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JUHA-HEIKKI TANSKANEN

An approach for evaluating the effects of source separation on municipal solid waste management

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17

Juha-Heikki Tanskanen

An approach for evaluating the effects of source separation on municipal solid waste management

Yhteenveto: Menetelmä syntypaikkalajittelun vaikutusten arvioimiseksi yhdyskuntajätehuollossa

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Contents

List of original publications

This thesis is based on the following papers which are referred to by their Roman numerals in the text:

I Tanskanen J.-H., Reinikainen A. & Melanen M. 1998. Waste Streams, Costs and Emissions in Municipal Solid Waste Management: A Case Study from Finland. Waste Management & Research 16:6, 503–513.

II Tanskanen J.-H. & Melanen M. 1999. Modelling Separation Strategies of Municipal Solid Waste in Finland. Waste Management & Research 17:2, 80–92.

III Tanskanen J.-H. 2000. Strategic Planning of Municipal Solid Waste Management. Resources, Conservation and Recycling 30:7, 111–133.

IV Tanskanen J.-H. & Kaila J. 200X. Comparison of Methods Used in the Collection of Source-Separated Household Waste. Waste Management & Research. (Accepted for publication)

Tanskanen is the principal author in all papers included in this thesis. The study which resulted in Paper III was conducted independently by Tanskanen. In Papers I, II and IV, he was the main researcher in all phases of the work, i.e. in the formulation of the research schemes and objectives of the studies, in the calculation of input data, in the development of methods and models, in the treatment of results and in the writing the papers. However, the co-authors played an essential role as commentators in all phases of these studies. The model applied in Paper I was constructed by Johan Sundberg of Chalmers University of Technology, Sweden.

An approach for evaluating the effects of source separation on municipal solid waste management

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Tanskanen, J.-H. 2000. An approach for evaluating the effects of source separation on municipal solid waste management, Monographs of the Boreal Environment Research No. 17, 2000.

An approach was developed for integrated analysis of recovery rates, waste streams, costs and emissions of municipal solid waste management (MSWM). The approach differs from most earlier models used in the strategic planning of MSWM because of a comprehensive analysis of on-site collection systems of waste materials separated at source for recovery. As a result, the recovery rates and sizes of waste streams can be calculated on the basis of the characteristics of separation strategies instead of giving them as input data. The modelling concept developed can also be applied in other regions, municipalities and districts.

This thesis consists of four case studies. Three of these were performed to test the approach developed and to evaluate the effects of separation on MSWM in Finland. In these case studies the approach was applied for modelling: (1) Finland's national separation strategy for municipal solid waste, (2) the effects of separation on MSWM systems in the Helsinki region and (3) the efficiency of various waste collection methods in the Helsinki region. The models developed for these three case studies are static and linear simulation models which were constructed in the format of an Excel spreadsheet. In addition, a new version of the original Swedish MIMES/Waste model was constructed and applied in one of the case studies.

The case studies proved that the approach is an applicable tool for various research settings and circumstances in the strategic planning of MSWM. The following main results were obtained from the case studies:

- A high recovery rate level (around 70 %wt) can be achieved in MSWM without incineration.
- Central sorting of mixed waste must be included in Finland's national separation strategy in order to reach the recovery rate targets of 50 %wt (year 2000) and 70 %wt (year 2005) adopted for municipal solid waste in the National Waste Plan. The feasible source separation strategies result in recovery rates around 35–40 %wt with the present separation activity of waste producers.
- The costs of MSWM will increase in Finland when recovery rate targets of 50 %wt and 70 %wt are aimed at. The increase in total costs seems to stay around 30–40 % when the total recovery rate is increased from the level of 20–30 %wt to the level of around 70 %wt in the Finnish city regions. If the smallest properties (e.g. properties smaller than 10 households) participate in on-site collection of source-separated materials, the increase in the total costs can be reduced by using simultaneous collection of several waste types instead of separate collection.
- Separation reduces most emissions caused by MSWM, e.g. nutrient load, greenhouse gas load and ozone formation according to the case study performed in the Helsinki region. However, the results obtained do not reveal the effects of separation on the total amounts of emissions because emissions outside MSWM system were excluded from the study.

Keywords: waste management, municipal solid waste, separation, waste collection, recovery rate, costs, emissions, models, Finland

Key definitions

The terminology used in Papers I–IV is not totally uniform partly because the thesis was completed in stages in the course of four separate case studies and partly because the terminology in waste management is not yet established and the meaning of the terms may vary from country to country. In this summary of Papers I–IV the major terms have been defined as follows:

Commercial establishment: a property with workplaces producing municipal solid waste.

Coverage of a collection system: in an area, the ratio of (a) the amount of a material produced in those properties in which separate collection is available and (b) the amount of the material in question produced in all properties of the area.

Energy waste: a waste type which consists of non-recyclable combustible waste components, e.g. plastics, wood and non-recyclable paper and cardboard. Recyclable waste components, e.g. cardboard, liquid packaging board and packages made of board, can be included in energy waste in separation strategies in which they are not separately collected. Energy waste can also be called recycled fuel (REF).

Functional element: an activity which is associated with the management of municipal solid waste between the point of generation and the final disposal or the markets for waste materials.

Municipal solid waste: household waste and those types of industrial, commercial and institutional wastes which have similar quality, quantity and composition characteristics to household waste.

On-site obligation limit: the minimum size of a property obliged to participate in on-site collection of a material in an area. In Finland, the size of a property is determined as the number of households among residential properties and as the generation of a material (kg per week) in commercial establishments.

Participation rate: the share of people providing sorted material to bins in those properties in which separate collection is available.

Pick-up time: the time spent at a collection area per tonne of waste collected.

Recoverable material: waste material which can be recovered as raw material or as energy, e.g. paper, biowaste and energy waste.

Recovery rate: the share of waste which is separated for recovery.

Recyclable material: waste material which can be recovered as raw material, e.g. paper and biowaste.

Recyclables: recyclable materials.

Residential property: detached house, terraced house or apartment house. The size of a residential property is expressed as the number of households.

Separation activity: the share of a material which is correctly separated in those properties in which separate collection is available. Separation activity consists of participation rate and separation efficiency.

Separation efficiency: the share of a material which is correctly separated by the people who participate in separation. Also, the share of a material which is correctly separated in a central sorting plant.

Waste component: waste material with a uniform quality, e.g. paper, cardboard, biowaste, glass, metal and plastics. Recoverable materials, waste types and waste streams consist of one or more waste components.

Waste stream: separate waste output of e.g. a property, functional element or study area.

Waste type: mixed waste and recoverable waste materials.

List of symbols

The symbols used in Papers I–IV are not consistent because the thesis was completed in stages in the course of four separate case studies. However, the symbols used in this summary of Papers I–IV were defined as follows:

$a_{d,g,i}$ = accumulation of waste type i in an average drop-off centre d of waste producer group g (t a^{-1})

$a_{g,m}$ = accumulation of mixed waste m in an average property of waste producer group g (t a^{-1})

$a_{o,g,i}$ = accumulation of waste type i in an average property participating in on-site collection o in waste producer group g (t a^{-1})

$b_{c,i}$ = annual cost of bin or container c for waste type i (EUR a^{-1})

b_v = unit cost of collection vehicle v (EUR h^{-1})

$c_{d,g,i}$ = coverage of drop-off centre collection d of material i in waste producer group g (%)

$c_{o,g,i}$ = coverage of on-site collection o of material i in waste producer group g (%)

$c_{x,g,i}$ = coverage of on-site collection of mixed waste for central sorting in waste producer group g including properties x from which material i is not separately collected (%)

$c_{y,g,i}$ = coverage of on-site collection of mixed waste for central sorting in waste producer group g including properties y from which material i is separately collected as on-site collection (%)

$c_{z,g,i}$ = coverage of on-site collection of mixed waste for central sorting in waste producer group g including properties z from which material i is separately collected as drop-off centre collection (%)

$e_{d,g,i}$ = separation efficiency of material i in waste producer group g in drop-off centre collection d (%wt)

e_i = separation efficiency of material i in central sorting plant (%wt)

$e_{o,g,i}$ = separation efficiency of material i in waste producer group g in on-site collection o (%wt)

$f_{o,g,i}$ = collection frequency for waste type i in waste producer group g in on-site collection o (a^{-1})

$g_{d,g,i,j}$ = generation of waste component j which is a part of waste type i per inhabitant in the coverage area of drop-off centre collection d of waste type i in waste producer group g (t inhabitant^{-1} a^{-1})

g_g = generation of municipal solid waste in an average property of waste producer group g (t a^{-1})

$g_{o,g,i,j}$ = generation of waste component j which is a part of waste type i in an average property participating in on-site collection o in waste producer group g (t a^{-1})

$h_{c,f,g,i,j}$ = unit emission c of functional element f resulting from treatment of waste component j which is part of waste type i in waste producer group g (e.g. mg CH_4 t^{-1} of biowaste landfilled)

$h_{d,g,i}$ = number of inhabitants in waste producer group g who live in the coverage area of drop-off centre collection d of waste type i and who are not connected to on-site collection of waste type i

$l_{v,i}$ = net load of collection vehicle v for waste type i (t)

$m_{f,g,i}$ = amount of waste type i produced by waste producer group g and treated with functional element f (t a^{-1})

$m_{f,g,i,j}$ = amount of waste component j in waste type i produced by waste producer group g and treated with functional element f (t a^{-1})

$n_{o,g,i,c}$ = number of bins or containers c of waste type i at an average property in waste producer group g in on-site collection o

O_c = total amount of emission component c (e.g. t CH_4 a^{-1})

$p_{d,g,i}$ = participation rate of material i in waste producer group g in drop-off centre collection d (%)

$p_{o,g,i}$ = participation rate of material i in waste producer group g in on-site collection o (%)

q = constant describing the average extra volume which arises when the number of bins or containers is rounded up at the collection points

R = total recovery rate (%wt)

R_g = recovery rate of waste producer group g (%wt)

$R_{g,i}$ = recovery rate of material i in waste producer group g (%wt)

$r_{1,g,i}$ = recovery rate of material i in waste producer group g which is achieved with source separation (%wt)

$r_{2,g,i}$ = recovery rate of material i in waste producer group g which is achieved with central sorting (%wt)

s_g = share of waste produced by waste producer group g in total waste (%)

$s_{g,i,j}$ = share of waste component j which is a part of material i in waste amount produced by waste producer group g (%)

T = costs of MSWM (EUR a^{-1})

$t_{o,c,v,g,i}$ = unit time of collection and transportation with bin or container c and collection vehicle v for waste type i in waste producer group g in on-site collection o (h t^{-1})

$u_{f,g,i}$ = unit cost of functional element f for waste type i produced by waste producer group g (EUR t^{-1})

$u_{o,c,g,i}$ = unit cost of bin or container c for waste type i in waste producer group g in on-site collection o (EUR t^{-1})

$u_{o,v,g,i}$ = unit cost of collection and transportation with collection vehicle v for waste type i in waste producer group g in on-site collection o (EUR t^{-1})

v_c = volume of bin or container c (m^3)

$v_{o,g,i}$ = total volume of bins or containers needed for waste type i at an average property in waste producer group g in on-site collection o (m^3)

$x_{v,A}$ = unit fuel consumption during idle running A for collection vehicle v (l h^{-1})

$x_{v,B}$ = unit fuel consumption for emptying B of a bin or container for collection vehicle v (l container^{-1})

$x_{v,C}$ = unit fuel consumption during driving between properties C for collection vehicle v (l h^{-1})

$x_{v,D}$ = unit fuel consumption during transportation D for collection vehicle v (l h^{-1})

$x_{v,E}$ = unit fuel consumption during unloading E for collection vehicle v (l h^{-1})

$y_{o,v,g,i}$ = emptying cost for waste type i in waste producer group g with collection vehicle v in on-site collection o (EUR (bin or container)$^{-1}$)

$z_{o,v,g,i}$ = unit fuel consumption of collection and transportation for waste type i in waste producer group g with collection vehicle v in on-site collection o (l t^{-1})

$\alpha_{o,g,i}$ = filling grade of bins and containers for waste type i in waste producer group g in on-site collection o (%)

$\beta_{i,c}$ = specific weight of waste type i as found in bin or container c (t m^{-3})

$\epsilon_{o,c,v,g,i}$ = emptying time of bins or containers c with collection vehicle v for waste type i in waste producer group g in on-site collection o (h property^{-1})

φ = off-road time for collection and transportation, e.g. breaks (%)

$\gamma_{v,g,i}$ = transportation time of waste type i in waste producer group g with collection vehicle v (h load^{-1})

$\eta_{o,v,g,i}$ = driving time between properties in on-site collection o of waste type i in waste producer group g with collection vehicle v (h property^{-1})

λ_v = unloading time of collection vehicle v (h load^{-1}).

