Technical University of Denmark

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Publication date:
2009

Document Version
Publisher's PDF, also known as Version of record

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Department of Environmental Engineering

PhD Thesis
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The thesis will be available as a pdf-file for downloading from the homepage of the department: www.env.dtu.dk

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Printed by:	Vester Kopi Virum, September 2009
Cover:	Torben Dolin
ISBN:	978-87-91855-72-6

Preface

The work reported in this PhD thesis, entitled 'Environmental assessment of waste collection seen in a system perspective', was conducted at the Department of Environmental Engineering at the Technical University of Denmark with Professor Thomas Højlund Christensen as supervisor. The PhD project ran from January 2006 to July 2009 and was funded by the Technical University of Denmark.

The content of the PhD thesis is based on eight papers prepared for scientific journals. The papers represent the many sub-projects which were included in the PhD project and conducted in collaboration with internal and external partners. In the text, the papers are referred to by the names of the authors and their appendix number written with roman numbers.

I Larsen, A.W. & Christensen, T.H. (2009). Bulky waste quantities and treatment methods in Denmark. Manuscript.

II Larsen, A.W., Vrgoc, M., Lieberknecht, P. & Christensen, T.H. (2009). Diesel consumption in waste collection and transport and its environmental significance. Waste Management & Research. DOI: 10.1177/0734242X08097636.

III Eisted, R., Larsen, A.W. & Christensen, T.H. (2009). Collection, transport and transfer of waste: Accounting of greenhouse gases and global warming contributions. Waste Management & Research, 27, DOI: 0734242X09.

IV Merrild, H., Larsen, A.W. & Christensen, T.H. (2009). Material-based life cycle assessment of municipal waste in Denmark: Recycling versus incineration with efficient energy recovery. Manuscript submitted to Resources, Conservation & Recycling.

V Larsen, A.W., Merrild, H. & Christensen, T.H. (2009). Recycling of glass: Accounting of greenhouse gases and global warming contributions. Waste Management & Research, 27, DOI: 10.1177/0734242X09342148.

VI Damgaard, A., Larsen, A.W. & Christensen, T.H. (2009). Recycling of metal: Accounting of greenhouse gases and global warming contributions. Waste Management & Research, 27, DOI: 0734242X09.

VII Larsen, A.W. & Christensen, T.H. (2009). Environmental assessment of treatment of bulky waste. Manuscript.

VIII Larsen, A.W., Merrild, H., Møller, J. & Christensen, T.H. (2009). Waste Collection Systems for Recyclables: an Environmental and Economic Assessment for the Municipality of Aarhus (Denmark). Manuscript submitted to Waste Management.

The papers are not included in this www-version but can be obtained from the library at DTU Environment. Contact info: Library, Department of Environmental Engineering, Technical University of Denmark, Miljoevej, Building 113, DK-2800 Kgs. Lyngby, Denmark or library@env.dtu.dk.

September 2009
Anna Warberg Larsen

Acknowledgements

The outcome of this PhD project is the result of good collaboration with internal and external partners whose efforts I greatly appreciate.

I would like to thank my supervisor, Professor Thomas Højlund Christensen, for presenting me with the challenge of doing a PhD project. I am grateful for the inspiration and guidance he has given me throughout the project.

I would also like to thank all of my colleagues in the Solid Waste Research Group at DTU Environment for creating a vivid working environment with room for professional, rewarding discussions and good cooperation. In particular, thanks goes to Hanna Merrild for her persistent support, professional as well as personal, through some challenging times. And thanks to Thilde and Jirka for keeping me company in the office and making my time at work even more fun.

Also many thanks to Torben Dolin and Lisbet Brusendorff from the graphic office, who did all illustrations in the papers and the thesis.

Many of the research results were achieved through collaboration projects with Herning Kommune and Århus Kommune. I wish to thank the many people in the municipal waste administrations and operational units who participated in the projects and provided the essential data.

Last, but not least, I would like to thank my family and friends outside the university for listening to, though not always understanding, my many ideas and frustrations about solid waste and life cycle assessments.

