equiv.	1.73	13.39	1.52	13.18	13.72
Optional factor group 2 (Level 1)						
Impact on employment*	employees	15	5	6	3	8
Public acceptability***	-	0.33	0.67	0.67	1	1
Optional factor group 3 (Level 1)						
Produced net heat energy*	GWh/a	283	71	100	52	137
Produced net electric energy*	GWh/a	71	18	25	13	34

* Based on the numerical values taken from Publication II

** Based on the numerical values taken from the Gabi calculations performed for Publication IV

*** Additional value, scale: [0,1]; 0 = not acceptable, 1 = fully acceptable.

Table 4-4. Example of the MEFLO decision matrix – ranking results.

Decision factors	**Weights**			**Result**	**Best option**	**Normalized results / Ranking**				
	$w(L1)_j$	**$w(L2)_k$**	**$w(L3)_m$**		**min/max**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Essential decision factors (Level 2)			2							
Essential factor group 1 (Level 1)		2								
Waste management fee*	1			$I^n_{i,j}$	min	0.18	1.00	0.49	0.63	0.46
Total annual system costs*	1			$I^n_{i,j}$	min	0.18	1.00	0.49	0.63	0.46
Investment costs*	1			$I^n_{i,j}$	min	1.00	0.25	0.35	0.18	0.48
Weighted sum of normalized factor results				**$I(L1)_{i,k}$**	min	1.36	2.25	1.33	1.45	1.40
Normalized sum of normalized factor results				**$I(L1)^n_{i,k}$**	min	0.60	1.00	0.59	0.64	0.62
Ranking according to the essential factor group 1 (Level 1)				**Ranking (L1)**	min	**2**	**5**	**1**	**4**	**3**
Essential factor group 2 (Level 1)		1								
Unrecovered MSW (calculated from the total recovery rate)*	2			$I^n_{i,j}$	min	0.24	1.00	0.28	0.43	0.37
Unrecovered MSW as material (calculated from the material recovery rate)*	1			$I^n_{i,j}$	min	1.00	0.99	0.45	0.46	0.63
Unrecovered MSW as energy (calculated from the energy recovery rate)*	1			$I^n_{i,j}$	min	0.22	0.93	0.87	1.00	0.76
Weighted sum of normalized factor results				**$I(L1)_{i,k}$**	min	1.70	3.92	1.87	2.33	2.13
Normalized sum of normalized factor results				**$I(L1)^n_{i,k}$**	min	0.43	1.00	0.48	0.59	0.54
Ranking according to the essential factor group 2 (Level 1)				**Ranking (L1)**	min	**1**	**5**	**2**	**4**	**3**
Weighted sum of Level 1 results				**$I(L2)_{i,m}$**	min	1.64	3.00	1.66	1.88	1.79
Normalized sum of Level 1 results				**$I(L2)^n_{i,m}$**	min	0.55	1.00	0.55	0.63	0.60
Combined ranking of essential factors (Level 2)				**Ranking (L2)**	min	**1**	**5**	**2**	**4**	**3**
Optional decision factors (Level 2)			1							
Optional factor group 1 (Level 1)		4								
CML2001, Abiotic Depletion (ADP)**	1			$I^n_{i,j}$	min	0.87	0.69	0.98	0.80	1.00
CML2001, Acidification Potential (AP)**	1			$I^n_{i,j}$	min	0.99	0.38	1.00	0.38	0.57
CML2001, Eutrophication Potential (EP)**	1			$I^n_{i,j}$	min	1.00	0.27	0.99	0.26	0.38
CML2001, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)**	1			$I^n_{i,j}$	min	0.61	0.96	0.62	0.97	1.00
CML2001, Global Warming Potential (GWP 100 years)**	1			$I^n_{i,j}$	min	0.92	0.73	1.00	0.81	0.77
CML2001, Human Toxicity Potential (HTP inf.)**	1			$I^n_{i,j}$	min	0.34	0.30	0.36	0.32	1.00
CML2001, Marine Aquatic Ecotoxicity Pot. (MAETP inf.)**	1			$I^n_{i,j}$	min	0.96	0.97	0.78	0.79	1.00
CML2001, Ozone Layer Depletion Potential (ODP, steady state)**	1			$I^n_{i,j}$	min	0.93	0.76	1.00	0.83	0.73
CML2001, Photochem. Ozone Creation Potential (POCP)**	1			$I^n_{i,j}$	min	0.39	0.33	0.40	0.34	1.00
CML2001, Radioactive Radiation (RAD)**	1			$I^n_{i,j}$	min	0.86	0.66	1.00	0.80	0.50
CML2001, Terrestric Ecotoxicity Potential (TETP inf.)**	1			$I^n_{i,j}$	min	0.13	0.98	0.11	0.96	1.00
Weighted sum of normalized factor results				**$I(L1)_{i,k}$**	min	8.00	7.03	8.23	7.27	8.95
Normalized sum of normalized factor results				**$I(L1)^n_{i,k}$**	min	0.89	0.79	0.92	0.81	1.00
Ranking according to the optional factor group 1 (Level 1)				**Ranking (L1)**	min	**3**	**1**	**4**	**2**	**5**
Optional factor group 2 (Level 1)		1								
Employment*	2			$I^n_{i,j}$	max	0.20	0.87	0.80	1.00	0.67
Public unacceptability (calculated from public acceptability)***	1			$I^n_{i,j}$	min	1.00	0.49	0.49	0.00	0.00
Weighted sum of normalized factor results				**$I(L1)_{i,k}$**	min	1.40	2.23	2.09	2.00	1.33
Normalized sum of normalized factor results				**$I(L1)^n_{i,k}$**	min	0.63	1.00	0.94	0.90	0.60
Ranking according to the optional factor group 2 (Level 1)				**Ranking (L1)**	min	**2**	**5**	**4**	**3**	**1**
Optional factor group 3 (Level 1)		1								
Produced net heat energy*	1			$I^n_{i,j}$	max	0.18	0.93	0.83	1.00	0.70
Produced net electric energy*	2			$I^n_{i,j}$	max	0.18	0.93	0.83	1.00	0.70
Weighted sum of normalized factor results				**$I(L1)_{i,k}$**	min	0.55	2.79	2.49	3.00	2.11
Normalized sum of normalized factor results				**$I(L1)^n_{i,k}$**	min	0.18	0.93	0.83	1.00	0.70
Ranking according to the optional factor group 3 (Level 1)				**Ranking (L1)**	min	**1**	**4**	**3**	**5**	**2**
Weighted sum of Level 1 results				**$I(L2)_{i,m}$**	min	4.39	5.08	5.45	5.15	5.30
Normalized sum of Level 1 results				**$I(L2)^n_{i,m}$**	min	0.80	0.93	1.00	0.94	0.97
Ranking according to the optional decision matrix factors (Level 2)				**Ranking (L2)**	min	**1**	**2**	**5**	**3**	**4**
Total impact for system i				**$I(L3)_i$**	min	1.90	2.93	2.11	2.20	2.17
Normalized total impact for system i				**$I(L3)^n_i$**	min	0.65	1.00	0.72	0.75	0.74
Final ranking (Level 3)				**Ranking (L3)**	min	**1**	**5**	**2**	**4**	**3**