1 Introduction

1.1 Background

Sustainable development is one of the major targets of present waste management according for example to Agenda 21 of the United Nations Conference on Environment and Development (UNCED). In the European Union, several regulations have been made to reach this target and the member states are also required to draw up waste management plans (Council of the European Communities 1991). The aim of these plans is to systematically promote prevention, safe recovery and safe final disposal of wastes.

The member states of the European Union can be divided into two groups on the basis of the approach applied in municipal solid waste management (MSWM). Firstly, there are countries in which incineration is an essential part of waste management systems, e.g. Belgium, Denmark, France, Germany, Luxembourg, the Netherlands and Sweden (Commission of the European Communities 1999). In these countries, comparatively high recovery levels can be reached with moderate separation strategies if the remaining mixed waste is incinerated for energy recovery. Secondly, there are member states like Finland, Greece, Italy, Ireland, Portugal, Spain and the United Kingdom in which incineration is of minor importance. In these countries, high recovery levels are far more difficult to reach and implementation of highly efficient separation strategies is of vital importance.

In Finland, MSWM is greatly affected by the first National Waste Plan which came into force in 1998 (Ministry of the Environment, Finland 1998). The following major goals have been set for MSWM in this plan with regard to waste minimization:

1. Waste avoidance: In the year 2000, the amount of waste generated shall not surpass that in 1994 and in 2005 it should be at least 15 % less than the amount in accordance with predicted growth rate without any reduction measures.
2. Waste recovery: The recovery rate of 30 %wt reached in 1994 shall be raised to at least 50 %wt by the year 2000 and to at least 70 %wt by the year 2005.

In 1994, the total amount of municipal solid waste generated in Finland was 2.1 Mtonnes and 70 %wt of the waste mass was directly disposed of to some 500 landfills. According to the new targets, the annual amount of waste disposed of to landfills should be reduced by 56 % (0.84 Mtonnes) by the year 2005. It has also been estimated that the number of landfills will be reduced to 50–80 during the same period of time (Ministry of the Environment, Finland 1998).

It appears that the Finnish municipalities try to achieve the recovery rate targets mainly by source separation activities and by co-operation. As a result, the character of MSWM in Finland is changing. Source separation divides the total waste mass into separate waste types, resulting in an increased number of waste streams, functional elements and interdependences in waste management systems. Waste treatment methods, such as composting and energy production, will become commonplace. On the other hand, co-operation between communities will lead to higher waste amounts and longer transfer distances in the systems. Thus, both the complexity and the size of waste management systems are increasing.

New political targets and changes in waste management practices are a challenge for waste management planning. In the Finnish MSWM, the following questions, for example, should be answered: What kind of strategies are needed to meet the Finnish recovery rate targets of 50 %wt and 70 %wt on national and on regional level? Is incineration needed? Is central sorting of mixed waste needed? How does enhanced separation affect the costs and emissions of MSWM? How do changes in separation strategies affect the efficiency of the various techniques, e.g. alternative waste collection methods? Modelling offers a systematic framework to study these questions.

1.2 Review of models used in the planning of MSWM systems

During the past three decades, models used in planning of MSWM have been developed in accordance with waste management objectives, especially waste minimization and emission control. The reviews compiled by Gottinger (1988) and MacDonald (1996) show that early MSWM models developed during the 1960s and 1970s focussed on studying individual functional elements, i.e. determining collection routes or facility locations, capacities or expansion patterns. In the

1980s, the focus was extended to cover MSWM on the system level, resulting in larger system boundaries. These models were mainly aimed at minimizing the costs of mixed waste management (Rushbrook 1987, Gottinger 1988), and recycling was included in some of them more or less comprehensively (Chapman and Berman 1983, Kaila 1987).

In the 1990s, recycling was extensively included in most models used for strategic planning of MSWM. Reduced system costs are the commonest objective (Lund 1990, Jacobs and Everett 1992, Zach 1992, Baetz and Neebe 1994, Anex et al. 1996, Everett and Modak 1996, Huhtala 1997, Ansems and Langerak 1998), but some models study MSWM from the point of view of the sizes and characteristics of waste streams (Haith 1998) or their emissions (Pictet et al. 1992). In several strategic planning models both costs and emissions of MSWM have been included (Sundberg 1993, White et al. 1995, Ljunggren 1997, Wang et al. 1998). In some models the whole life cycle of products has been included in the study instead of only the waste management system when environmentally optimal waste management strategies are sought (Kaila 1996, Gielen 1998).

Despite the development of strategic planning models, the analysis of factors affecting the amount of materials which can be separately collected with a given separation strategy has usually been omitted from the models. The amount of a material separately collected depends on two factors: (1) the coverage of a collection system applied and (2) the separation activity of waste producers, consisting of participation rate and separation efficiency. The coverage of a collection system in an area is defined as the ratio of (a) the amount of a material produced in those properties in which separate collection is available and (b) the amount of the material in question produced in all properties of the area. Participation rate is defined as the share of people providing sorted material to bins in those properties in which separate collection is available. Separation efficiency is defined as the share of a material which is correctly separated by those participating in separation.

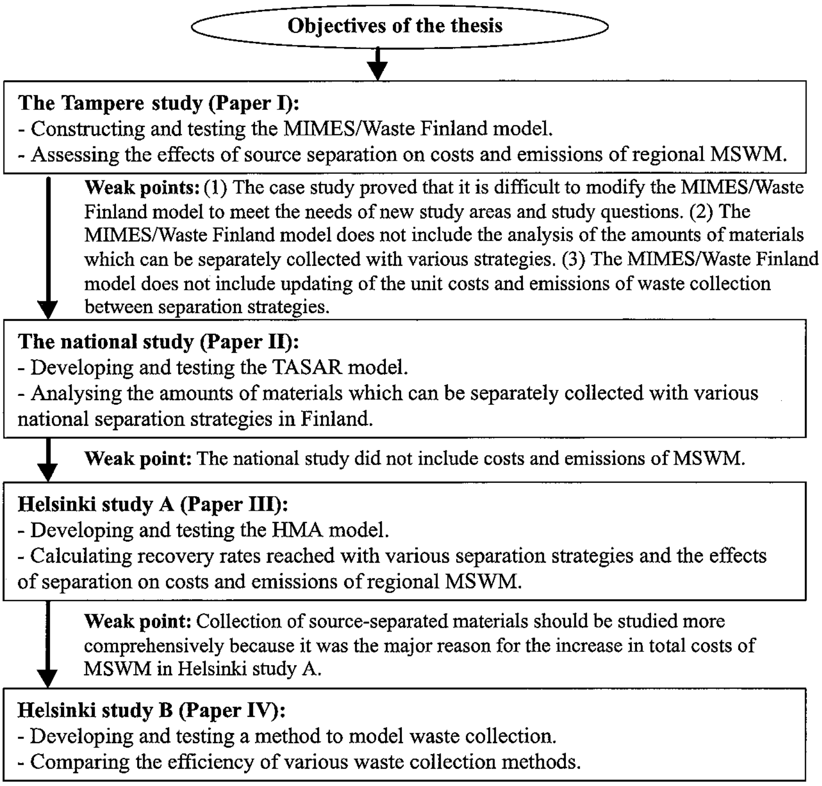
1.3 Objectives and scope of the thesis

This thesis has two major objectives which can be divided into more detailed subobjectives:

1. To develop an approach for analysing MSWM based on source separation.
    - To develop a method for calculating the amounts of materials which can be separately collected for recovery with various separation strategies.
    - To develop models for integrated analysis of recovery rates, waste streams, costs and emissions of MSWM systems.
2. To test the approach and evaluate the effects of separation on MSWM in Finland.
    - To analyse the major factors affecting the amount of materials which can be separated at source and collected for recovery.
    - To determine the upper limit of recovery rate which can be reached with source separation.
    - To assess the likelihood of reaching the Finnish recovery rate targets by complementing source separation strategies with central sorting of mixed waste.
    - To calculate the effects of separation on waste streams, costs and emissions of MSWM and on costs, fuel consumption and working hours of waste collection.

The thesis consists of four case studies which were performed by modelling MSWM (I–IV, Fig. 1). Firstly, in the Tampere study, the effects of separation on costs and emissions of MSWM were examined in the Tampere region with the MIMES/Waste (a Model for description and optimization of Integrated Material flows and Energy Systems) Finland model (I). MIMES/Waste Finland was modified from the original Swedish MIMES/Waste model to meet the Finnish circumstances (Sundberg 1993, Tanskanen 1996). Secondly, in the national study, a model called TASAR (a Tool for Analysing Separation Actions and Recovery) was developed in order to analyse separation strategies of municipal solid waste on national level in Finland (II). Thirdly, in Helsinki study A, the HMA (Helsinki Metropolitan Area) model was developed for integrated analysis of recovery rates, waste streams, costs and emissions of MSWM in the Helsinki region (III). Finally in Helsinki study B, efficiencies of various waste collection methods were compared in the Helsinki region (IV). In addition to the case studies included in this thesis, the approach developed has also been applied for modelling MSWM in the Lahti region (Tanskanen 1997a, 1997b).

The thesis covers extensively the potential separation alternatives and functional elements of



Objectives of the thesis

The Tampere study (Paper I):
- Constructing and testing the MIMES/Waste Finland model.
- Assessing the effects of source separation on costs and emissions of regional MSWM.

Weak points: (1) The case study proved that it is difficult to modify the MIMES/Waste Finland model to meet the needs of new study areas and study questions. (2) The MIMES/Waste Finland model does not include the analysis of the amounts of materials which can be separately collected with various strategies. (3) The MIMES/Waste Finland model does not include updating of the unit costs and emissions of waste collection between separation strategies.

The national study (Paper II):
- Developing and testing the TASAR model.
- Analysing the amounts of materials which can be separately collected with various national separation strategies in Finland.

Weak point: The national study did not include costs and emissions of MSWM.

Helsinki study A (Paper III):
- Developing and testing the HMA model.
- Calculating recovery rates reached with various separation strategies and the effects of separation on costs and emissions of regional MSWM.

Weak point: Collection of source-separated materials should be studied more comprehensively because it was the major reason for the increase in total costs of MSWM in Helsinki study A.

Helsinki study B (Paper IV):
- Developing and testing a method to model waste collection.
- Comparing the efficiency of various waste collection methods.

Fig. 1. Description of the case studies included in the thesis.

MSWM. In Paper IV, only household waste was included in the comparison of waste collection methods. Wastes generated e.g. by construction and demolition activities as well as by waste water treatment plants (sewage sludge) were totally excluded from the study. Recovery rate was determined as the share of waste which is separated for recovery.

2 Materials and methods

2.1 Methods and models developed

2.1.1 Approach for evaluating MSWM systems (II–IV)

The approach developed in this thesis consists of formulation, analysis and comparison of various MSWM systems and it includes the calculation of the amounts of materials which can be collected for recovery with various separation strategies. The approach can be divided into six stages (Fig. 2). Firstly, potential separation strategies are formulated for recoverable waste materials on the basis of an analysis in which the coverages of different kinds of collection systems are determined. Waste producers are divided into groups, e.g. residential properties and commercial establishments, so that differences in the amounts of materials produced can be taken into consideration when planning separation strategies. In addition to source separation, strategies may include central sorting of waste materials. Secondly, the total recovery rate and the recovery rates of individual materials are calculated (Eqs. 1–7). After the second stage, the separation strategies can be modified if the recovery level is too low.

$$R = \sum_g (R_g * \frac{s_g}{100}) \qquad (1)$$

$$R_g = \sum_i (R_{g,i} * \frac{\sum_j s_{g,i,j}}{100}) \qquad (2)$$

$$R_{g,i} = r_{1,g,i} + r_{2,g,i} \qquad (3)$$

$$r_{1,g,i} = c_{o,g,i} * \frac{p_{o,g,i}}{100} * \frac{e_{o,g,i}}{100} + c_{d,g,i} * \frac{p_{d,g,i}}{100} * \frac{e_{d,g,i}}{100} \qquad (4)$$

$$c_{o,g,i} + c_{d,g,i} \leq 100 \qquad (5)$$

$$r_{2,g,i} = \frac{e_i}{100} * \left[c_{x,g,i} + c_{y,g,i} * (1 - \frac{p_{o,g,i}}{100} * \frac{e_{o,g,i}}{100}) + c_{z,g,i} * (1 - \frac{p_{d,g,i}}{100} * \frac{e_{d,g,i}}{100}) \right] \qquad (6)$$

$$c_{x,g,i} + c_{y,g,i} + c_{z,g,i} \leq 100 \qquad (7)$$

where

$c_{d,g,i}$ = coverage of drop-off centre collection d of material i in waste producer group g (%)

$c_{o,g,i}$ = coverage of on-site collection o of material i in waste producer group g (%)

$c_{x,g,i}$ = coverage of on-site collection of mixed waste for central sorting in waste producer group g including properties x from which material i is not separately collected (%)

$c_{y,g,i}$ = coverage of on-site collection of mixed waste for central sorting in waste producer group g including properties y from which material i is separately collected as on-site collection (%)

$c_{z,g,i}$ = coverage of on-site collection of mixed waste for central sorting in waste producer group g including properties z from which material i is separately collected as drop-off centre collection (%)

$e_{d,g,i}$ = separation efficiency of material i in waste producer group g in drop-off centre collection d (%wt)

e_i = separation efficiency of material i in central sorting plant (%wt)

$e_{o,g,i}$ = separation efficiency of material i in waste producer group g in on-site collection o (%wt)

$p_{d,g,i}$ = participation rate of material i in waste producer group g in drop-off centre collection d (%)

$p_{o,g,i}$ = participation rate of material i in waste producer group g in on-site collection o (%)

R = total recovery rate (%wt)

R_g = recovery rate of waste producer group g (%wt)

$R_{g,i}$ = recovery rate of material i in waste producer group g (%wt)

$r_{1,g,i}$ = recovery rate of material i in waste producer group g which is achieved with source separation (%wt)

$r_{2,g,i}$ = recovery rate of material i in waste producer group g which is achieved with central sorting (%wt)

s_g = share of waste produced by waste producer group g in total waste (%)

$s_{g,i,j}$ = share of waste component j which is a part of material i in waste amount produced by waste producer group g (%).