Summary

The legislation of waste management contains various requirements to recycling of waste and sets political targets for recycling in order to minimise the environmental damage caused by waste management. Municipalities in Denmark are responsible for establishing the needed collection schemes and fulfilling the targets. This has resulted in implementation of various well-functioning, but sometimes complex, collection schemes. On this background, three issues regarding the environmental impact from waste collection were identified:

- As the waste hierarchy is the guiding principle for waste management, it is often assumed that material recycling will be environmentally better than incineration, but the recycling industries are often located far from where the waste is generated. The question is whether use of extra energy for collection, pre-treatment and transport of recyclables can undermine the potential benefits from recycling.
- Collecting a source-separated waste fraction for intended recycling presupposes that the waste can be collected in sufficient quantity and quality to make the waste treatment feasible.
- Some of the most easily achievable improvements have probably been implemented already. The question is how waste collection systems can be further expanded and optimised with regard to environmental performance.

The aim of this PhD project was to address these issues by quantifying the environmental impact from waste collection as a sole activity and assess its importance as a part of a waste management system. The subject was studied by performing life cycle assessments of household waste and bulky waste. Data were collected from two Danish municipalities and literature surveys.

A consistent way of modelling waste collection systems in life cycle assessments was suggested. Collection schemes should be characterised by the following parameters: waste type/fraction, equipment for temporary storage, collection vehicle, collection method and type of residential area, because these were determining for the energy and material flows in the waste collection system. Defining the waste composition in terms of material fractions, amounts and chemical composition and describing the degree of source-separation by so-

called ‘sorting efficiencies’ were necessary input data for modelling of mass flows through the waste management systems. A literature survey showed that property-close collection was likely to yield the highest sorting efficiency, and there was a tendency of higher sorting efficiencies for paper and glass than for cardboard, plastics and metals.

A thorough study of collection and its environmental impact showed that the fuel consumption in the collection area, the distance to the pre-treatment plant and the exhaust emissions, which are regulated by emission standards, all were important for the resulting environmental impact from collection. Thus both optimisation of collection routes, planning of waste facilities and legislative requirements were important instruments in relation to reduction of environmental impact from collection. The fuel consumption in the collection area was found to increase with decreasing population or waste density in the catchment area. The study also showed that implementation of successive European exhaust emission standards had significantly reduced the environmental impact from collection and transport.

Additional energy consumption for collection and pre-treatment of recyclables from household waste did not undermine the potential benefits of recycling compared with incineration with energy recovery. This meant that new collection schemes for recyclables and simple pre-treatment technologies could be implemented without compromising the benefits of recycling. In some cases, transport was a limiting factor, but in practice paper, glass, steel and aluminium could be transported several thousand kilometres to recycling facilities, providing appropriate means of transport were used. In some situations, incineration would be a better solution for cardboard and plastic, especially if the energy recovery rate at the incinerator was high. In cases of doubt, waste management planners should take the efficiency of energy recovery from incineration, the transport distances and the means of transport into consideration.

When considering the actual amounts of recyclables in Danish household waste, paper was potentially the most beneficial material to sort out for recycling. It was followed by aluminium, cardboard and glass; the least beneficial materials were plastic and steel. Although aluminium was the second most beneficial material, the amount found in household waste was low. This has some practical implications because it would probably not be feasible to initiate a collection scheme for one of the small fractions only.

A case study of waste collection systems for recyclable household waste showed that improvements of a well-functioning system might be limited to a relatively narrow interval due to limitations in the organisational and technical structure. Enhanced recycling was recommendable because it improved the environmental performance in several impact categories but increased collection and transport worsened air pollution. Based on the conditions in the modelling scenarios, kerbside collection would provide the highest recycling rate, but bring schemes with drop-off containers would also be a reasonable solution. Collection of recyclables at recycling centres only was not recommendable because the recycling rate assumingly would decrease. However, solutions for mitigation of air pollution caused by enhanced collection and transport should at the same time be sought.

In conclusion, defining the waste collection system was a key factor for the life cycle assessments of waste management systems because describing parameters, such as collection schemes, waste composition and sorting efficiencies, influenced the waste flows. Thus waste collection had a significant influence on the environmental impact of the waste management system, even though its own environmental impact was of minor importance in a life cycle perspective.