* Based on numerical values taken from Publication II

** Based on numerical values taken from the Gabi calculations performed for Publication IV

*** Based on the additional numerical values presented in Table 4-3

The system alternatives are rated first according to the nature of each decision factor. For the following factors the highest ranking has been given to the case which has the lowest value:

- waste management fee,
- total annual system costs,
- investment costs,
- unrecovered MSW (calculated from the total MSW recovery rate),
- unrecovered MSW as material (calculated from the material recovery rate),
- unrecovered MSW as energy (calculated from the energy recovery rate),
- abiotic depletion,
- acidification potential,
- eutrophication potential,
- freshwater aquatic ecotoxicity potential,
- global warming potential,
- human toxicity potential,
- marine aquatic ecotoxicity potential,
- ozone layer depletion potential,
- photochemical ozone creation potential,
- radioactive radiation,
- terrestric ecotoxicity potential, and
- public unacceptability (calculated from the level of acceptability).

For the following factors the highest ranking has been given to the highest value:

- employment,
- produced net heat energy, and
- produced net electric energy.

In Table 4-4, values $I^n_{i,j}$ are the normalized factor results calculated according to Eq. 3.22 and Eq. 3.23. The alternatives can be ranked (0-level) according to each decision factor separately. For example, if global warming potential is considered, cases 3 and 1 are clearly the least preferable system alternatives, Case 2 is the most preferable, and Cases 5 and 4 are closer to Case 2 than Cases 1 and 3.

In this context it is assumed that the rankings according to public acceptability and the weights for the decision factors, factor groups and main categories have been achieved by a panel consisting of regional decision-makers and some experts (see e.g. Soares et al., 2006, Dahlbo, 2007).

At Level 1, the factor results are combined according to Eq. 3.24 and Eq. 3.25. In the essential factor group 1 and the optional factor group 1 the factor weights ($w(L1)_j$) are assumed equal inside the factor groups. In the essential factor group 2, the total MSW recovery rate is assumed to be twice as important as the material and energy recovery rates. In the optional factor group 2, employment is assumed to be twice as important as public acceptance, and in the optional factor group 3, the net electric energy is considered twice as important as heat. Level 1 rankings for the example are:

- essential factor group 1: Case 3 > Case 1 > Case 5 > Case 4 > Case 2
- essential factor group 2: Case 1 > Case 3 > Case 5 > Case 4 > Case 2

- optional factor group 1: Case 2 > Case 4 > Case 1 > Case 3 > Case 5
- optional factor group 2: Case 5 > Case 1 > Case 4 > Case 3 > Case 2
- optional factor group 3: Case 1 > Case 5 > Case 3 > Case 2 > Case 4

At Level 2, the factor group results are combined (Eq. 3.26) and normalized (Eq. 3.27). The weights (Table 4-4; $w(L2)_k$) used in the calculation of the example are assumed to be 2 and 1 for the essential factor groups 1 and 2, respectively. This means that the essential factor group 1 is considered twice as important as the essential group 2 by the decision-makers. The optional factor group weights are assumed as 4, 1 and 1 for the optional factor groups 1, 2 and 3. In other words, the optional factor groups 2 and 3 are considered equal in importance and the optional factor group 1 is considered 4 times as important as the optional groups 2 and 3. The Level 2 ranking results for the example are:

- essential decision matrix factors: Case 1 > Case 3 > Case 5 > Case 4 > Case 2
- optional decision matrix factors: Case 1 > Case 2 > Case 4 > Case 5 > Case 3

According to the normalized essential decision factor sums ($I(L2)^n_{i,m}$ in Table 4-4), it can be stated that Case 2 would be clearly the worst alternative. Cases 1 and 3 get practically the same normalized value, Case 1 being slightly better. Cases 5 and 4 are relatively close to each other. According to the normalized optional decision factor sums, it appears that Case 1 would be clearly the best alternative. The other results are more uniform than in the case of the essential category.

Finally, the results of the main categories are combined by multiplying the category results by the category weights (Eq. 3.28) and normalized (Eq. 3.29). The decision-making is based for two thirds on the essential (e.g. techno-economical) factors and for one third on more subjective decision-making information. The final ranking for the alternatives is:

- Final ranking: Case 1 > Case 3 > Case 5 > Case 4 > Case 2

From the normalized results of the cases (Table 4-4; $I(L3)^n_i$), it can be seen that Case 1 is the most recommendable option, whereas Case 3, Case 5 and Case 4 are relatively close to each other. Case 2 is by far the worst option.