Thirdly, the sizes of waste streams in the waste management system and the accumulations of waste types (mixed waste and recoverable materials) at the average collection points (i.e. the average property and drop-off centre) of each waste producer group are calculated (Eqs. 8–10). Waste streams and waste types are described by their

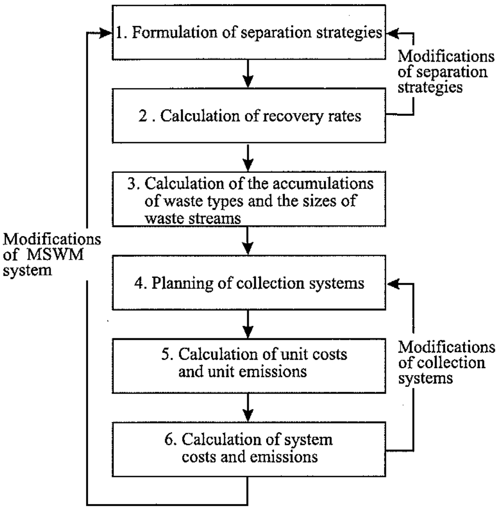


Fig. 2. Stages of the modelling approach developed in the study.

waste components. Thus, the effect of separation on the composition of mixed waste, for example, is calculated by the model.

$$a_{o,g,i} = \sum_j g_{o,g,i,j} * \frac{p_{o,g,i}}{100} * \frac{e_{o,g,i}}{100} \tag{8}$$

$$a_{d,g,i} = \sum_j g_{d,g,i,j} * h_{d,g,i} * \frac{p_{d,g,i}}{100} * \frac{e_{d,g,i}}{100} \tag{9}$$

$$a_{g,m} = \sum_i (g_g * \sum_j \frac{s_{g,i,j}}{100} * \frac{(100 - r_{1,g,i})}{100}) \tag{10}$$

where

$a_{o,g,i}$ = accumulation of waste type i in an average property participating in on-site collection o in waste producer group g ($t\ a^{-1}$)

$a_{d,g,i}$ = accumulation of waste type i in an average drop-off centre d of waste producer group g ($t\ a^{-1}$)

$a_{g,m}$ = accumulation of mixed waste m in an average property of waste producer group g ($t\ a^{-1}$)

$g_{d,g,i,j}$ = generation of waste component j which is a part of waste type i per inhabitant in the coverage area of drop-off centre collection d of waste type i in waste producer group g ($t\ inhabitant^{-1}\ a^{-1}$)

g_g = generation of municipal solid waste in an average property of waste producer group g ($t\ a^{-1}$)

$g_{o,g,i,j}$ = generation of waste component j which is a part of waste type i in an average property participating in on-site collection o in waste producer group g ($t\ a^{-1}$)

$h_{d,g,i}$ = number of inhabitants in waste producer group g who live in the coverage area of drop-off centre collection d of waste type i and who are not connected to on-site collection of waste type i.

Fourthly, collection systems, i.e. the types and numbers of bins and containers and collection frequencies, are dimensioned separately for each waste type, waste producer group and separation strategy. Calculation is based on accumulations of waste types at the average collection points, filling grades of bins and containers and specific weights of waste types as found in containers. The equations applied for dimensioning on-site collection systems are shown as an example and corresponding equations are used for drop-off centre collection (Eqs. 11 and 12).

$$v_{o,g,i} = \frac{a_{o,g,i}}{\frac{\alpha_{o,g,i}}{100} * \beta_{i,c} * f_{o,g,i}} \tag{11}$$

$$n_{o,g,i,c} = \frac{v_{o,g,i}}{v_c} + q \tag{12}$$

where

$f_{o,g,i}$ = collection frequency for waste type i in waste producer group g in on-site collection o (a^{-1})

$n_{o,g,i,c}$ = number of bins or containers c for waste type i at an average property in waste producer group g in on-site collection o

q = constant describing the average extra volume which arises when the number of bins or containers is rounded up at the collection points

v_c = volume of bin or container c (m^3)

$v_{o,g,i}$ = total volume of bins or containers needed for waste type i at an average property in waste producer group g in on-site collection o (m^3)

$\alpha_{o,g,i}$ = filling grade of bins and containers for waste type i in waste producer group g in on-site collection o (%)

$\beta_{i,c}$ = specific weight of waste type i as found in bin or container c ($t\ m^{-3}$).

Fifthly, the unit costs and unit emissions of functional elements are determined. The unit costs are connected to the sizes of waste streams. The unit emissions are determined separately for each waste component of a waste stream and expressed, for example, as kg CH_4 per tonne of biowaste landfilled. The unit costs of bins and containers are calculated on the basis of the annual costs, numbers of bins and containers and accumulations of waste types (Eq. 13). The unit costs of collection work can be calculated either on the basis of emptying costs, numbers of bins and containers, collection frequencies and accumulations of waste types as in Helsinki study A (Eq. 14) or on the basis of collection times and hourly costs as in the Tampere study and in Helsinki study B (Eqs. 15 and 16). The calculation of unit fuel consumption is based on the phases of collection work whose number varied slightly in the case studies of this thesis, depending on the input data available. For example, in Helsinki study B, the collection work was divided into five phases (Eq. 17). In Eqs. 13–17 on-site collection is shown as an example but corresponding equations are used for drop-off centre collection.

$$u_{o,c,g,i} = \frac{b_{c,i} * n_{o,g,i,c}}{a_{o,g,i}} \qquad (13)$$

$$u_{o,v,g,i} = \frac{y_{o,v,g,i} * n_{o,g,i,c} * f_{o,g,i}}{a_{o,g,i}} \qquad (14)$$

$$u_{o,v,g,i} = t_{o,c,v,g,i} * b_v \qquad (15)$$

$$t_{o,c,v,g,i} = \left[\frac{(\varepsilon_{o,c,v,g,i} + \eta_{o,v,g,i}) * f_{o,g,i}}{a_{o,g,i}} + \frac{(\gamma_{v,g,i} + \lambda_v)}{l_{v,i}} \right] * \frac{(100 + \varphi)}{100} \qquad (16)$$

$$z_{o,v,g,i} = \frac{(\varepsilon_{o,c,v,g,i} * x_{v,A} + n_{o,g,i,c} * x_{v,B} + \eta_{o,v,g,i} * x_{v,C}) * f_{o,g,i}}{a_{o,g,i}} + \frac{(\gamma_{v,g,i} * x_{v,D} + \lambda_v * x_{v,E})}{l_{v,i}} \qquad (17)$$

where

$b_{c,i}$ = annual cost of bin or container c for waste type i (EUR a^{-1})

b_v = unit cost of collection vehicle v (EUR h^{-1})

$l_{v,i}$ = net load of collection vehicle v for waste type i (t)

$t_{o,c,v,g,i}$ = unit time of collection and transportation with bin or container c and collection vehicle v for waste type i in waste producer group g in on-site collection o (h t^{-1})

$u_{o,c,g,i}$ = unit cost of bin or container c for waste type i in waste producer group g in on-site collection o (EUR t^{-1})

$u_{o,v,g,i}$ = unit cost of collection and transportation with collection vehicle v for waste type i in waste producer group g in on-site collection o (EUR t^{-1})

$x_{v,A}$ = unit fuel consumption during idle running A for collection vehicle v (l h^{-1})

$x_{v,B}$ = unit fuel consumption for emptying B of a bin or container for collection vehicle v (l container^{-1})

$x_{v,C}$ = unit fuel consumption during driving between properties C for collection vehicle v (l h^{-1})

$x_{v,D}$ = unit fuel consumption during transportation D for collection vehicle v (l h^{-1})

$x_{v,E}$ = unit fuel consumption during unloading E for collection vehicle v (l h^{-1})

$y_{o,v,g,i}$ = emptying cost for waste type i in waste producer group g with collection vehicle v in on-site collection o (EUR (bin or container)$^{-1}$)

$z_{o,v,g,i}$ = unit fuel consumption of collection and transportation for waste type i in waste producer group g with collection vehicle v in on-site collection o (l t^{-1})

$\epsilon_{o,c,v,g,i}$ = emptying time of bins or containers c with collection vehicle v for waste type i in waste producer group g in on-site collection o (h property^{-1})

φ = off-road time for collection and transportation, e.g. breaks (%)

$\gamma_{v,g,i}$ = transportation time of waste type i in waste producer group g with collection vehicle v (h load^{-1})

$\eta_{o,v,g,i}$ = driving time between properties in on-site collection o of waste type i in waste producer group g with collection vehicle v (h property^{-1})

λ_v = unloading time of collection vehicle v (h load^{-1}).

Sixthly, the annual costs and emissions of MSWM are calculated as a product of the sizes of waste streams and the unit costs and unit emissions (Eqs. 18 and 19). Finally, alternative MSWM systems can be created by modifying the collection systems and the separation strategies. The aim of these modifications may be reduction of the costs and emissions of MSWM.

$$T = \sum_f \sum_g \sum_i (u_{f,g,i} * m_{f,g,i}) \qquad (18)$$

$$O_c = \sum_f \sum_g \sum_i \sum_j (h_{c,f,g,i,j} * m_{f,g,i,j}) \qquad (19)$$

where

$h_{c,f,g,i,j}$ = unit emission c of functional element f resulting from treatment of waste component j which is part of waste type i in waste producer group g (e.g. mg CH_4 t^{-1} of biowaste landfilled)

$m_{f,g,i}$ = amount of waste type i produced by waste producer group g and treated with functional element f (t a^{-1})

$m_{f,g,i,j}$ = amount of waste component j in waste type i produced by waste producer group g and treated with functional element f (t a^{-1})

O_c = total amount of emission component c (e.g. t CH_4 a^{-1})

T = costs of MSWM (EUR a^{-1})

$u_{f,g,i}$ = unit cost of functional element f for waste type i produced by waste producer group g (EUR t^{-1}).

An essential part of the approach described above is a method which was developed for calculating the coverages of on-site collection systems ($c_{o,g,i}$) and corresponding accumulations of waste materials at the average properties of waste producer groups (g_g and $\Sigma_j\, g_{o,g,i,j}$). The coverages of collection systems are needed to calculate the recovery rates which can be reached with various separation strategies and the accumulations of materials are needed to calculate the corresponding unit costs and unit emissions of waste collection.