Dansk sammenfatning

Lovgivningen på affaldsområdet stiller krav om genanvendelse af affald og fastsætter politiske mål for genanvendelse med henblik på at minimere miljøbelastningen fra affaldshåndtering. Danske kommuner er ansvarlige for at etablere de nødvendige indsamlingsordninger og opfylde de fastsatte mål. Dette har udmøntet sig i implementering af mange velfungerende, men til tider komplekse, indsamlingsordninger. På grundlag af dette blev tre problemstillinger vedrørende miljøbelastningen fra affaldsindsamling identificeret:

- Med affaldshierarkiet som vejledende princip for affaldshåndtering antages det ofte, at materialegenanvendelse er miljømæssigt bedre end affaldsforbrænding, men genanvendelsesindustrierne er ofte lokaliseret fjernt fra, hvor affaldet genereres. Spørgsmålet er om det ekstra energi, der bruges på indsamling, forsortering og transport af genanvendelige materialer, kan sætte den potentielle miljøgevinst ved genanvendelse over styr.
- Indsamling af kildesorteret affald med henblik på genanvendelse forudsætter, at dette kan indsamles i tilstrækkelig mængde og kvalitetet.
- De nemmeste miljøforbedrende tiltag er formodentligt allerede er implementeret. Spørgsmålet er, hvor meget eksisterende indsamlings-systemer kan udbygges og miljømæssigt optimeres.

Målet med dette Ph. D.-projekt var at undersøge disse tre problemstillinger ved at kvantificere miljøbelastningen fra affaldsindsamling og vurdere affalds-indsamlingens betydning for det samlede affaldssystem. Undersøgelsen blev udarbejdet som en livscyklusvurdering af dansk dagrenovation og storskrald. Anvendte data stammede fra to danske kommuner og forskellige litteraturundersøgelser.

En metode til modellering af indsamlingssystemer i livscyklusvurderinger blev opstillet i projektet. Affaldsordninger kunne karakteriseres ved følgende parametre: Affaldstype/fraktion, opsamlingsudstyr, indsamlingskøretøj, indsamlingsmetode og type af beboelsesområde. Disse havde betydning for energi- og materialestrømmene i affaldsindsamlingssystemet. Definition af affaldssammensætningen med hensyn til materialefraktioner, mængder og kemisk sammensætning samt beskrivelse af kildesorteringsgraden i form af såkaldte sorteringseffektiviteter var essentielle data for modellering af massestrømme i affaldssystemet. En litteraturundersøgelse viste, at de højeste sorteringseffektiviteter i overvejende grad blev opnået i systemer med henteordninger. Der var også en tendens til højere sorteringseffektiviteter for papir og glas end for pap, plast og metaller.

En dybdegående undersøgelse af miljøbelastningen ved affaldsindsamling viste, at både brændstofforbruget i indsamlingsområdet, afstanden til modtageanlægget og specificering af udstødningsgasser, som reguleres af emissionsstandarder, alle havde betydning for indsamlingens miljøbelastning. Således var både ruteoptimering, placering af behandlingsanlæg og lovgivningsmæssig regulering vigtige værktøjer til at reducere miljøbelastningen fra affaldsindsamling. Måling af brændstofforbruget i forskellige indsamlingsområder, viste at dette steg med faldende befolkningstæthed og dermed tæthed af opsamlingspunkter. Undersøgelsen viste også, at implementeringen af europæiske emissions-standarder havde reduceret miljøbelastningen fra indsamling og transport betydeligt.

Miljøgevinsten ved genanvendelse fremfor forbrænding med energigenvinding blev ikke underminereret af ekstra energiforbrug til indsamling og forsortering af genanvendelige materialer fra dagrenovation. Det betød, at nye indsamlings-ordninger for genanvendelige materialer og simple forsorteringsanlæg kunne indføres uden at sætte miljøgevinsten ved genanvendelse over styr. I nogle tilfælde ville transport dog være en begrænsende faktor, men i praksis ville papir, glas, stål og aluminium kunne transporteres flere tusinde kilometer, hvis det mest rationelle transportmiddel blev anvendt. Forbrænding af pap og plast ville dog nogle gange være at bedre, især hvis energigenvindingsgraden ved forbrænding var høj. I tvivlstilfælde burde affaldsplanlæggere nøje overveje betydningen af energigenvindingsgraden, transportafstande og mulige transportmidler.

Når de faktiske mængder af genanvendelige materialer i dansk dagrenovation blev taget i betragtning, var miljøgevinsten størst for genanvendelse af papir. Herefter fulgte aluminium, pap og glas, og mindst var genvinsten for plast og stål. Selvom aluminium gav den næststørste potentielle miljøgevinst, var mængden i dagrenovation ganske lille. Det har praktisk betydning, da det formodentligt ikke er rentabelt at i værksætte en indsamlingsordning for en lille fraktion alene.