The presentation is the unambiguous ranking of cases 1-5 according to defined decision criteria determined by the results of the SISMan system model and utilizing the MEFLO method. The original decision matrix including 21 lines, i.e. decision factors, presented in Table 4-3 is consequently reduced to one line, which defines the order of preference for the system alternatives, case 1 being the most feasible solution. Furthermore, the rankings according to each factor, factor group and main category can be seen in the decision matrix presentation. Hence, the ranking procedure is fully transparent.

The effects of different variables on the results of the model can be studied by sensitivity analysis:

- waste generation rate (or collection area size);
- energy prices (electricity and/or heat);
- costs of material recycling processes and landfill disposal;
- efficiency of the energy conversion system; and
- weights between factors, factor groups and main categories.

Normally only one variable should be varied at a time in the sensitivity analysis to avoid misinterpretation of the results.

The example presented above includes all stages of the MEFLO decision matrix. By dividing the problem of weighting into three stages, the identification of relations between different factors may be easier of decision-makers compared to the one-level weighting used in LCIAs (e.g. Soares et al., 2006, Zhou & Schoenung, 2007). The addition makes it possible to group the categories according different properties. For example, LCIA categories can be included in one group, economic results in another group, social impacts, such as public acceptance of treatment technologies and impacts on regional employment, in one group, etc. It should be noted that LCIA studies do not need more than one-level weighting because they compare environmental impacts, which are categorized in this context in the same factor group. Furthermore, if Level 3 weighting is decided to be an unnecessary stage, it can be bypassed by giving the same weights for the essential and optional category results. In some cases, Level 2 weighting can be left out, and include Levels 1 and 3. The three levels of weighting can be interpreted as the maximum number of weighting stages needed for the selection of a system alternative.

In Appendices 1-3, three examples of decision matrices are presented. In the following, the utilization of the MEFLO method and the transparency of the results compared to the methods utilized in the reference studies are discussed. The purpose of the comparison is not to criticize the methods, results or conclusions presented in the reference studies, but to illustrate how the MEFLO method could have been applied in these studies and what could have been the contribution of the method in each study.

In Appendix 1, the MEFLO decision matrix is utilized to compare four selected waste management system alternatives for Asturias, Spain according to seven environmental decision factors presented by Rodríguez-Iglesias et al. (2003). In the reference study the IWM-1 model was used to calculate the following overall environmental burdens for the system alternatives:

- greenhouse effect,
- acidification,
- eutrophication,
- heavy metals,
- carcinogens,
- winter smog, and
- summer smog.

The IWM-1 model includes a parallel economical model. The following economical scores are presented in separate diagrams of the reference study:

- total system costs,
- total costs per treated MSW ton, and
- cost per person receiving the service per year.

In addition, the following scores are presented in separate diagrams:

- net employment of energy,

- the final volume of MSW sent to landfill,
- the total production of dioxins and furans,
- total recovery rate of materials, and
- recovery of glass and paper.

Environmental, economical and additional scores are not combined in the reference study. The conclusions are presented separately from the point of view of:

- economic costs,
- energy exploitation,
- emissions of CO_2, NO_x and SO_2,
- recovery rates of materials, and
- environmental impacts.

In this context only the environmental impact scores have been included in the MEFLO decision matrix presented in Appendix 1, since the numerical values for economical and additional scores are not included in the reference study. In Rodríguez-Iglesias et al. (2003), the environmental impact category results of the IWM-1 model are combined as one single score. After the characterization stage, processes of normalization and weighting have been carried out following the EcoIndicator 95 methodology. External normalization based on the calculated effects that an average European causes in a year has been utilized in the reference study.

The factor results in Appendix 1 have been calculated by first dividing the normalized results by the normalization factors presented in Table 2 of the reference study. This has been carried out in order to reformulate the original numerical values which are needed in the case-specific normalization. Furthermore, the negative numerical values of the "Summer smog" –factor have been transformed to positive values according to the requirements of the normalization method presented in this thesis. The alternative having the highest numerical value is ranked the highest, whereas for the rest of the factors the highest value gives the lowest ranking. Only Level 1 comparison is needed in this context. The same factor weights have been utilized as in the reference study.

In the reference study, the ranking order of the situations according to the calculated environmental impacts has been formed by comparing the total scores after weighting presented in Table 2. The best ranking is given to the lowest score. Hence, the final ranking according to the reference study and the MEFLO method is:

- Rodríguez-Iglesias et al. (2003): Situation 14 > 17 > 1 > 4
- the MEFLO method: Situation 17 > 14 > 1 > 4.

The MEFLO results differ slightly from the results presented by Rodríguez-Iglesias et al. (2003). The most preferable alternative according to the MEFLO decision matrix is Situation 17, whereas Rodríguez-Iglesias et al. have ranked Situation 14 better than Situation 17. However, the MEFLO results are not inconsistent compared to the reference study results, as the scores of Situation 1, 14 and 17 are close to each other in both methods.

A transparent final conclusion based on all decision factors is not presented in the reference study. Using the MEFLO method to combine the environmental, economical and additional results of the reference study would have been easy to carry out, if the numerical values were available. In this sense, the MEFLO method could have contributed to a more complete and transparent interpretation of the separate results presented in the reference study. However, this would have required weighting of the environmental, economical and additional factors.