Calculation of the coverages of on-site collection systems is based on the fact that large properties are usually obliged to participate in on-site collection of recoverable materials before smaller

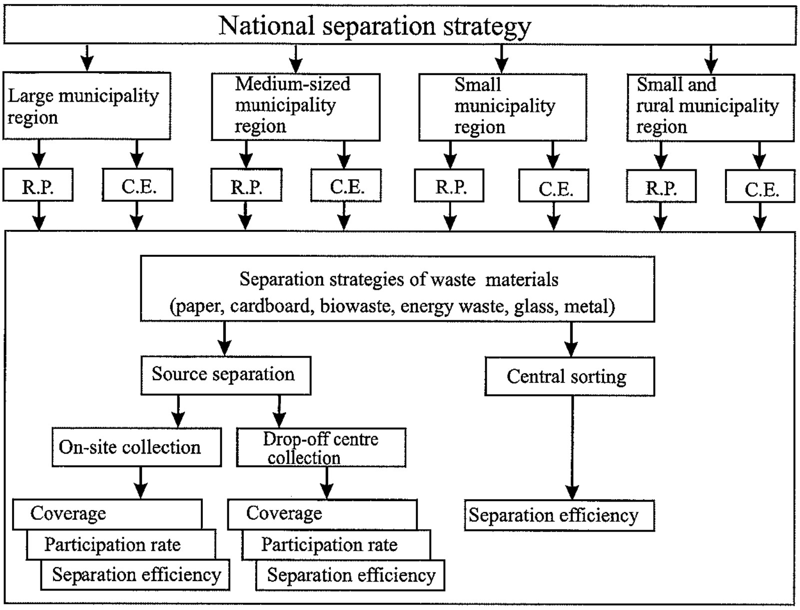


Fig. 3. Elements from which a national separation strategy can be compiled in the TASAR model (R.P. = residential properties, C.E. = commercial establishments).

ones. Thus, the coverages of on-site collection systems can be determined on the basis of the size distribution of properties. In Finland, the minimum size of a property obliged to participate in on-site collection of a material, termed on-site obligation limit, is determined on the basis of the number of households in residential properties and on the basis of the amount of a material produced in commercial establishments. The shares of the total amount of a material produced in properties of different sizes can be presented as a cumulative distribution function and the average amount of the material generated in properties greater than or equal to the on-site obligation limit can be included in the same graph (see e.g. Fig. 10).

2.1.2 Applications of the approach

2.1.2.1 National model – TASAR (II)

The TASAR (a Tool for Analysing Separation Actions and Recovery) model was developed for analysing the effects of separation actions on recovery rates and waste streams of MSWM on the national level in Finland (see stages 1–3 in Fig. 2). In TASAR, a national separation strategy can be established from 1–4 regional strategies which all consist of separate strategies for residential properties and commercial establishments (Fig. 3). Separation of six recoverable materials was included in the model: paper, cardboard, biowaste, energy waste, glass and metal. Energy waste was determined to consist of plastics, nonrecyclable paper and cardboard, liquid packaging board and miscellaneous combustible waste components. Separation strategies of waste materials may consist of both source separation and central sorting. Source-separated materials can be collected as on-site collection or as drop-off centre collection, which are both defined on the basis of coverage, participation rate and separation efficiency. Costs and emissions were excluded from this model. TASAR is a static and linear simulation model created using the format of an Excel spreadsheet.

In TASAR, the Finnish municipalities (numbering 452 in 1995) were classified into the following four categories on the basis of their population and location:

1. Large municipality region: Municipalities with at least 50 000 inhabitants or located not further than 50 km from a city with 50 000 inhabitants.
2. Medium-sized municipality region: Municipalities with 20 000–50 000 inhabitants or located not further than 50 km from a city with 20 000–50 000 inhabitants.
3. Small municipality region: Municipalities with fewer than 20 000 inhabitants and located 50–100 km from a city with at least 20 000 inhabitants.
4. Small and rural municipality region: Municipalities having fewer than 20 000 inhabitants and located more than 100 km from a city with at least 20 000 inhabitants.

The number of inhabitants was chosen as the first criterion because it describes the scale of the waste management system in a municipality. The first limiting value, 50 000 inhabitants, was assessed to be the minimum size for a municipality to have a landfill of its own. The second value, 20 000 inhabitants, was selected because after mapping it was found to be the minimum limit which covers the important Finnish city regions.

The transfer distance was chosen as the second criterion because it characterizes the possibility of a small municipality to arrange waste management in co-operation with a larger city. The main limiting value, 50 km, describes the maximum reasonable transfer distance for compacting collection vehicles used in Finland. The second limit, 100 km, specifies the need for transshipments in regional waste management systems.

The classification of municipalities was done with the help of the Monitoring System of Spatial Structure in Major Finnish Urban Regions (Ristimäki 1997) and the distances between municipalities were measured as direct lines between the focuses of the settlements of municipalities.

2.1.2.2 Regional model – HMA (III)

The HMA (Helsinki Metropolitan Area) model was developed for integrated analysis of separation strategies and their effects on recovery rates, waste streams, costs and emissions of regional MSWM (see stages 1–6 in Fig. 2, Fig. 4, Table 1). Waste producers were divided into three groups: (1) residential properties smaller than five households (detached houses and small terraced houses), (2) residential properties greater than or equal to five households (terraced houses and apartment houses) and (3) commercial establishments. In addition to mixed waste, source separation of seven materials was included in the model: paper, cardboard, biowaste, energy waste, glass, metal and liquid packaging board, e.g. juice cartons. Energy waste may consist of plastics, non-recyclable paper and cardboard, liquid packaging board and miscellaneous combustible waste components.

Table 1. Functional elements, costs and emission components of MSWM included in the HMA model.

Functional element	Costs	Emission components
Waste collection		
bins and containers at the properties	yes	–
containers at drop-off centres	yes	–
structures of collection points	yes	–
collection work at the collection area	yes	CO_2, NO_x, SO_2, VOCs
transportation	yes	CO_2, NO_x, SO_2, VOCs
Transfer station	yes	–
Backyard composting	yes	CO_2, CH_4, N_2O, NH_3, VOCs
Central composting	yes	COD, CO_2, CH_4, N_2O, NH_3, NO_x(1, NH_4, SO_2(1, VOCs
Processing of source-separated energy waste	yes	–
Central sorting and processing of mixed waste	yes	–
Landfilling	yes	
decomposition of waste		COD, NH_4, CO_2, CH_4, VOCs
landfill compactors		CO_2, NO_x, SO_2, VOCs
recovery of landfill gas		CO_2, NO_x, SO_2, VOCs
Waste tax	yes	–
Revenues from recovered materials	yes	–

(1 Emissions from the production of energy needed in composting.

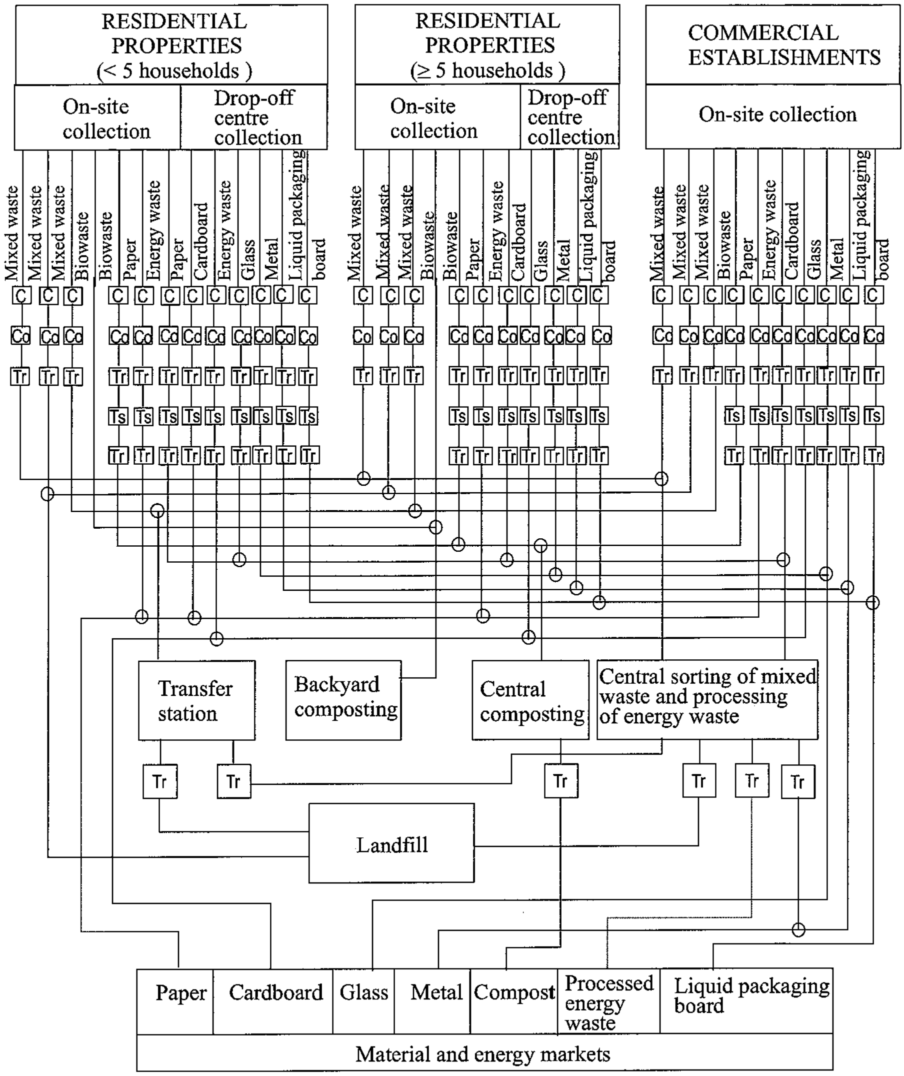


Fig. 4. Graphic presentation of the HMA model (C = containers, Co = collection, Tr = transportation, Ts = transfer station).

The collection systems of source-separated materials include both on-site collection and drop-off centres which are defined on the basis of coverage, participation rate and separation efficiency. In addition to source separation, the combustible components of mixed waste can be sorted centrally for energy recovery. The HMA model is a static and linear simulation model in the format of an Excel spreadsheet (version 5.0).

Nine emission components from collection, backyard composting, central composting and landfilling were included in the HMA model (Table 1). The individual emission components were expressed as four groups of emissions as follows:

1. nutrient load (O_2 consumption) consisting of COD, NO_x, NH_4 and NH_3,
2. greenhouse gas load (CO_2 equivalents) consisting of CO_2, CH_4 and N_2O,

3. acid load (SO_2 equivalents) consisting of SO_2, NO_x and NH_3,
4. ozone formation (C_2H_4 equivalents) consisting of VOCs.

The coefficients needed to convert the individual emission components to the equivalents of emission groups were selected to correspond to the Scandinavian environmental conditions by Pelkonen et al. (1996) from the data compiled by the Nordic Council of Ministers (1995).

2.1.2.3 Analysis of waste collection (IV)

In Helsinki study B, the effects of source separation on the efficiency of four different kinds of waste collection methods were compared. The criteria selected for the comparison were: system costs, fuel consumption, working hours and recovery rates. System costs consisted of both fixed and operational costs caused by bins and containers, collection and transportation. In addition, the costs of a central sorting plant were included in the costs of commingled collection. The structures of collection points were excluded from the study because a shelter is not required for bins in the general regulations about waste management in the Helsinki Metropolitan Area (YTV 1996).

Four different kinds of collection methods were included in Helsinki study B (Table 2). Firstly, in the present method (M1), all types of waste are separately collected with 120–600 l bins and single-compartment compacting collection vehicles. Secondly, in the large container method (M2), the present method was modified by using 1.3–5.0 m^3 containers at properties greater than or equal to 30 households. These properties produce 62 %wt of household waste in the Helsinki region. Thirdly, in the combined collection method (M3), mixed waste, paper and energy waste were collected simultaneously with multi-compartment compacting vehicles from properties smaller than 30 households. As a result, the share of household waste collected with multi-compartment vehicles varied between 11 %wt and 34 %wt, depending on the separation strategy studied. Fourthly, in the commingled collection method (M4), the same bin was used to collect mixed waste, biowaste and energy waste from the properties smaller than 30 households. The different types of waste were packed into plastic bags of different colours at the properties, collected with single-compartment compacting collection vehicles and sorted centrally at an optical sorting plant. Commingled collection was applied for 11–28 %wt of household waste depending on the strategy studied.

2.1.3 MIMES/Waste Finland model (I)

The MIMES/Waste Finland model was developed for analysing costs and emissions of separation based MSWM on the regional level. It is a static and linear optimization model which includes several source separation alternatives and functional elements of MSWM. MIMES/Waste Finland is a modified version of the original Swedish MIMES/Waste model developed by Sundberg (1993). The MIMES/Waste models have been built on the modelling concept of MIMES (a Model for description and optimization of Integrated Material flows and Energy Systems) which has been com-

Table 2. Collection methods included in Helsinki study B.

Character	Collection method			
	M1	M2	M3	M4
Size of properties to which the method was applied (number of households)	≥ 1	≥ 30[(1]	< 30[(1]	< 30[(1]
Size of bins and containers (m^3)	0.12–0.60	1.3–5.0	0.12–0.60	0.12–0.60
Type of collection vehicle				
number of compartments	1	1	3	1
compaction	yes	yes	yes	yes
Source separation needed	yes	yes	yes	yes
Central sorting needed	no	no	no	yes

[(1] Method M1 was applied to all other properties.