En undersøgelse af et velfungerende indsamlingssystem for dagrenovation i en dansk kommune viste, at den organisatoriske og tekniske udformning af systemet satte begrænsninger for potentielt øget genanvendelse. Øget genanvendelse kunne dog anbefales, da dette kunne forbedre affaldssystemets miljøbelastning målt på adskillige parametre, men luftforurening som følge af øget indsamling og transport blev forværret. Baseret på de opstillede scenarier ville henteordninger give den højeste genanvendelsesgrad, men bringeordninger med kuber ville også være en fornuftig løsning. Indsamling af genanvendelige materialer på genbrugsstationer alene var ikke en egnet løsning, da genanvendelsesgraden antageligt ville falde. Tiltag til forebyggelse af luftforurening fra indsamling og transport burde dog også foretages.

Studiet viste, at beskrivelse af indsamlingssystemer spillede en central rolle i livscyklusvurderinger af affaldssystemer, fordi variable parametre så som indsamlingsordninger, affaldssammensætning og sorteringseffektiviteter havde betydning for affaldsstrømmene. Således havde affaldsindsamling stor betydning for affaldssystemets samlede miljøbelastning, selvom miljøbelastningen fra affaldsindsamling alene var af mindre betydning set i et livscyklusperspektiv.

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1 Introduction

1.1 Legislative background for waste collection in Denmark

Collection of waste is regulated by the municipalities in Denmark. They have the obligation of preparing regulations for collection schemes within their geographic boundaries and ensuring that the waste generated is managed in an environmentally acceptable way (The Danish Government, 2004). The requirements to municipal waste management are laid down in the national legislation, which is based on implementation of EU directives. Waste management should be carried out in accordance with the guiding principles in the waste hierarchy which prioritise waste prevention over recycling, recovery and disposal. This is supported by various initiatives such as requirements for recycling of certain waste fractions, economic instruments and voluntary agreements with industries in order to ensure the most environmentally acceptable waste management of various waste fractions. EU directives on specific waste fractions, for example hazardous waste, waste oils, batteries and accumulators, waste electrical and electronic equipment, PCBs and PCTs, packaging waste and waste for landfilling, specify how these waste fractions should be collected and/or treated. Additionally, voluntary agreements are made with industries or professional organisations, for instance, on take-back schemes for tyres and lead accumulators and on recycling of transport packaging. One of the latest initiatives is the producer responsibility on waste electrical and electronic equipment. As a result of these developments in the legislation, the municipal regulations must relate to collection and treatment of many different waste types and fractions. The municipalities must either establish the required collection schemes or assign the waste to a given form of waste management. In both cases, the waste producers are obliged to comply with the regulation. One of the advantages of such waste management strategies is that minimisation of environmental damage has been brought into focus, but the downside is that the waste collection systems might become complex. It also requires that the waste producers have knowledge of how to separate the waste and where to take that waste. An example of growing complexity is collection of household waste where source-separation of paper, glass, bio-waste, batteries and packaging waste stepwise has been introduced.

1.2 Evaluation of waste collection

Waste collection can be seen as the linkage between the waste producer who wants to dispose of the waste and the waste treatment sector which has a financial interest in receiving the waste from the waste producer. The waste producer's willingness to participate in waste collection is crucial for the quantity and the quality of the waste and thereby affects the quality of the waste treatment. Various factors influence the activities taking place during waste collection; therefore, the municipalities have an important task in planning and operating waste collection in a way that takes aspects such as legislation, economy, service, working environment and also environmental issues into consideration.

Planning, optimisation and benchmarking of waste collection in order to minimise costs and fuel consumption and increase service level and participation rates have been researched since the 1970s. Various methods and tools based on mathematical models have been developed; the most recent ones are based on GIS. Examples of model development and application in case studies can be found in e.g. Chang & Wei (1999), Gautam & Kumar (2005), Karadimas et al. (2004), Sonesson (2000), Tavares et al. (2009), Teixeira et al. (2006) and Wang (2001). The methods and tools are not all comparable because they differ in their approach to collection, degree of parameterisation and data requirements, but they might be useful for different purposes.

People's participation in waste collection, especially in source-separation of recyclables, has also been the subject of much research. Identification of determining factors and the importance of collection scheme designs have been investigated in various case studies and used for model development. Examples of such studies are Barr et al. (2003), Hage et al. (2009), Matsui et al. (2007), McDonald & Oates (2003), Noehammer & Byer (1997), Shaw et al. (2007), Sörbom (2003), Tucker & Speirs (2002) and Vincente & Reis (2008). As a general conclusion, it seems that most people have the intention of participating in source-separation, based on environmental values and social norms. However, their actions might be limited if the waste collection system is perceived as inconvenient. User-friendly system design and adequate information about the system are two important factors for encouraging people to participate.