In Appendix 2, the MEFLO decision matrix is utilized to compare six waste management options for the Pamplona region in Spain (Wilson, 2002). In the reference study, the Life Cycle Inventory model created by White et al. (1995) has been used in studying the evaluation of environmental burdens, i.e. the weight and volume of solid waste, energy use and air and water emissions. The economic costs have been calculated separately. In addition, six MSW scenarios are assessed for their ability to fulfill EU targets, i.e. fulfilling the targets of the Packaging Directive and Landfill Directive, and objectives of the Pamplona region, i.e. to involve citizens in the management of MSW and to manage MSW in an environmentally responsible way. A table including eight decision criteria has been formed as the basis of the conclusions, carried out by deduction.

The MEFLO decision matrix formed on the basis of Table 9 of the reference study is presented in Appendix 2. Factors involving both negative and positive values, i.e. the Annual energy use, Annual net energy use and Global warming potential, have been re-scaled from zero upwards so that the lowest score has been set to zero. It should be noted that in these cases a different normalization method has been used. The lowest score is zero for all re-scaled factors. Furthermore, the factor results describing the level of fulfillment of the Packaging Directive have been presented as rankings according to Table 9 of the reference study. An additive transformation has been carried out to the optional factors in order to make the MEFLO comparison. For the factors “Proposed landfill directive fulfilled” and “Fulfillment of regional objectives”, the following definitions have been utilized:

- no = 0,
- to be determined = 0.5,
- better chance, but… = 0.75, and
- yes = 1.

The factors have been divided into two essential and two optional groups. The grouping has been formed by the author of this thesis. Furthermore, Level 1, Level 2 and Level 3 weights have been composed by the author of this thesis. The purpose was to find a set of weights that would give the same ranking as in the reference study, if possible.

Wilson (2002) concludes that Scenarios 3 and 5 are the most attractive alternatives, followed by Scenarios 4 and 6. It can be concluded from table 9 of the reference study that Scenario 1 is the worst scenario, as it does not meet EU or regional targets. The MEFLO ranking according to the selected criteria and assumptions is presented in Appendix 2. Hence, the following comparison of the rankings can be presented:

- Wilson (2002): Scenario $3 \approx 5 > 4 \approx 6 > 2 > 1$
- the MEFLO method: Scenario $5 > 3 > 6 > 4 > 2 > 1$.

The MEFLO results are consistent with the reference study results. In fact, the MEFLO method is able to present a clearer ranking for the alternatives than presented in the reference study. However, it should be noted that the MEFLO results presented here are based on several assumptions made by the author of this thesis. However, the MEFLO ranking is unambiguous and transparent. Furthermore, the MEFLO matrix presents a set of weights that lead to a similar ranking as in the reference study. A more comprehensive comparison would have required more usable numerical data.

In Appendix 3, the MEFLO decision matrix has been utilized to compare six waste management options for Hong Kong presented by Chung and Poon (1996). In the reference study, the multiple criteria analysis (MCA) approach has been used to evaluate the system alternatives. Twenty decision factors divided into three major impact groups, i.e. economic factors, socio-political impacts and environmental impacts, were included in the process. Questionnaires have been used to determine the weights for the decision factors included in the study. Five interest groups have been included in the process:

- environmentalists (represented by major local green groups);
- governmental and decision-makers (including the legislators);
- academics;
- the private sector (represented by private sector associations); and
- technical groups.

The raw MCA scores have been normalized according to the rule that the most desirable score is set to 1 and the least desirable to 0. The normalized scores have then been weighted with the overall mean weights obtained from the interest groups. The weights have been assigned by the ranking technique. The first criterion of each major impact group has been given the rank of 1. Each respondent has been requested to assign a rank that reflects the relative importance between the first criterion and the subsequent ones. The higher the rank, the more important the criterion. In addition to the decision factor weights, weights for each factor group are presented in the reference study. Hence, a two-stage weighting is used in the study. This makes it easy to compare the results of the reference study and the MEFLO method.

Seventeen decision factors, divided in three factor groups, have been utilized in the MEFLO decision matrix presented in Appendix 3. In this example only one main category is included, since the reference study presents the weights for the major impact groups related to each other. Hence, Level 3 weighting has not been used. The three factor groups require Level 2 weighting. Three of the decision factors presented in Appendix 4 of the reference study have been discarded. Two of the factors (F_{16} and F_{19}) do not include numerical results. Factor F_{15} has been discarded because the factor results include both negative and positive values. This would have required different normalization than used for the rest of the factors.

The following comparison of the rankings can be presented:

- Chung and Poon (1996): $A_5 > A_6 > A_4 > A_2 > A_1 > A_3$
- the MEFLO method: $A_5 > A_6 > A_2 > A_1 > A_4 > A_3$.

The MEFLO results are not inconsistent with the reference study results. The two most recommendable options and the least recommendable option are ranked similarly in both methods. The rankings of the “middle range”, i.e. options A_1, A_2 and A_4, are different. In the reference study, a dominance pair-wise comparison has been used to determine the ranking of the alternatives. In this method, a dominance matrix has been formed so that the column vector indicates the number of times the alternative dominates the others, while the row vector represents the number of times the alternative is dominated by the others. The higher the column sum, the better the ranking. The comparison shows that both methods are consistent with each other, at least in finding the most recommendable option. In fact, the method used by Chung and Poon (1996) can be interpreted as a close relative to the MEFLO method. Both methods use normalization and weighting on more than one level. However, the MEFLO method does not apply dominance pair-wise comparison to produce the final rankings. The MEFLO method could prove more practical in studies including several factors, as formation of dominance pair-wise matrices requires a lot of effort. Moreover, the presentation of the results and used weights is clearer in the MEFLO method, as the initial scores, i.e. factor results, normalized scores, weights and final rankings are presented in the same decision matrix. Furthermore, the MEFLO matrix includes rankings inside the factor groups. Finally, one more level of weighting can be added, if required.