Table 3. Functional elements, costs and emission components of the MIMES/Waste Finland model used in the Tampere study.

Functional element	Costs	Emission components
Waste collection		
bins and containers at the properties	yes	–
bins and containers at drop-off centres	yes	–
structures of collection points	yes	–
collection	yes	CO_2, NO_x, SO_2
transportation	yes	CO_2, NO_x, SO_2
Transfer station	yes	–
Backyard composting	yes	–
Central composting	yes	–
Energy waste processing	yes	–
Landfilling	yes	CO_2, CH_4
Revenues from recovered materials	yes	–

prehensively presented by Sundberg (1993). The MIMES/Waste Finland model and its application in the Tampere region have been presented in detail in Paper I and by Tanskanen (1996, Table 3).

2.2 Case studies and example areas (I–IV)

This thesis consists of four case studies which were conducted in three separate example areas (Fig. 5, Table 4). Firstly, in the Tampere study, two separation strategies were studied with the MIMES/Waste Finland model in order to ascertain the effects of enhanced separation on the costs and emissions of regional MSWM (Table 5). The study area consisted of six municipalities, i.e. Kangasala, Lempäälä, Nokia, Pirkkala, Orivesi and Tampere.

Secondly, in the national study, the TASAR model was developed and applied in order to answer the following questions: What kind of a national strategy is needed to reach the Finnish recovery rate targets, i.e 50 %wt by the end of 2000 and 70 %wt by 2005? Which waste components have to be recovered? What kind of collection systems are needed? Do we need to complement source separation with central sorting of mixed waste? In the national study, six separation strate-

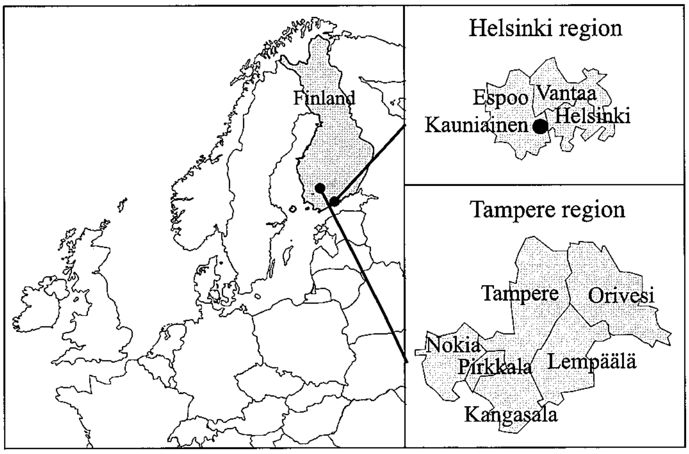


Fig. 5. Example areas studied.

Table 4. Characteristics of the example areas in the case studies conducted.

Character	Case study Tampere (1993)	Finland (1995)	Helsinki A (1995)	Helsinki B[1] (1998)
Waste amount (t a^{-1})	126 000	2 100 000	520 000	250 000
Number of municipalities	6	452	4	4
Number of inhabitants	260 000	5 117 000	891 000	920 000
Area (km^2)	2 580	338 100	760	760
Population density (person km^{-2} land area)	96	17	1 229	1 269

[1] Only residential properties were included in the study.

gies were formulated and analysed (Table 5). The study included all the Finnish municipalities (452 in 1995).

Thirdly, in Helsinki study A, the TASAR model was further developed to include costs and emissions of MSWM on the regional level. As a result, the HMA model was developed and applied in the Helsinki Metropolitan Area. In Helsinki study A, three separation strategies were formulated and analysed in order to answer the following questions (Table 5): What kind of separation strategies fulfill the Finnish recovery rate targets? How would the implementation of these strategies affect costs and emissions of MSWM? Fourthly, in Helsinki study B, the effects of source separation on the efficiency of waste collection were examined and different collection methods were compared. Both in Helsinki study A and in Helsinki study B the example areas consisted of Espoo, Helsinki, Kauniainen and Vantaa. However, only residential properties were included in Helsinki study B.

2.3 Input data (I–IV)

The input data used in the case studies were based on statistical data, empirical data and earlier studies from the example areas, earlier studies from other areas and estimates made on the basis of the statements of experts and other available data (Table 6). The input data used in the case studies have been presented in detail as follows:

- the Tampere study in Paper I and in greater detail by Tanskanen (1996),
- the national study in Paper II,
- Helsinki study A in Paper III, by Tanskanen (1997c) and by Pelkonen et al. (1996),
- Helsinki study B in Paper IV.

3 Results

3.1 Factors affecting the share of materials collected separately (II–III)

The following factors were included in the analysis of source separation strategies: (1) the geographical distribution of production of municipal solid waste in Finland, (2) composition of municipal solid waste, (3) coverages of on–site collection systems and (4) separation activity of waste producers.

The classification of Finnish municipalities in the TASAR model showed that production of municipal solid waste is unevenly distributed in Finland. The major share, i.e. 68 %wt, of the total waste amount is produced in the large municipality region which covers 21 % of the surface area of Finland (Fig. 6). The corresponding figures for the medium-sized municipality region are 17 %wt and 20 % and for the small municipality region 13 %wt and 30 %. Finally, 2 %wt of municipal solid waste is produced in the small and rural municipality region which covers 29 % of the surface area of the country. The uneven distribution indicates the importance of regional separation decisions from the perspective of national recovery rates.

The share of recoverable materials in municipal solid waste is 93 %wt on average in Finland. The major recoverable materials, i.e. paper, cardboard, biowaste and energy waste, comprise 87 %wt of the total waste and the share of each of these materials is at least 11 %wt. The combined share of glass and metal is about 6 %wt on the average. Liquid packaging board can also be separately collected, reducing the share of energy waste by 2 %wt-units. The remaining 7 %wt consists of tex-

Table 5. Description of separation strategies included in the Tampere study, National study and Helsinki study A.

Strategy	Description of the separation strategy			
	Materials	On-site obligation limits		Materials collected via drop-off centres
		Residential properties (number of households)	Commercial establishments (kg week^{-1})	
Tampere study				
T1	Paper, biowaste	(1	(1	Paper, glass
	Cardboard, glass	–	(1	
T2	Paper, biowaste, energy waste	2	> 0	Paper, cardboard, energy waste, glass, metal
	Cardboard, glass, metal	–	> 0	
National study				
N1	Paper, biowaste, energy waste, glass, metal	1	> 0	–
	Cardboard	–(2	> 0	
N2	Paper, biowaste, energy waste, glass, metal	2	20	Paper, energy waste, glass, metal
	Cardboard	–(2	20	
N3	Paper, biowaste, energy waste, glass, metal	10	50	Paper, energy waste, glass, metal
	Cardboard	–(2	50	
N4	Paper, biowaste, energy waste	10	50	Paper, energy waste
	Cardboard	–(2	50	
N5(3	Paper, biowaste, energy waste	10	50	Paper, energy waste
	Cardboard	–(2	50	
N6(4	Paper, biowaste, energy waste	10	50	Paper, energy waste
	Cardboard	–(2	50	
Helsinki study A				
H1	Paper	5	50	Paper, cardboard, glass, liquid packaging board
	Biowaste(5	10	50	
	Cardboard	–	50	
	Glass, liquid packaging board	–	–	
H2	Paper, biowaste, energy waste	1	20	Glass, metal
	Cardboard, glass, metal	–(2	20	
H3(6	Paper, energy waste	5	50	Paper, cardboard, glass, metal, liquid packaging board
	Biowaste	10	50	
	Cardboard, glass, metal	–(7	50	
	Liquid packaging board	–	–	

(1 The on-site obligation limits were not determined.

(2 Cardboard was included in energy waste.

(3 Separation was totally discontinued in the small and rural municipality region.

(4 Separation was totally discontinued both in the small and in the small and rural municipality regions.

(5 On-site obligation limits were only applied in one fourth of the region.

(6 In addition to source separation, mixed waste was sorted centrally for energy recovery.

(7 Cardboard was included in energy waste in residential properties greater than five households.

tile waste, rubber, nappies and miscellaneous non-combustible waste components which are difficult to recover even in energy production.

The classification of Finnish municipalities in the TASAR model highlighted the difference between the coverages of on-site collection systems reached with a given on-site obligation limit in various regions (Fig. 7). Among residential properties the highest average coverages are reached in the large municipality region and the lowest in the small municipality region. On the national level, the average coverages of 51 %, 49 % and 44 % are reached with the on-site obligation limits of three, five and ten households, which are currently com-

Table 6. Main input data and their sources used in the case studies (a: statistical data, b: empirical data from the example area, c: previous studies from the example area, d: previous studies from other areas, e: estimates on the basis of statements of experts and other available data, –: data was not used in the study).

Input data	Case study			
	Tampere study	National study	Helsinki study A	Helsinki study B
Amount and quality of waste				
– number of inhabitants	a	a	a	a
– numbers of employees by working field	a	a	a	–
– unit waste generation rates (t (person*a)$^{-1}$)	d,e	c,e	b,c	b,c
– waste composition (%wt)	d,e	c,e	b,c	b,c
– calorific values of waste components (MWh t^{-1})	d	–	c,d	–
– contents of harmful elements of waste components (g g^{-1})	d	–	c,d	–
Coverages of on-site collection systems				
– numbers of inhabitants and households at individual properties	–	a	a	a
– numbers and working fields of employees at individual properties	–	a	a	–
Efficiency of separation				
– separation activities for source separation (%wt)	d,e	c,e	b,c,e	b,c,e
– separation efficiencies for central sorting (%wt)	–	e	e	e
Planning of collection systems				
– volumes of bins and containers (m^3)	e	–	b,e	b,e
– specific weights of waste types as found in bins and containers (t m^{-3})	d,e	–	b,d,e	b,d,e
– filling grades of bins and containers (%)	e	–	b,e	b,e
– collection frequencies (d^{-1})	e	–	b,e	b,e
Unit costs of collection systems				
– annual costs of collection points (EUR a^{-1})	d	–	c,e	–
– annual costs of bins and containers (EUR a^{-1})	e	–	b	b
– costs of emptying bin or container (EUR)	–	–	b,e	–
– costs of waste collection (EUR h^{-1}, EUR km^{-1})	e	–	–	b,e
Unit emissions of collection systems				
– unit times of collection work (h t^{-1})	d	–	b,c,d	b,c
– transfer distances (km)	b	–	b	b
– fuel consumption (l h^{-1} or l (100 km)$^{-1}$)	d,e	–	d,e	c,e
– net load of a collection vehicle (t)	e	–	e	b
– coefficients for emission components (mg l^{-1})	d	–	d	–
Unit costs of functional elements and revenues				
– fixed costs (EUR a^{-1})	d,e	–	b,e	b,e
– operational costs (EUR a^{-1})	d,e	–	b,e	b,e
– revenues from recovered waste (EUR t^{-1})	e	–	b,e	b,e
Unit emissions of functional elements				
– coefficients for emission components (mg t^{-1})	d,e	–	b,c,d,e	–
– weighting factors for grouping of emissions	–	–	d,e	–

monly applied in Finnish municipalities. The corresponding values in the most densely populated area in Finland, i.e. in the Helsinki region, are 86 %, 82 % and 77 %. On the national level, detached houses are of major importance when high coverages are sought, because 43 % of Finnish people lived in them in 1996. In contrast, in the Helsinki region only 9 % of inhabitants lived in detached houses in 1995.

Among commercial establishments the greatest average coverages are achieved in the large municipality region and the smallest in the small or in the small and rural municipality regions, depending on the material studied (Fig. 8). Average na-

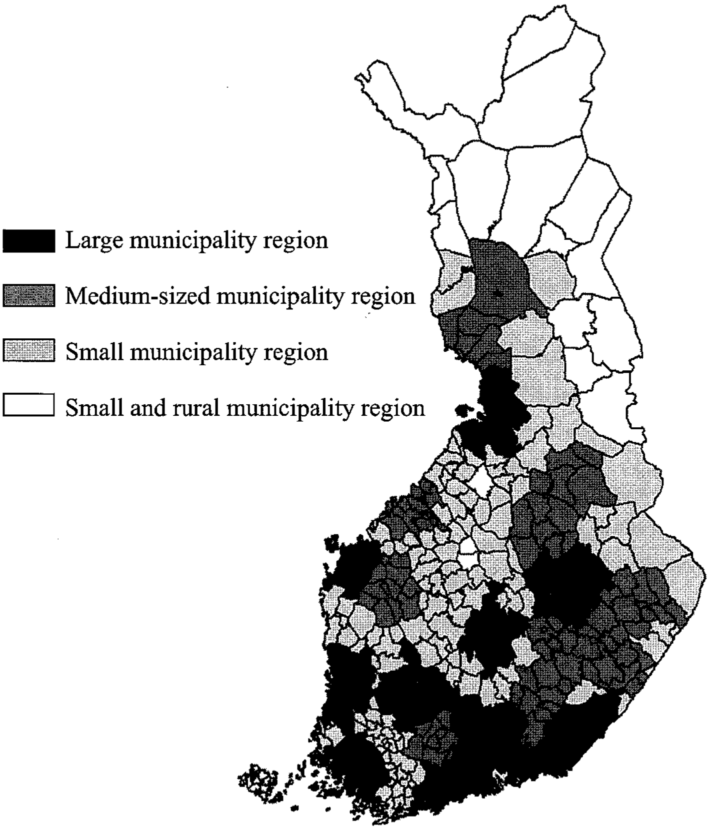


Fig. 6. Finnish municipalities classified into four categories on the basis of population and location in the TASAR model.

tional coverages between 23 % and 77 % are reached in the on-site collection of paper, cardboard, biowaste, energy waste, glass and metal when a typical Finnish limit of 50 kg per week is applied. In the Helsinki region, the corresponding coverages varied between 45 % and 91 %.