The success of a waste management system can be measured by its environmental performance, and waste management was a part of the focus on sustainable development emerging in the beginning of the 1990s. The previous national waste strategies in Denmark set goals on desirable recycling rates and reduction of waste going to landfills. Many municipalities have in addition to this made their own goals and benchmarks in order to monitor and improve their environmental performance. Examples of used indicators are recycling rate, number of source-sorted fractions, number of waste prevention initiatives, energy recovery rate from incineration and reduction of emissions from incineration. Recently, the environmental focus has shifted to mitigation of climate changes, especially in terms of reduction of carbon dioxide and methane emissions from waste treatment. Methods for assessment of the environmental aspect are for example environmental management systems such as EMAS and ISO 14001, environmental impact assessments or life cycle assessments (Finnveden et al., 2007). Some of the methods, e.g. life cycle assessments, account for both direct and indirect emissions from the waste management system by including the effects on sectors outside the municipal waste management system. Among case studies with environmental assessments that consider the waste collection system and not only different treatment options are Beigl & Salhofer (2004), Calabrò (2009), De Feo & Malvano (2009), Iriarte et al. (2009), Luoranen et al. (2009), Rigamonti el al. (2009) and Wada et al. (2009). The studies are site-specific and no general conclusions about the role of waste collection systems in environmental assessments can be drawn. Recycling is in most cases preferable to incineration and landfilling, but there are exceptions for some materials, treatment technologies and waste collection systems. Thus environmental performance is probably always best assessed in site-specific studies.

The various approaches to analysing and assessing waste collection systems are sometimes integrated in models that analyse the whole waste management system and use several aspects as assessment criteria. Integrated assessment models are developed for decision support because local authorities often have several choices regarding waste management, despite the guidelines provided by the waste hierarchy and legislative requirements. Such models are often based on a life cycle approach with focus on the environmental aspect of waste management, especially the benefits from utilisation of waste. LCA-IWM (den Boer et al., 2005) and the evaluation model described by Klang et al. (2008) are models that contain indicators for environmental, economic and social aspects.

1.3 Aim of the PhD project

The PhD project was initiated because there seems to be a need for more detailed evaluation of the environmental impact related to waste collection. Even though various methods for planning and evaluation of waste collection systems have been developed, these have mainly focused on economic and sociological issues. Evaluation methods for the environmental aspect often consider waste collection in a broader perspective taking the benefits from recycling and recovery into account but neglecting any insight into the preconditions of the waste collection system.

The following three issues regarding environmental impact from waste collection were treated in the PhD project. Firstly, waste collection activities require use of energy and cause direct and indirect emissions to the environment. As the waste hierarchy is the guiding principle for waste management, it is often assumed that material recycling will be environmentally better than incineration or landfilling, but the recycling industries are often located far away from where the waste is generated. The question is whether use of extra energy for collection, pre-treatment and transport for recyclable materials can undermine the potentially obtainable benefits from recycling. Secondly, collecting a source-separated waste fraction for intended recycling presupposes that the waste can be collected in a sufficient quantity and quality to make the waste treatment feasible. This will depend on the waste generation rate as well as the design and functioning of the waste collection system. Thirdly, source-separation and recycling of many waste types is widespread in Denmark, meaning that some of the most easily achievable improvements have probably already been implemented. This situation calls for investigation of how well-established waste collection systems could be further expanded and optimised with regard to environmental performance.

The aim of this PhD project was to address these issues by quantifying the environmental impact from waste collection as a sole activity and assessing its importance as a part of a waste management system. Waste collection is seen as the first phases in a waste management system where separated waste streams and intended treatment options are defined and the waste is physically collected, possibly sorted, and transported to the actual treatment facilities.