4.2 *Advantages and restrictions of utilizing the SISMan model and MEFLO-ranking as decision-support tools*

The use of the SISMan model and MEFLO ranking method has several advantages:

- The SISMan model takes into account the advantages of integrated waste management and energy supply system in order to minimize financial and environmental burdens caused by the systems. This aspect has not been widely discussed.
- The SISMan model includes only technically realistic, i.e. proven, combinations of waste management treatment processes. Every case is a separate model of the integrated system.
- Case comparison of system alternatives allows simplifying the SISMan model, if there is no sufficient information of a certain service or production process available. For example, the financial and environmental effects of waste transportation can be left aside during the preliminary consideration of system alternatives by assuming the effects equal in each case. Naturally, the ignored process must be present and equal in all system alternatives.
- Case comparison based on differences between the alternatives leads quickly to the most feasible system alternative.
- The choice of the best system alternative is based on fully transparent information, as the SISMan model and the MEFLO decision matrix include all necessary information relevant to the decision. The designer and decision-makers determine what is necessary information required for the decision-making process. All weights can be seen in the MEFLO decision matrix table.
- The system alternatives can be ranked on three different levels, which contributes to transparency of the assessment system, as the rankings inside different groups (Levels 1 and 2) can be compared to the final ranking (Level 3). This feature has not been introduced in other studies.
- The MEFLO decision matrix results in an unambiguous ranking of system alternatives according to selected criteria. The alternatives can be ranked in spite of data including different units.
- All applicable commercial and shareware softwares can be utilized in the formation of the SISMan model and the MEFLO decision matrix.
- The formation of the SISMan model and MEFLO decision matrix can be interpreted as part of a consistent way of selecting and constructing the most feasible system alternative for regional integrated waste management and energy supply.
  - 1st stage: formation of a SISMan system model, selection of the most feasible system alternative according to the MEFLO ranking method; and
  - 2nd stage: further studies and construction of the system.

- The results of the SISMan model and MEFLO ranking can be utilized in the next stages of the decision-making process. More accurate calculations based on binding offers can be performed according to the formed SISMan model. The model can be updated and completed during further system design.
- The principle of SISMan model formation and MEFLO is easily utilizable also in other system studies and assessments.

The following deficiencies and needs for further development of different methods can be pointed out:

- Accurate information concerning the region under study (waste composition, mass and energy flows etc.) is usually hard to get. This is a general deficiency in modelling.
- Difficulties in defining which factors should be included in the decision-making process. This is a common feature of decision-making processes.
- Uncertainties in the weighting of different characteristics of the system. The weighting methods are improving constantly, and more knowledge is gained from the effects of different processes currently. This is common for all methods that utilize weighting.
- The MEFLO ranking does not necessarily give a direct answer to the question of how much better a system alternative is compared to the other cases. This is a common problem in decision-support models. However, the normalized results of the MEFLO method show whether the alternatives are close to each other or far apart.

The following requirements can be set for the designer of a SISMan model including integration of waste management and energy supply services:

- The designer has to be familiar with the operation principles of both the service systems and technologies involved. Simplifications which involve deep understanding of the systems are required during the model formation process. If the principle of the operation of the integrated system is not understood correctly, the results of the MEFLO ranking method can be misleading.
- The designer has to be aware of the characteristics which are essential in determining the most feasible alternative. The selection of relevant factors in order to reach the desired result, which is the most feasible system alternative, is a very important stage of the process. Most of the decision-making factors should be included in the model from the beginning in order to minimize the time and effort in the model formation.
- The designer has to be able to recognize the realizable options for the system alternatives. This includes knowledge of the BAT available for treatment of waste and recyclable materials, as well as incineration technologies.
- The designer has to be familiar with the relevance of weighting and aware of the most up-to-date weighting methods in order to produce and interpret the results correctly. The weights are usually case-specific, and have to be determined separately for each regional project. Furthermore, a couple of years can change attitudes, and hence the weights, inside a region. Therefore, the weighting process should be carried out also in the case of assessing an existing integrated system, if the circumstances have changed after the former weighting.
- The designer has to be aware of the limitations of the formed model and the effects caused by the limitations.

- The designer has to be able to evaluate the model and decision matrix in the context of how well the decision-making process is supported by the SISMan model and the MEFLO decision matrix.

4.3 *Relevance of the SISMan model and MEFLO ranking method*

The presented methods broaden the perspective formed according to various publications concerning the integration of municipal waste management and energy supply systems (see Table 1-3). Naturally, the proposed methods have many similarities with some of the presented system models (e.g. Korhonen et al. 2004, Dornburg et al. 2006, Eriksson et al. 2007, Chang & Chang 1998), simply because of the restricted number of available system choices, e.g. recycling, composting, landfill disposal and CHP. There is a limited number of ways to describe a municipal waste management system utilizing energy from MSW. However, the most significant difference between the proposed methods and the approaches of the former studies in the area is the choice of perspective. The differences between the SISMan and other models are mainly due to differences in setting the system boundaries. In that sense, the novelty of the SISMan method is including both the waste management system and energy supply system entirely in the integrated system. This contributes to better understanding of municipal waste management and energy service systems by bringing in the customer's point of view, as the system costs have been calculated in order to determine how the operation of the integrated energy and waste management system could be financed.

In addition to the SISMan model, the MEFLO method of combining the factors needed in decision-making concerning the integrated waste management and energy supply system has been presented in this study. MEFLO can be interpreted as a MCDM support method. The MEFLO method utilizes common methods used in supporting decision-making involving municipal systems, such as LCIA and weighting. These tools have been utilized successfully in a number of previous studies, e.g. Dahlbo et al., (2007), Eriksson et al., (2007). However, the novelty of the MEFLO method is the three-level ranking of selected factors, which is introduced in this context for the first time. The three-level ranking contributes to the transparency of the assessment process.