Recovery rates reached with a given source separation strategy depend on the separation activity of waste producers. Separation activities, especially the highest attainable activities, have not been studied comprehensively enough in Finland. In the case studies in this thesis, the current separation activities varied between 40 %wt and 75 %wt for on-site collection and between 20 %wt and 50 %wt for drop-off centre collection, depending on the type of material collected. The greatest attainable activities (i.e. the target activities) were estimated to vary between 60 %wt and 95 %wt for on-site collection and to be 50 %wt for drop-off centre collection. The willingness and ability of waste producers to separate their wastes can be increased, for example through guidance and a high standard of service in collection systems.

3.2 Upper limit of recovery rate for source separation based MSWM (I–III)

On the national level (II), a maximal recovery rate of 54 %wt was achieved in MSWM based on source separation with the present separation activities. The upper limit was reached with a strategy in which all recoverable materials (paper, cardboard, biowaste, energy waste, glass and metal) were separated and collected for recovery from all Finnish properties (see Strategy N1 in Table 5). When the greatest attainable separation activities were used as input data instead of the present ac-

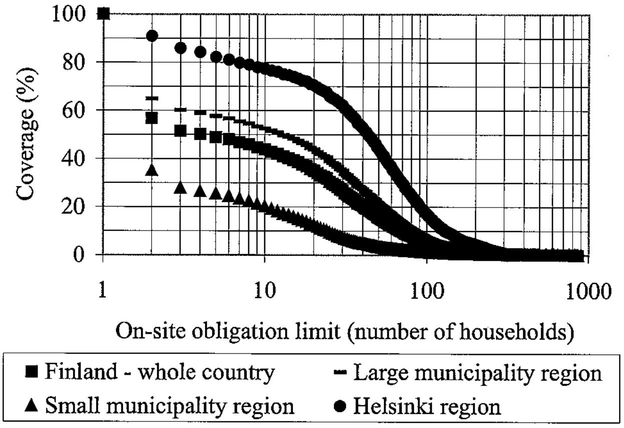


Fig. 7. Interdependence between the coverage of on-site collection and on-site obligation limit among residential properties in Finland – whole country, large and small municipality regions and in the Helsinki region.

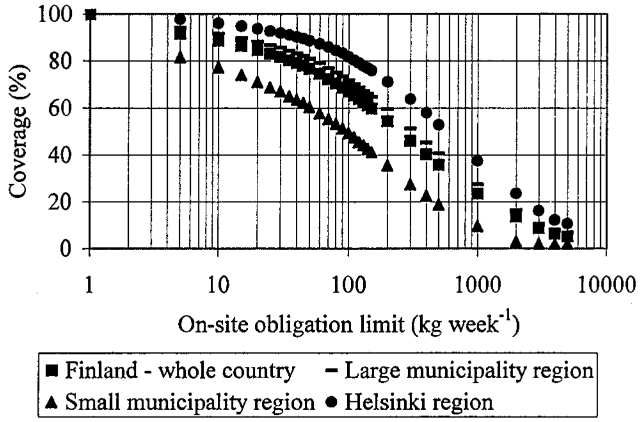


Fig. 8. Interdependence between the coverage of on-site collection and the on-site obligation limit of paper among Finnish commercial establishments in Finland – whole country, large and small municipality regions and in the Helsinki region. Paper is given as an example.

tivities the maximal recovery rate increased from 54 %wt to 72 %wt. However, both of these recovery rates can only be regarded as theoretical maximal values because Strategy N1 appears unfeasible in a sparsely populated country like Finland with 43 % of inhabitants living in detached houses.

In further national strategies N2–N6, the completeness of Strategy N1 was cut down to assess the upper limit for a feasible national source separation strategy (Fig. 9). In Strategy N2, the national recovery rate decreased from 54 %wt to 41 %wt with the present separation activity when on-site collection of all materials was replaced by drop-off centre collection among detached houses (i.e. the on-site obligation limits were raised from one household to two households) and separation was discontinued in commercial establishments in which the generation of a material was less than 20 kg per week. A further decrease from 41 %wt to

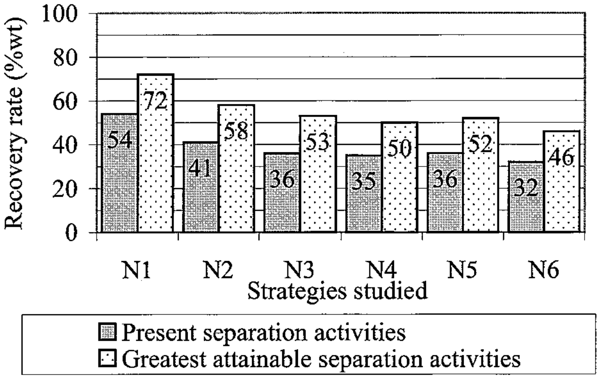


Fig. 9. Total recovery rates achieved with the national source separation strategies N1–N6 (see Table 5).

36 %wt occurred in Strategy N3, in which the on-site obligation limits were raised from two households to 10 households and from 20 kg per week to 50 kg per week. In Strategy N4, Strategy N3 was modified by omitting recovery of glass and metal totally in all categories of municipalities. As a result, the national recovery rate decreased one percentage unit from 36 %wt to 35 %wt. In Strategy N5, the national recovery rate was reduced less than one percentage unit when Strategy N3 was modified by stopping separation totally in the small and rural municipality regions. A further decrease of four percentage units occurred from Strategy N5 to Strategy N6 when separation was also discontinued in the small municipality region.

On the regional level, the theoretical maximal recovery rate was not determined. In Helsinki study A (III), a maximal feasible recovery rate of 52 %wt was reached in Strategy H2 with the present separation activities (see Table 5). The maximal recovery rate increased up to 66 %wt when the highest attainable activities were used as input data in the HMA model. Strategy H2 was formulated on the basis of an analysis of the separation strategy used in the Helsinki region in 1995, by which a total recovery rate of 27 %wt was attained (see Strategy H1 in Table 5, Table 7, Fig. 10). Strategy H2 was as follows:

- Paper, biowaste and energy waste were collected on-site from all residential properties. In addition, glass and metal were collected as drop-off centre collection.
- Paper, cardboard, biowaste, energy waste, glass and metal were collected on-site from commercial establishments producing at least 20 kg per week of a given material.

Table 7. Analysis of separation strategy used in the Helsinki region in 1995 (Strategy H1 in Helsinki study A, see Table 5).

Material	Coverage of the collection system (%)		
	Residential properties		Commercial establishments(1
	On-site collection	Drop-off centre collection	
Paper	82	18	89
Biowaste	19	–	23
Cardboard	–	100	87
Glass	–	100	–
Liquid packaging board	–	100	–
Energy waste	–	–	–
Metal	–	–	–

(1 Only on-site collection was applied.

In the Tampere study (I), the maximal feasible recovery rate of 64 %wt was reached in Strategy T2 with the highest attainable separation activities. In the present state (Strategy T1), the total recovery rate was 21 %wt. Strategy T2 consisted of the following separation measures:

- Paper, biowaste and energy waste were collected on-site from residential properties

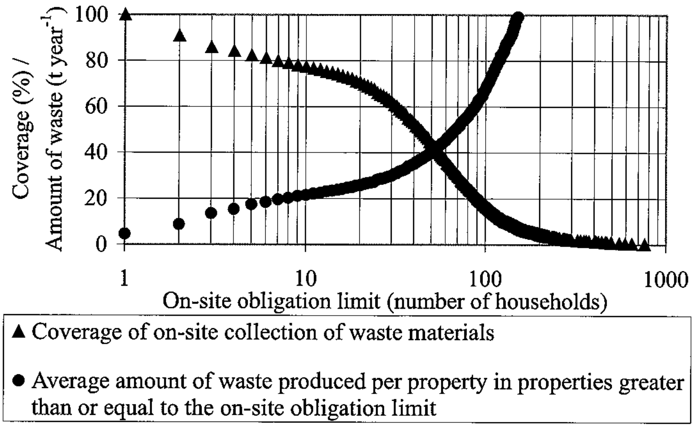


Fig. 10. Coverage of on-site collection of waste materials and the average amount of waste generated per property in the residential properties greater than or equal to the on-site obligation limit in the Helsinki region. Residential properties are given as an example.

greater than one household. In addition, paper, cardboard, energy waste, glass and metal were collected as drop-off centre collection.

- Paper, cardboard, biowaste, energy waste, glass and metal were collected on-site from all commercial establishments.

3.3 Source separation complemented with central sorting (II–III)

Despite extensive source separation strategies, a large share of remaining mixed waste consisted of recoverable waste materials both in the national and regional studies. In the national separation strategies N1–N6, the share of combustible waste components (i.e. paper, cardboard, plastics, liquid packaging board and miscellaneous combustibles) varied between 48 %wt and 53 %wt in mixed waste with the present separation activities and between 32 %wt and 48 %wt with the target activities. In Helsinki study A (Strategy N2), the share of combustible waste components in mixed waste was 46 %wt with the present and 36 %wt with the target separation activities.

On the national level (II), the total recovery rates increased by 20–33 percentage units when Strategies N1–N6 were complemented with central sorting of mixed waste for energy recovery (Fig. 11). Thus, the total recovery rates reached after central sorting varied between 65 %wt and 74 %wt. Calculation was based on the present separation activities and the separation efficiency of 90 %wt in the central sorting plant. When the target activities were used as input data in the TASAR model, central sorting increased the total recovery rate by 8–23 percentage units in strategies N1–N6, resulting in the total recovery rates between 69 %wt and 80 %wt.

In Helsinki study A (III), the total recovery rate increased from 52 %wt to 70 %wt when Strategy H2 was complemented with central sorting of mixed waste and the present separation activities were applied. The corresponding increase from 66 %wt to 74 %wt was attained with the target separation activities. In the resulting strategy (Strategy H3 in Table 5), separate collection of materials was also reduced compared to Strategy H2 as follows: (1) Separate collection of biowaste from residential properties smaller than 10 households was discontinued; (2) The on-site obligation limits of all materials were raised from 20 kg per week to 50 kg per week among commercial establishments; and (3) Separate collection of paper and energy waste was replaced with drop-off centre collection of paper, cardboard and liquid packaging board among residential properties smaller than five households.

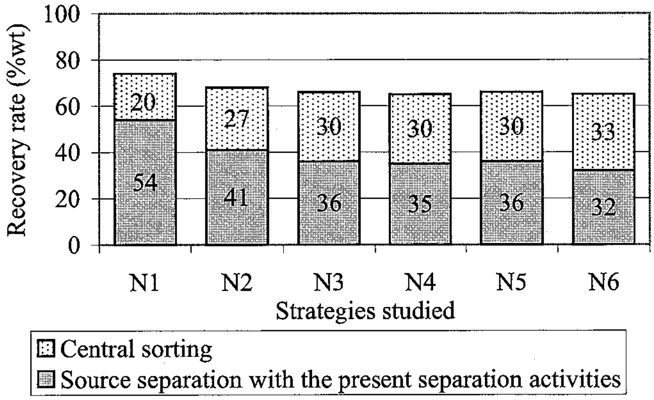


Fig. 11. Total recovery rates achieved with the national source separation strategies N1–N6 combined with central sorting of mixed waste (see Table 5).