Environmental assessments were performed as life cycle assessments of waste management systems. A method for modelling of waste collection systems in a transparent and consistent way was suggested. Consequences for other aspects, such as economy and service, were considered only when relevant. The project was limited to include two types of Danish residential waste: household waste and bulky waste. Household waste is the daily generated waste from households. The average amount generated in 2005 was 316 kg per capita, of which 41 kg paper, 18 kg glass and 8 kg bio-waste was separately collected; the rest was collected as residual waste for incineration (Environmental Protection Agency, 2007). Bulky waste consists mainly of large items, for example, furniture, refrigerators and cardboard boxes. The amount collected was 146 kg per capita in 2005 (Environmental Protection Agency, 2007). For these two waste types, waste collection followed by treatment in terms of either recycling or incineration were the most relevant options to compare. Only collection of dry recyclables and residual waste fractions was considered; bio-waste was not included. Dry recyclables such as paper, cardboard, glass, metal and plastic was chosen because the recycling targets for these materials are likely to increase. According to the latest revision of the European Union's directive on waste, the member states are required to establish collection of paper, glass, metal and plastic by 2015 and reuse or recycle 50% of the recyclable materials (at least paper, glass, metal and plastic) from households by 2020 (European Parliament and Council Directive, 2008).

1.4 Content of the PhD thesis

The contents of the individual sections are as follows. In Section 2 the methodology for the environmental assessment is outlined. The system boundaries for waste management systems in a life cycle perspective are defined, and the application of a life cycle assessment method is described. Section 3 deals with the analysis of waste collection systems. It describes the technical parameters that can be used to characterise a waste collection system. Factors essential for modelling of waste collection are identified. In Section 4 ranges of the environmental impact from collection, pre-treatment, transport and treatment of waste are quantified. In Section 5 the environmental impact from waste collection is compared with the environmental impact from the whole waste management system. The results show if the environmental impact from collection, pre-treatment and transport can be a limitation for the benefit of recycling. They also show which materials have the largest potential for improving the environmental performance of the waste management system when being recycled instead of incinerated. Finally, the results of a case study illustrate how important the design of waste collections systems is for the overall environmental performance of a waste management system. The outcome of the study and its implications are summed up in the Discussion, Section 6, and Conclusions, Section 7 .

The research results presented in the PhD thesis are a summary of eight scientific papers, which are enclosed in appendices.

2 Waste management systems and life cycle assessments

2.1 Conceptual framework

Life cycle assessment was chosen as the method for environmental assessment because it enables estimation of direct as well as indirect environmental impact and resource consumption related to the waste management activities being investigated. Furthermore, it is a standardised method (ISO, 2006a; 2006b) that is commonly used for environmental assessments of waste management systems. To compare different waste management options, scenarios should be set up in a consistent way with the same functional unit in all scenarios. The following approach was used throughout the project.

A waste management system is composed of different activities that can be grouped into individual, but interrelated, phases. The output from one phase is the input of the next phase. A conceptual model is outlined in Figure 1. The central part of the system comprises the direct waste management activities, but in a life cycle perspective the system is expanded to include indirect upstream and downstream activities. Generation of waste at the source is the starting point of the waste management system. The first activities take place in the collection phase. During collection the waste is moved from the source to the first facility where initial sorting or pre-treatment takes place. One or more waste fractions are then moved from the first facility to the appropriate treatment facilities during the transport phase. At the treatment facility, the waste is prepared for final disposal, and energy or materials are possibly recovered from the waste. The recovered energy substitutes for other energy production in the energy system, and recovered materials substitute for virgin production of similar materials. Inclusion of avoided production is considered as an activity downstream of the waste management system. All phases require input of energy and/or materials. Production of these is considered as activities upstream of the waste management system.

This somewhat simple model of activities associated with waste management could be expanded to include further downstream effects, for example, the avoided virgin production could create a cascade of other effects. However, the purpose of the project was not to go into detailed system analyses of such effects.

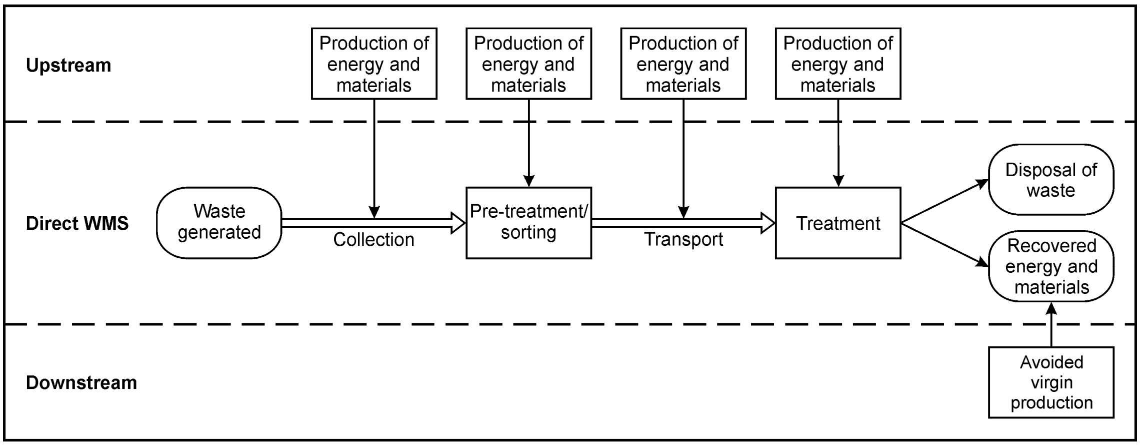

Figure 1. Direct and indirect upstream and downstream activities associated with waste management.