On the basis of what has been presented above, it can be concluded that forming an integrated system model according to the SISMan model principles, and utilizing the MEFLO ranking method is a consistent method to produce easy-to-understand decision-support data for the decision-makers. The SISMan model describes the system in a simplified form, which is easy to comprehend. The MEFLO ranking method gathers all data necessary in the decision-making process into one matrix. Furthermore, the MEFLO method adds transparency to the evaluation of different decision criteria used in the decision-making processes. The proposed methods lead to an unambiguous ranking of pre-selected, realizable system options for an integrated waste management and energy supply system according to selected decision criteria and weights.

5 *Conclusions*

Methods for assessing the most sustainable system solution for an integrated municipal waste management and energy system have been presented in this study. The assessment process includes:

- formation of a SISMan model of an integrated system including mass, energy and financial flows; and
- formation of a MEFLO decision matrix according to the selected decision criteria including essential and optional decision criteria.

The assessment process involves the selection of different system alternatives (process alternatives for treatment of different waste fractions) and comparison between the alternatives. The first of the two novelty values of the utilization of the presented methods is the perspective selected for the formation of the SISMan model. Normally waste management and energy systems are operated separately according to the targets and principles set for each system only. In the present context, the waste management and energy supply systems have been considered as one larger integrated system which has one primary target: to serve the customers, i.e. citizens, as efficiently as possible in the spirit of sustainable development, including the following requirements:

- reasonable overall costs including waste management costs and energy costs;
- minimum environmental burdens caused by the integrated waste management and energy system, taking into account the requirement above; and
- social acceptance of the selected waste treatment and energy production methods.

The integrated waste management and energy system has been described by forming a SISMan model including three different flows of the system: energy, mass and financial flows. By defining the three types of flows for an integrated system, all material, energy and financial flows required for the decision-making process involving the selection of waste management treatment processes for different waste fractions can be calculated. Life cycle assessment can be utilized in the assessment of environmental aspects of the system according to the results of the SISMan flow model. The model and its results form a transparent description of the integrated system under discussion.

The MEFLO decision matrix is formed from the results of the SISMan model combined with additional data, including e.g. environmental restrictions and regional aspects. System alternatives which do not meet the requirements set by legislation can be deleted from the comparisons before any closer numerical considerations. The second novelty value of this thesis is the three-level ranking method introduced for combining the factor results of the MEFLO decision matrix. As a result of the MEFLO decision matrix, a transparent ranking of different system alternatives, including selection of treatment processes for different waste fractions, is achieved.

The use of the SISMan model formation and MEFLO ranking has been tested in case studies presented in Publications I-IV. Some of the cases are hypothetical, some are based on real world systems. The experiences gained from the formation process of the SISMan model support the conclusions, suggesting that the methods presented in this thesis contribute to the design of municipal integrated systems and decision-making. The presented methods add transparency in the design and decision-making processes by describing the integrated system and its characteristics in an easy-to-understand manner.

The formation of the SISMan model of the integrated system requires profound understanding of the purposes, functions, and principles of the waste management and energy systems. Also the synergy possibilities of integrating the systems should be clear in the mind of the designer.

SISMan and MEFLO are methods aimed at being utilized in municipal decision-making processes concerning waste management and energy supply as simple, transparent and easy-to-understand tools. The methods can be utilized in the assessment of existing systems, and particularly in the planning processes of future regional integrated systems.

The SISMan flow model and the MEFLO decision matrix can be formed with or without any applicable commercial or free-of-charge tool and software. SISMan and MEFLO are not bound to any libraries or data-bases including process information, such as different emission data libraries utilized in life cycle assessments. Thus, SISMan and MEFLO are not competitors of assessment models concerning waste management systems and/or energy systems, they are methods for further understanding of the benefits that can be achieved by the integration of processes which have similar operating principles. Integrating systems can lead to savings in e.g. environmental impacts, operating costs and administrational costs. Furthermore, possible joint investments (e.g. EfW plant or WDF production plant) lower the risks of the parties involved.

The principles of SISMan and MEFLO can be utilized also in other environments, where synergies of integrating two (or more) systems can be obtained.

As the results of every assessment process depend critically on assumptions concerning efficiencies, costs, emissions etc., further development of data related to different waste management and energy processes is necessary. This is a continuous requirement. Especially, concrete information about the long term environmental impacts caused by different processes and improved weighting procedures are welcome.

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Appendix 1

Decision factors		**Weights**	**Factor results**				**Result**	**best option**	**Normalized results / Ranking**			
	Unit	**L1**	**Situation 1**	**Situation 4**	**Situation 14**	**Situation 17**		**min/max**	**Situation 1**	**Situation 4**	**Situation 14**	**Situation 17**
Environmental decision factors (Level 1)												
Greenhouse	EL*/s	2.5	351 834 231.8	343 830 188.7	344 982 479.8	348 613 207.5	$I^{n}_{i,j}$	min	1.00	0.98	0.98	0.99
Acidification	EL*/s	10	367 038.3	369 583.3	336 261.3	369 099.1	$I^{n}_{i,j}$	min	0.99	1.00	0.91	1.00
Eutrophication	EL*/s	5	39 744.3	35 164.1	18 049.6	19 103.1	$I^{n}_{i,j}$	min	1.00	0.88	0.45	0.48
Heavy Metals	EL*/s	5	317.2	8 881.2	353.9	347.6	$I^{n}_{i,j}$	min	0.04	1.00	0.04	0.04
Carcinogens	EL*/s	10	0.00245	671.93774	0.00085	0.00085	$I^{n}_{i,j}$	min	0.00	1.00	0.00	0.00
Winter smog	EL*/s	5	111 264.2	112 141.5	113 122.6	112 122.6	$I^{n}_{i,j}$	min	0.98	0.99	1.00	0.99
Summer smog**	EL*/s	2.5	26 018.9	3 226.4	22 566.0	42 575.5	$I^{n}_{i,j}$	max	0.46	1.00	0.55	0.08
Weighted sum of normalized category results							$I(L1)_{i,k}$	min	23.69	39.32	20.38	20.21
Normalized sum of normalized category results							$I(L1)^{n}_{i,k}$	min	0.60	1.00	0.52	0.51
Final Ranking							**Ranking (L1)**	min	**3**	**4**	**2**	**1**
							Ranking according to the reference study:		**3**	**4**	**1**	**2**

* EL = Environmental load, for definition: see Rodríguez-Iglesias (2003) et al. p. 537.