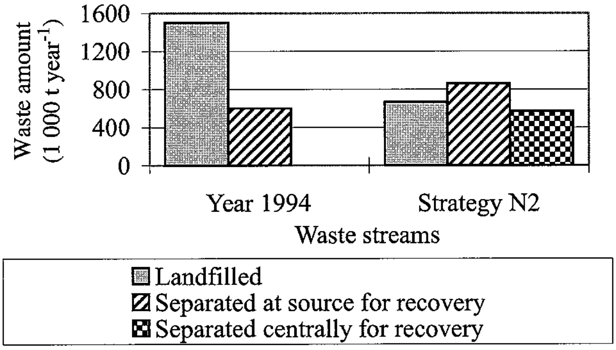


Fig. 12. Waste streams in Finnish MSWM in 1994 and according to national Strategy N2 complemented with central sorting (see Table 5). The present separation activities were used as input data in the TASAR model.

3.4 Effects of separation on MSWM

3.4.1 Waste streams (I–III)

Separation of recoverable materials directly affected waste streams in MSWM systems. On the national level (II), the amount of municipal solid waste landfilled in 1994 was reduced from 1.5 Mtonnes to 0.7 Mtonnes when the national recovery rate was increased from 30 %wt to 68 %wt according to Strategy N2 combined with central sorting of mixed waste (Fig. 12). At the same time, the amount of materials recovered increased from 0.6 Mtonnes to 1.4 Mtonnes. Increased source separation yielded 31 %wt (0.26 Mtonnes) of this increase and central sorting 69 %wt (0.57 Mtonnes).

In Helsinki study A (III), the amount of waste directly disposed of to the landfill was reduced from 380 000 tonnes per year in Strategy H1 to 180 000 tonnes in Strategy H2 and to 135 000 tonnes in Strategy H3. At the same time, the recovery rates of all waste materials increased (Table 8).

Table 8. Recovery rates of waste materials in the strategies studied in Helsinki study A. The target separation activities were applied in Strategies H2 and H3 (see Table 5).

Material	Recovery rate (%wt)		
	Strategy H1	Strategy H2	Strategy H3
Paper	69	87	98
Cardboard	64	83	98
Energy waste	0	68	96
Liquid packaging board	20	70	97
Biowaste	12	58	51
Metal	0	51	46
Glass	27	49	44
Total	27	66	74

3.4.2 Costs of MSWM (I, III)

Enhanced separation increased the costs of MSWM both in Helsinki study A and in the Tampere study. In Helsinki study A (III), the increase in the total costs was 41 % from Strategy H1 to Strategy H2 when the total recovery rate was increased from 27 %wt to 66 %wt with the target separation activities. In Strategy H3, the increase in the total costs was 30 % compared to Strategy H1 and the total recovery rate achieved was 74 %wt. In the year of comparison (Strategy H1), the costs of MSWM were 41.4 million euros in the Helsinki region (79.3 euros per waste tonne and 46.5 euros per inhabitant). In the Tampere study (I), the costs of MSWM increased by 36 % from Strategy T1 to Strategy T2 when the total recovery rate was increased from 21 %wt to 64 %wt with the greatest attainable separation activities.

Both in Helsinki study A and in the Tampere study the most important reason for the increase in the costs of MSWM was collection of source-separated materials (Table 9). This was because mixed waste was divided into several smaller waste streams at properties by starting separate collection of new materials and by extending on-site collection systems of other materials. In Strategy H3, central sorting of mixed waste was also an important functional element increasing the total costs. Processing of source-separated energy waste and composting increased the total costs in all strategies, because of the greater amount of waste treated. The costs caused by landfilling and by the governmental waste tax decreased because of reduced amount of waste disposed of to the landfill. The revenues from recovered materials also increased. Both in Helsinki study A and in the Tampere study collection was based on 0.12–0.6 m^3 bins, 1.3–8.0 m^3 containers and single compartment compacting collection vehicles.

In Strategies H2 and H3, the importance of separation strategies and collection systems applied among small properties was indicated (Fig. 13). In Strategy H2, residential properties smaller than five households caused 47 % of the increase in the costs of MSWM. This was mainly because on-site collection of paper, biowaste and energy waste was started from these properties. However, the share of these properties of the increase in the total recovery rate was only 10 %. In Strategy H3,

Table 9. Effect of various functional elements on the change in the costs of MSWM from Strategy H1 to Strategies H2 and H3 in Helsinki study A and from Strategy T1 to Strategy T2 in the Tampere study (see Table 5).

Functional element	Change of the costs of MSWM (%)		
	Strategy H2	Strategy H3	Strategy T2
Waste collection	+45	+22	+38
Central sorting and processing of mixed waste	–	+17	–
Processing of source separated energy waste	+7	+6	+3
Central composting	+6	+6	+3
Backyard composting	0	0	+3
Landfilling	–2	–2	–4
Waste tax	–7	–9	–
Revenues from recovered materials	–8	–10	–7
Total	+41	+30	+36

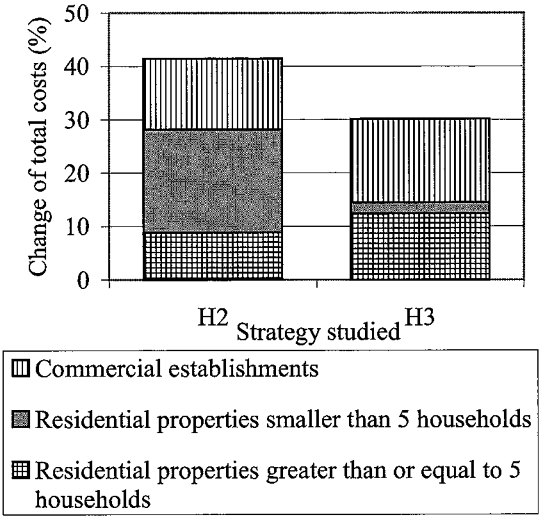


Fig. 13. Share of various waste producer groups of the change of the costs of MSWM in Strategies H2 and H3 compared to Strategy H1 in Helsinki study A (see Table 5).

on-site collection of recoverable materials was replaced with drop-off centre collection and central sorting among residential properties smaller than five households. As a result, the share of these properties of the increase in the costs of MSWM was only seven per cent and of the increase in the total recovery rate 5 %.

3.4.3 Costs of waste collection (IV)

In Helsinki study B (IV), separation of new types of materials and reduction of on-site obligation limits increased the costs of household waste collection independently of the collection method applied (see Table 2). Commingled collection (M4) was economically the most efficient method despite the costs of central sorting plant. The combined collection method (M3) also resulted in lower costs than the present method (M1). However, in strategies in which the smallest properties (i.e. properties smaller than 5 or 10 households) were excluded from on-site collection systems of recoverable materials the difference between collection costs of the present method, combined collection and commingled collection was less than 2 percentage units. The large container method (M2) was economically the most inefficient in all separation strategies.

Separation of new types of materials and reduction of on-site obligation limits decreased the efficiency of waste collection for two reasons. Firstly, the volume of bins and containers needed per tonne of waste increased when mixed waste was divided into several smaller waste streams for which the number of bins was rounded up separately at properties. Secondly, pick-up times per tonne of waste increased because the amount of waste collected per pick-up decreased (Fig. 14). Pick-up time is the time spent at the collection area per tonne of waste collected. The amount of waste collected per pick-up affects the efficiency of waste collection, because the time used for preparations before loading at a property and the driving time between properties do not depend on the amount of waste collected per pick-up. High separation activities reduced the costs of waste collection because the smallest amounts of waste collected per pick-up increased when the accumulations of recoverable materials increased.

Commingled collection (M4) was more efficient than the present collection method (M1) be-

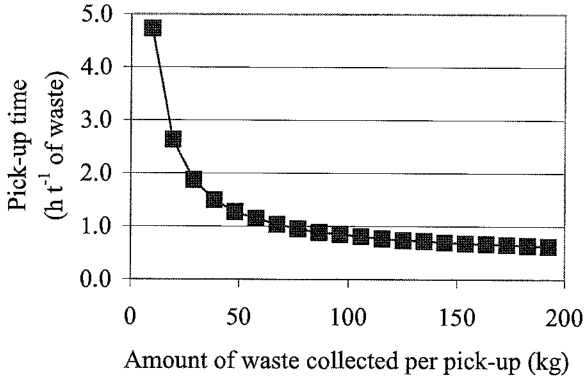


Fig. 14. Example of the interdependence between the amount of waste collected per pick-up and pick-up time needed per tonne of waste in Helsinki study B. The calculation was done for mixed waste, 600 l bins and compacting collection vehicle with collection frequency of 52 times per year.

cause it reduced the number of waste types for which separate bins were needed and because it increased the amount of waste collected per pick-up. Combined collection (M3) also increased the amount of waste collected per pick-up. However, synchronization of collection frequencies of three separate waste types increased the volume of bins needed per tonne of waste. The major reasons for the inefficiency of the large container method (M2) were: (1) the large volume of large containers compared to the minimum permissible frequency, especially of biowaste collection, in the Helsinki region; and (2) higher annual costs of large containers compared to bins. For example, the annual cost of a volume which is needed to store one tonne of mixed waste was 30 % higher for 3.0 m^3 containers than for 600 l bins.

3.4.4 Emissions (I, III, IV)

In Helsinki study A (III), the amount of emissions caused by MSWM was reduced from Strategy H1 to Strategies H2 and H3 as follows: nutrient load by 23 % and by 28 %, greenhouse gas load by 37 % and by 53 % and ozone formation by 17 % and by 33 % (Fig. 15). In the Tampere study, separation reduced the combined greenhouse gas load caused by waste collection and landfilling by 59 % from Strategy T1 to Strategy T2. However, the amount of acid load increased in Helsinki study A by 125 % in Strategy H2 and by 114 % in Strategy H3 compared to Strategy H1. The reason for the reduction in the amount of emissions was the decreased amount of waste disposed of to the landfill. On the other hand, the acid load increased in Helsinki study A for the same reason because less landfill gas was available for energy production to replace fossil fuels. In Strategy H1 of Helsinki study A, the total amounts of emissions were as follows: the total nutrient load 3 100 t a^{-1} expressed as O_2 consumption, the total greenhouse gas load 75 300 t a^{-1} expressed as CO_2 equivalents, the total ozone formation 36 t a^{-1} expressed as C_2H_4 equivalents and the total acid load 46 t a^{-1} expressed as SO_2 equivalents.

Enhanced source separation increased the emissions caused by waste collection in Helsinki study A, in the Tampere study and in Helsinki study B. In Helsinki study A, the emissions increased by 30 % from Strategy H1 to Strategy H2 and by 16 % from Strategy H1 to Strategy H3. In the Tampere study, the increase was 40 % from Strategy T1 to Strategy T2. In addition, Helsinki study B showed that emissions from waste collection increase despite the collection method applied. However, commingled collection was ecologically the most efficient collection method.

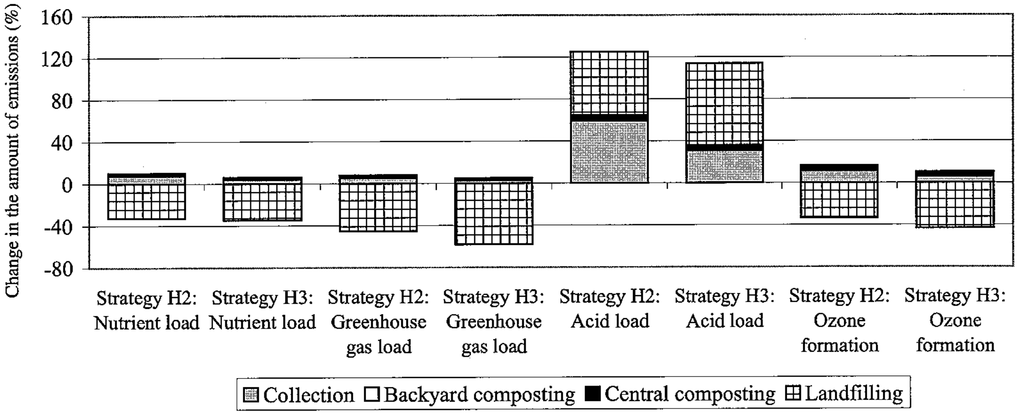


Fig. 15. Effect of various functional elements on the change of the total emissions of MSWM in Strategies H2 and H3 compared to Strategy H1 in Helsinki study A (see Table 5).

4 Discussion

The approach developed

In this thesis, a new approach was developed for evaluating the effects of source separation on MSWM. The approach differs from most earlier models used in the strategic planning of MSWM because of an analysis of the on-site collection systems. Thus, the amounts of materials which can be separately collected with a given separation strategy can be calculated on the basis of coverages of collection systems, participation rates and separation efficiencies. In addition, the on-site collection systems of waste materials can be adapted to the characteristics of study area on the basis of the interdependence between the coverage of on-site collection and the average amount of a material produced in properties participating in on-site collection. In most earlier models, the amounts (or the ranges of the amounts) of materials separately collected are treated as input data (Sundberg 1993, Baetz and Neebe 1994, White et al. 1995, Huhtala 1997, Ljunggren 1997). In some models, the amounts of materials are calculated on the basis of participation rates and separation efficiencies but these models, too, omit the analysis of the coverages of collection systems (Anex et al. 1996, Everett and Modak 1996).