The conceptual model was used in two different ways: one where a waste management system (or a part of it) was analysed and one where the consequences of changes in a waste management system (or a part of it) were analysed. These two approaches are often referred to as 'attributional' life cycle assessment, which uses average data; and 'consequential' life cycle assessment, which uses marginal data (Curran et al., 2005; Weidema, 2003). However, for nearly all processes no marginal technology was identified and therefore average data were used. The only exception was the choice of using a process for marginal coal-based electricity production in analysis of both existing and alternative systems. Arguably, these choices were not consistent with the life cycle assessment methodologies; nevertheless, it is a common practice which calls for further research of market responses and system boundaries in life cycle assessments of waste management.

In a life cycle assessment, the functional unit is defined based on the type of waste generated and the treatment option. Material and energy flows related to each phase as well as upstream and downstream activities are then made up in a life cycle inventory, which is the foundation of the life cycle impact assessment. The flows are characterised and aggregated into several categories representing different types of environmental impact and resource consumption. The total life cycle inventory is calculated as the direct flows associated with the waste management operations *plus* the indirect flows arising from upstream production of energy and material *minus* the indirect flows from downstream avoided production (Clift et al., 2000; Finnveden, 1999).

2.2 Life cycle assessment method

The applied life cycle assessment method was the EDIP1997 method (Wenzel et al., 2007), and the life cycle assessment model EASEWASTE (Kirkeby et al., 2006) was used for all calculations. The method includes several impact categories, of which the following were used in the presentation of the results: global warming (GW), acidification (AC), nutrient enrichment (NE), photochemical ozone formation (POF), human toxicity via air (HT) and persistent toxicity (PT). The first four impact categories are collectively referred to as the energy-related impact categories and the remaining ones as the toxic impact categories. Assessment of resource consumption, which is also part of the method, encompasses different kinds of fossil fuels, renewable resources, metals and other minerals. The results were centred on the energy-related impact categories because the method is more robust and the data basis is often better with regards to these. The importance of the toxic impact categories and resource consumptions in relation to waste collection is considered in the discussion.

The results for the environmental impact categories were either characterised (e.g. in kg CO_2-eq.) or normalised (presented in the unit 'person equivalents' (PE)). 1 PE expresses the average environmental impact generated from all of one person's activities in one year in the given category. The results for the resource consumptions were either shown as amounts (in kg) or normalised and weighted with regard to supply horizons (presented in the unit 'person reserves' (PR)). 1 PR expresses the amount of a given resource available for one person and that person's descendants. If the functional unit is for instance one tonne of waste, it is more convenient to present the results in thousandths of PE or PR, i.e. mPE or mPR. It makes the numbers more readable, even though these might be thought of as odd units.

3 Characterisation of waste collection systems

3.1 Collection schemes

Collection schemes are often described by several technical parameters. During the PhD project the following five parameters were identified as suitable for characterisation of collection schemes in the context of life cycle assessment because they are determining for energy and material flows in the waste collection system: waste type/fraction, equipment for temporary storage, collection vehicle, collection method and type of residential area. Other variables such as container volume, collection frequency and density of collection points are imbedded in the aforementioned parameters.

The waste producers, in this case households, are obliged or encouraged to sort the waste in several recyclable waste fractions defined by provided sorting guidelines. The waste fractions are most often defined by the types of material accepted. Some materials are collected commingled, which means that they are purposely mixed and separated later in the waste treatment system. Any other waste should end up in the residual waste fraction. In addition to material type, a waste fraction is often characterised by the amount, bulk density and frequency in which it appears. The waste is temporarily stored from the time it is generated until the time it is collected by a collection vehicle. The most commonly used equipment is either bags made of paper or plastic or containers, such as wheelie bins. Bulky types of waste are often placed at the kerbside without use of storage equipment. At collection, bags are loaded on the vehicle, or the content of containers is emptied into the vehicle. The type of collection vehicle used is characterised by, e.g. its gross vehicle weight, payload capacity and compaction equipment. The two basic collection methods are property-close collection, e.g. kerbside collection where each house is a collection point, and bring systems, e.g. drop-off containers placed at central collection points such as supermarkets and other public places. The bring system involves fewer stops for the collection vehicle and more waste is picked up at each collection point, but citizens have to carry the waste to the collection point. The last parameter is the type of residential area, which affects the amount of waste generated and the distance between collection points in the catchment area. The density of citizens, and thereby the density of waste, in the area is described by the housing type, e.g.