** Numbers have been transformed to positive values (maximum value is ranked as the best)

Appendix 2

Decision factors		**Weights**			**Factor results**						**Result**	**best option**	**Normalized results / Ranking**					
	Unit	**L1**	**L2**	**L3**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**		**min/max**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Essential decision factors (Level 2)				5														
Essential factor group 1 (Level 1)			1															
Total costs	M€/a	2			6.72	10.19	10.31	11.84	9.86	11.38	$I^{n}_{i,j}$	min	0.57	0.86	0.87	1.00	0.83	0.96
Final disposal	t/a	1			108 000	97 300	72 000	72 000	67 000	67 000	$I^{n}_{i,j}$	min	1.00	0.90	0.67	0.67	0.62	0.62
Weighted sum of normalized category results											**$I(L1)_{i,k}$**	min	2.14	2.62	2.41	2.67	2.29	2.54
Normalized sum of normalized category results											**$I(L1)^{n}_{i,k}$**	min	0.80	0.98	0.90	1.00	0.86	0.95
Ranking according to the essential factor group 1 (Level 1)											**Ranking (L1)**	min	**1**	**5**	**3**	**6**	**2**	**4**
Essential factor group 2 (Level 1)			1															
Ranking according to fulfillment of Packaging directive targets	-	1			5	5	3	3	1	1	$I^{n}_{i,j}$	min	1.00	1.00	0.60	0.60	0.20	0.20
Unfulfilled Landfill Directive targets*	-	1			1	1	0.5	0.5	0.25	0.25	$I^{n}_{i,j}$	min	1.00	1.00	0.50	0.50	0.25	0.25
Unfulfilled regional objectives*	-	1			1	0	0	0	0	0	$I^{n}_{i,j}$	min	1.00	0.00	0.00	0.00	0.00	0.00
Weighted sum of normalized category results											**$I(L1)_{i,k}$**	min	3.00	2.00	1.10	1.10	0.45	0.45
Normalized sum of normalized category results											**$I(L1)^{n}_{i,k}$**	min	1.00	0.67	0.37	0.37	0.15	0.15
Ranking according to the essential factor group 2 (Level 1)											**Ranking (L1)**	min	**6**	**5**	**3**	**3**	**1**	**1**
Weighted sum of Level 1 results											**$I(L2)_{i,m}$**	min	1.80	1.65	1.27	1.37	1.01	1.10
Normalized sum of Level 1 results											**$I(L2)^{n}_{i,m}$**	min	1.00	0.92	0.71	0.76	0.56	0.61
Ranking according to the essential factors (Level 2)											**Ranking (L2)**	min	**6**	**5**	**3**	**4**	**1**	**2**
Optional decision factors (Level 2)				2														
Optional factor group 1 (Level 1)			1															
Global warming potential, 100 years relative percent change from existing**	-				39 %	29 %	3 %	4 %	0 %	2 %	$I^{n}_{i,j}$	min	1.00	0.74	0.08	0.10	0.00	0.05
Weighted sum of normalized category results											**$I(L1)_{i,k}$**	min	1.00	0.74	0.08	0.10	0.00	0.05
Normalized sum of normalized category results											**$I(L1)^{n}_{i,k}$**	min	1.00	0.74	0.08	0.10	0.00	0.05
Ranking according to the optional factor group 1 (Level 1)											**Ranking (L1)**	min	**6**	**5**	**3**	**4**	**1**	**2**
Optional factor group 2 (Level 1)			1															
Annual net energy use, total IWM only**	GJ_{th}/a	1			0	27 398	72 701	85 567	75 322	90 605	$I^{n}_{i,j}$	min	0.00	0.30	0.80	0.94	0.83	1.00
Annual net energy use, with benefits of recycling**	GJ_{th}/a	1			65 688	0	45 313	58 179	93 770	109 053	$I^{n}_{i,j}$	min	0.60	0.00	0.42	0.53	0.86	1.00
Weighted sum of normalized category results											**$I(L1)_{i,k}$**	min	0.60	0.30	1.22	1.48	1.69	2.00
Normalized sum of normalized category results											**$I(L1)^{n}_{i,k}$**	min	0.30	0.15	0.61	0.74	0.85	1.00
Ranking according to the optional factor group 2 (Level 1)											**Ranking (L1)**	min	**2**	**1**	**3**	**4**	**5**	**6**
Weighted sum of normalized factor group results											**$I(L2)_{i,m}$**	min	1.30	0.89	0.69	0.84	0.85	1.05
Normalized sum of normalized factor group results											**$I(L2)^{n}_{i,m}$**	min	1.00	0.69	0.53	0.65	0.65	0.81
Ranking according to the optional factors (Level 2)											**Ranking (L2)**	min	**6**	**4**	**1**	**2**	**3**	**5**
Total impact for system i											**$I(L3)_{i}$**	min	7.00	5.96	4.58	5.09	4.10	4.68
Normalized total impact for system i											**$I(L3)^{n}_{i}$**	min	1.00	0.85	0.65	0.73	0.59	0.67
Final ranking (Level 3)											**Ranking (L3)**	min	**6**	**5**	**2**	**4**	**1**	**3**
Ranking according to the reference study:													**6**	**5**	**1**	**3**	**1**	**3**