The modelling approach developed includes both costs and emissions of MSWM, which is also the case in several other strategic planning models developed in the 1990s (Sundberg 1993, White et al. 1995, Ljunggren 1997, Wang et al. 1998). A weak point in this approach, as well as in most other models, is the description of emissions. The system boundaries used show the effects of recycling on the emissions caused by MSWM. However, emissions outside MSWM, e.g. effects of recycling on raw material acquisition and production processes, have been excluded from the models. To identify emissions comprehensively system boundaries should be extended to cover the life cycles of products in which waste materials are utilized. This kind of life cycle approach has only been applied in a few MSWM models (Kaila 1996, Gielen 1998).

The approach of this thesis can be applied to all countries, regions, municipalities and districts provided that: (1) The properties from which source-separated materials are collected on-site are selected on the basis of their size, e.g. the number of households or the accumulations of materials; and (2) Sufficient statistical data about the characteristics of the properties are available. The applications can be created in the format of spreadsheets (Excel 5.0 was used in the TASAR and HMA models). Spreadsheets are effective and flexible tools when describing large systems such as MSWM with numerous fairly simple internal and external connections. Flexibility is an important feature for a planning tool because the questions to be answered vary a lot in modern MSWM. Several recent MSWM models have been created in the format of spreadsheets (White et al. 1995, Anex et al. 1996, Haith 1998).

Effects of separation on MSWM

The results of the case studies proved that incineration is not necessarily needed in order to reach a high recovery rate of municipal solid waste. As a result, countries like Finland, in which incineration has been excluded from the national approach, can confidently develop their MSWM based on separation. In Finland, the recovery rate target of 70 %wt presented in the National Waste Plan can be achieved by complementing efficient source separation strategies with central sorting of mixed waste for energy recovery. Instead, feasible source separation strategies result only in recovery rates around 35–40 %wt with the present separation activity of waste producers. Although incineration is not needed, the combustible components of mixed waste have to be refined for recovery as a complementary fuel in the present industrial boilers and cement kilns.

Separation of municipal solid waste increases the costs of MSWM in the Finnish situation when a high total recovery rate is sought. The increase in the costs of MSWM seems to be around 30–40 % when the total recovery rate is increased from the level of 20–30 %wt to a level of around 70 %wt in the Finnish city regions. Separate collection of waste materials is the most important reason for the increase in the total costs. Separate collection increases the costs of MSWM for two reasons: (1) The volume of bins and containers needed per tonne of waste increases when mixed waste is divided into several smaller waste streams for which the number of bins is rounded up separately at properties; and (2) Pick-up times per tonne of waste increase because the amount of waste collected per pick-up decreases. Similar result has been presented by Everett and Shahi (1996a, 1996b, 1997) and Everett (1999), who developed a procedure for estimating route times for curbside collection of recyclables. Commingled collection results in smaller costs than separate collection if recoverable materials are collected on-site from small properties (e.g. residential properties smaller than 10 households). This conclusion holds true despite the extra cost of central sorting plant needed in commingled collection.

The increase in the amount of emissions caused by waste collection is much smaller than the reduction in the amount of emissions caused by final disposal when separate collection of waste materials is increased. It is also evident that the total amounts of most emissions caused by MSWM (greenhouse gas load, nutrient load and ozone formation) decrease when the total recovery rate increases. However, the results of this thesis do not indicate the effects of separation on the amount of total emissions. This is because all emissions outside the MSWM system, e.g. the effects of recycling on raw materials acquisition and on production processes, were excluded from the study.

The results of this thesis are difficult to compare to results obtained in other studies for two main reasons. Firstly, a maximal recovery rate which can be achieved with source separation has generally not been studied on the basis of the characteristics of a study area, separation strategies and collection systems. Instead, recovery rates have been determined by minimizing the costs of MSWM (Sundberg 1993, Baetz and Neebe 1994, Everett and Modak 1996). Secondly, the characteristics of study areas (e.g. the present MSWM system and size distribution of properties) and definitions of the case studies (e.g. objectives, system boundaries and strategies applied) vary greatly. For example, Sundberg (1993) reported that composting would be a cost-effective alternative in the Gothenburg region because it releases incineration capacity. In the case studies of this thesis, separation measures increased the costs of MSWM. However, incineration was not analysed as an alternative in this thesis because it has been excluded from the national strategy in Finland. Tanskanen (1997a) reported very similar results to those obtained in Papers I–IV when applying the approach of this thesis to the study of MSWM in the Lahti region: (1) The costs of MSWM increased by 4–35 % when the total recovery rate was increased from 26 %wt to 55–63 %wt; (2) Separate collection of waste materials was the most important reason for the increase in the total costs and combined collection resulted in smaller costs than separate collection alone; and (3) Separation reduced the amounts of emissions caused by MSWM.

Validation of the approach, results and input data

The approach adopted was applied in three case studies in this thesis (II–IV) and in a case study conducted by Tanskanen (1997a). The results of these four case studies are consistent. In addition, the MIMES/Waste Finland model resulted in very similar results in the Tampere region (I). Thus, the approach of this thesis would appear to function logically. The uncertainty and sensitivity analyses conducted in Papers II–IV also proved that the approach is a reliable tool for formulating separation strategies and for comparing recovery rates, costs and emissions of various MSWM systems.

Verification of the results obtained is difficult because there are no reliable data available about the total costs and total emissions of MSWM in the study areas. For example, the Helsinki Metropolitan Area Council does not record the total costs of MSWM because the organisation is not responsible for separate collection and recycling of paper and cardboard, bins and containers of waste types at most properties and collection of mixed waste in the central area. The only reliable data available in the Helsinki region is the total recovery rate. According to the statistics of the Helsinki Metropolitan Area Council the total recovery rate of municipal solid waste was 28 %wt in 1995 (Tanskanen 1997c). The HMA model resulted in a total recovery rate of 27 % wt in Strategy H1 (year 1995) in Helsinki study A. Verification of the input data is also difficult because all available information, i.e. statistics, empirical data, previous studies and statements of experts, had to be applied in the case studies. For this reason, the effects of chance in the input data on the results were studied in uncertainty and sensitivity analyses in Papers I–IV. According to these analyses, the results obtained and especially the relative superiority of the strategies studied are not sensitive to most changes in the input data.

5 Conclusions

The two major objectives of this thesis were: (1) To develop an approach for analysing MSWM based on source separation; and (2) To test the approach and evaluate the effects of separation on MSWM in Finland. The results of the case studies indicate that both of these objectives were achieved. The approach and models developed made it possible to find alternative means to increase separation and to calculate the recovery rates both on a national and on a regional level. The regional models also made it possible to calculate the effects of separation strategies on costs and emissions of MSWM.

The following recommendations can be made for Finnish MSWM:

- The national recovery rate targets should be divided into regional subtargets on the basis of local conditions. As a result, the feasibility of high recovery levels should be reconsidered, for example, in small and rural municipalities in which only 2 %wt of municipal solid waste is produced in an area which covers 29 % of the surface area of Finland.
- Central sorting of mixed waste must be implemented as an integrated part of the national and regional source separation strategies. As a result, the rationality of the most expensive source separation measures could also be reconsidered without significant reduction in recovery levels.
- Commingled collection of source-separated materials should be considered instead of separate collection, especially in areas with small accumulations of waste materials, e.g. in areas of detached houses.
- In addition to the technical system, motivation and guidance of waste producers are crucial means to improve separation. Increase in separation activities also results in lower collection costs.

An ultimate goal in the modelling of MSWM systems is to determine economically and ecologically optimal recovery rate levels for various materials in various conditions. In order to reach this target, a life cycle approach has to be incorporated into MSWM models. In addition, the follow-up systems must be significantly improved to ensure reliable input data.

Yhteenveto

Tutkimuksessa on kehitetty menetelmä, jolla voidaan arvioida syntypaikkalajittelun vaikutukset yhdyskuntajätehuollon hyödyntämisasteisiin, jätevirtoihin, kustannuksiin ja päästöihin. Menetelmä mahdollistaa syntypaikalla lajiteltavien jätemateriaalien keräysjärjestelmien perusteellisen analysoinnin. Näin yhdyskuntajätteen hyödyntämisasteet ja jätevirtojen suuruudet voidaan laskea lajittelu- ja keräysjärjestelmien ominaisuuksien perusteella. Yleensä keräysjärjestelmien ominaisuuksien arviointia ei ole sisällytetty jätehuollon strategiseen tarkasteluun käytettyihin malleihin. Nyt kehitetty menetelmä soveltuu yleisesti käytettäväksi myös muilla kuin tähän tutkimukseen sisällytetyillä esimerkkialueilla.

Tämä tutkimus koostuu neljästä tapaustarkastelusta, joista kolmessa testattiin kehitettyä menetelmää syntypaikkalajittelun vaikutusten arvioimiseksi yhdyskuntajätehuollossa. Menetelmän testaamisen lisäksi näiden tarkasteluiden tavoitteena oli arvioida lajittelun vaikutuksia yhdyskuntajätehuollon hyödyntämisasteisiin, jätevirtoihin, kustannuksiin ja päästöihin Suomen oloissa. Tapaustarkasteluissa menetelmällä mallinnettiin: (1) yhdyskuntajätteen valtakunnallista lajittelustrategiaa, (2) lajittelun vaikutuksia yhdyskuntajätehuoltoon Helsingin seudulla ja (3) eri keräysmenetelmien tehokkuutta Helsingin seudulla. Tapaustarkasteluihin kehitetyt mallit ovat staattisia ja lineaarisia simulointimalleja, jotka tehtiin Excel-taulukkolaskentaohjelmaa käyttäen. Neljännessä tapaustarkastelussa rakennettiin Suomen olosuhteisiin sovellettu versio ruotsalaisesta MIMES/Waste-mallista ja sovellettiin sitä Tampereen seudun yhdyskuntajätehuollon tarkastelussa.

Tapaustarkastelut osoittavat, että kehitetty menetelmä soveltuu hyvin yhdyskuntajätehuollon strategiseen suunnitteluun erilaisilla alueilla ja kysymyksenasetteluilla. Tämän tutkimuksen keskeiset tulokset ovat seuraavat:

- Yhdyskuntajätehuollossa voidaan saavuttaa korkea hyödyntämisaste (noin 70 %) ilman sekajätteen massapolttoa.
- Valtakunnallisessa jätesuunnitelmassa asetettujen hyödyntämistavoitteiden (50 % vuoteen 2000 mennessä ja 70 % vuoteen 2005 mennessä) saavuttaminen edellyttää, että syntypaikkalajittelun lisäksi Suomeen rakennetaan lajittelulaitosten verkko. Toteuttamiskelpoisilla pelkkään syntypaikkalajitteluun perustuvilla lajittelustrategioilla yhdyskuntajätteen hyödyntämisaste voidaan Suomessa nostaa ainoastaan 35–40 %:n tasolle. Tulos perustuu jätteentuottajien nykyiseen lajittelutehokkuuteen.
- Hyödyntäminen lisää yhdyskuntajätehuollon kustannuksia. Suomen kaupunkiseuduilla kustannusten kasvu on noin 30–40 %, kun hyödyntämisaste nostetaan 20–30 %:sta 70 %:n tavoitetasolle. Jos pienimmätkin kiinteistöt (alle 10 huoneistoa) osallistuvat hyödyntämiskelpoisten jätejakeiden kiinteistökohtaiseen erilliskeräykseen, voidaan kustannusten kasvua hillitä selvästi soveltamalla erilliskeräyksen sijaan yhteiskeräystä. Yhteiskeräyksessä useita jätelajeja kerätään samassa astiassa ja autossa esimerkiksi erivärisiin pusseihin lajiteltuina. Pussit lajitellaan keskitetysti hyödyntämistä varten.
- Helsingin alueella tehdyn tarkastelun perusteella hyödyntäminen vähentää yhdyskuntajätehuollon aiheuttamia rehevöittäviä päästöjä, kasvihuonekaasupäästöjä sekä alailmakehään muodostuvan otsonin määrää. Tämän tutkimuksen perusteella ei voida kuitenkaan arvioida hyödyntämisen vaikutusta päästöjen kokonaismäärään, sillä hyödyntämisen vaikutukset raaka-aineiden hankinnan ja tuotannon päästöihin on rajattu tarkastelun ulkopuolelle.

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Helsinki, February 2000

Juha-Heikki Tanskanen

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