* Calculated from the level of fulfillment

** Re-scaled: the lowest score is reset to zero

Appendix 3

Decision factors		Weights			Factor results						Result	best option	Normalized results / Ranking					
	Unit	L1	L2	L3	A_1	A_2	A_3	A_4	A_5	A_6		min/max	A_1	A_2	A_3	A_4	A_5	A_6
Economic Impacts			30.3															
F_1 - Internal cost	HK$/t	1.00			345	291	890	177	72	188	$I^n_{i,j}$	min	0.39	0.33	1.00	0.20	0.08	0.21
F_2 - Transport cost	HK$/t	1.10			252	252	252	336	336	336	$I^n_{i,j}$	min	0.75	0.75	0.75	1.00	1.00	1.00
F_3 - Marketability of the recovered materials and energy	-	2.13			2.45	2.55	2.45	2.97	2.79	2.94	$I^n_{i,j}$	max	1.00	0.97	1.00	0.82	0.89	0.84
Weighted sum of normalized category results											**$I(L1)_{i,k}$**	min	3.34	3.21	3.96	3.06	3.07	3.09
Normalized sum of normalized category results											**$I(L1)^n_{i,k}$**	min	0.85	0.81	1.00	0.77	0.78	0.78
Ranking according to the economic impacts (Level 1)											**Ranking (L1)**	min	**5**	**4**	**6**	**1**	**2**	**3**
Socio-political impacts			25.3															
F_4 - Social equity	-	1.00			3	3	3	3	3	3	$I^n_{i,j}$	min	1.00	1.00	1.00	1.00	1.00	1.00
F_5 - Ease of administration/implementation	-	1.09			4	4	4	3	2	2	$I^n_{i,j}$	max	0.50	0.50	0.50	0.75	1.00	1.00
F_6 - Social acceptability	-	1.77			4	4	4	3	3	3	$I^n_{i,j}$	max	0.75	0.75	0.75	1.00	1.00	1.00
F_7 - Compability with the public administration principles	-	1.13			3	3	3	3	3	3	$I^n_{i,j}$	max	1.00	1.00	1.00	1.00	1.00	1.00
Weighted sum of normalized category results											**$I(L1)_{i,k}$**	min	4.00	4.00	4.00	4.72	4.99	4.99
Normalized sum of normalized category results											**$I(L1)^n_{i,k}$**	min	0.80	0.80	0.80	0.95	1.00	1.00
Ranking according to the socio-political impact category (Level 1)											**Ranking (L1)**	min	**1**	**1**	**1**	**4**	**5**	**5**
Environmental impacts			44.3															
F_8 - Land used	hectares	1.00			15.4	15.4	3.2	3.2	2.3	17.2	$I^n_{i,j}$	min	0.90	0.90	0.19	0.19	0.13	1.00
F_9 - Unrecovered material (calculated from recovered material percentage)	%	1.37			83	83	87	82	10	70	$I^n_{i,j}$	min	0.95	0.95	1.00	0.94	0.11	0.80
F_{10} - Uncovered waste (calculated from waste coverage percentage)	%	1.60			0	0	15	15	57	15	$I^n_{i,j}$	min	0.00	0.00	0.26	0.26	1.00	0.26
F_{11} - Uneliminated waste (calculated from waste elimination percentage)	%	2.99			83	83	34	77	0	17	$I^n_{i,j}$	min	1.00	1.00	0.41	0.93	0.00	0.20
F_{12} - Net energy recovered	GJ/t	1.40			0	284.4	0	3170.9	0	2848.9	$I^n_{i,j}$	max	1.00	0.91	1.00	0.00	1.00	0.10
F_{13} - Local air pollution	HK$	2.15			0.006	0.046	11.3	7.8	0.1	6.1	$I^n_{i,j}$	min	0.00	0.00	1.00	0.69	0.01	0.54
F_{14} - Transportation	-	2.05			0.68	0.68	0.9	1.13	0.91	1.08	$I^n_{i,j}$	min	0.60	0.60	0.80	1.00	0.81	0.96
F_{17} - Potential for land contamination and restriction on end-use of the land	-	2.07			2	2	3	3	5	4	$I^n_{i,j}$	min	0.40	0.40	0.60	0.60	1.00	0.80
F_{18} - Disamenity	-	1.82			1	1	2	2	4	3	$I^n_{i,j}$	max	1.00	1.00	0.75	0.75	0.25	0.50
F_{20} - Noise		1.33			0	0	1	1	2	1.5	$I^n_{i,j}$	max	1.00	1.00	0.50	0.50	0.00	0.25
Weighted sum of normalized category results											**$I(L1)_{i,k}$**	min	11.81	11.69	11.66	11.48	7.49	9.30
Normalized sum of normalized category results											**$I(L1)^n_{i,k}$**	min	1.00	0.99	0.99	0.97	0.63	0.79
Ranking according to the environmental impacts (Level 1)											**Ranking (L1)**	min	**6**	**5**	**4**	**3**	**1**	**2**
Weighted sum of normalized factor group results											**$I(L2)_{i,m}$**	min	90.20	88.74	94.34	90.40	76.89	83.86
Normalized sum of normalized factor group results											**$I(L2)^n_{i,m}$**	min	0.96	0.94	1.00	0.96	0.82	0.89
Final ranking (Level 2)											**Ranking (L2)**	min	**4**	**3**	**6**	**5**	**1**	**2**
Ranking according to the reference study:													**5**	**4**	**6**	**3**	**1**	**2**