single-family or multi-family housing, and the geographic distribution of houses, e.g. urban or rural area.

In addition to this suggestion for characterisation of collection schemes, two other collection schemes are relevant to consider. One is a bring system in terms of recycling centres where the waste is delivered by the citizens by car. The other is automated waste collection in which the waste is collected and sometimes transported in underground vacuum systems.

3.2 Waste composition

The composition of the waste is the starting point for modelling of a waste management system. Defining the waste composition serves as the basis for quantification of the amount of each waste fraction and specification of the chemical composition of the waste. This is used for making life cycle inventories of the direct and indirect flows related to the waste management activities, e.g. reported as emissions and resource consumption per tonne of waste processed. The chemical composition is used for calculation of emissions that depend on the properties of the processed waste, e.g. its methane production potential, concentration of heavy metals or heating value. Furthermore, both the quantity and quality of waste are determining for the choice of treatment option for the waste.

3.2.1 Household waste

The composition of Danish household waste implemented in the EASEWASTE database is based on the conceptual model and waste sampling survey reported by Kirkeby (2005) and Riber et al. (2009). The waste is categorised in 48 material fractions with a known chemical composition. The distribution of the material fractions for average single-family and multi-family housings in 2001 is also estimated. The waste composition represents all household waste discarded by private households in the waste management area, but often the waste is separated at the source into several waste fractions that are collected individually. When the total waste composition is known, the consequences of sorting different types of hazardous or recyclable waste fractions can be modelled. The EASEWASTE model keeps track of the material fractions in the waste and the chemical composition of these. This allows modelling of how the chemical composition of different waste fractions varies depending on the material fractions of which they are composed.

The names of 48 material fractions are listed in Table 1, and the ones that can easily be sorted at the source for biological treatment, material recycling or special treatment of hazardous waste are indicated.

Table 1. The 48 material fractions in EASEWASTE (Kirkeby, 2005). Potential treatment: # biological treatment, * recycling, • hazardous waste.

#	Vegetable food waste		Wood
#	Animal food waste		Textiles
*	Newsprints		Shoes and leather
*	Magazines		Rubber
*	Advertisements		Composite products
*	Books and telephone books		Cigarette butts
*	Office paper		Other combustibles
*	Other clean paper		Vacuum cleaner bags
*	Paper and cardboard containers	*	Clear glass
*	Cardboard	*	Green glass
*	Milk cartons	*	Brown glass
*	Cartons with aluminium foil		Other glass
	Kitchen tissues	*	Aluminium cans
	Dirty paper	*	Aluminium foil
	Dirty cardboard	*	Steel cans
*	Soft plastic		Plastic/metal foils (laminates)
*	Plastic bottles	*	Other metals
*	Hard plastic		Soil
	Non-recyclable plastic		Stones and concrete
#	Flowers and garden waste		Ceramics
#	Straws and excrements		Cat litter
	Nappies and tampons	•	Batteries
	Cotton and bandages		Other non-combustibles
	Other sanitary products		Residue

The data in EASEWASTE are generic and should be corrected for local deviations with regard to amounts, material fraction distribution and chemical composition when applied in a case study. The amount of, for example, beverage containers, newspapers, advertisements delivered by post and food waste will depend on local consumption patterns and socioeconomic conditions. In the case study reported in Larsen et al. (VIII), the generic waste composition was adjusted for a relatively higher share of paper caused by a recent increase in distribution of free newspapers and advertisements. Furthermore, the modelled chemical composition of the residual waste fraction was adjusted based on measurements of the residual waste fraction. The latter was estimated in an incineration test where the substance flows through the incinerator were measured. This is an example of how generic data are modified to represent a real case.

The waste composition must remain the same when different waste management scenarios are compared. It is reasonable to assume that the waste composition is unaffected by the waste collection system, except in one case. Introduction of a weight-based billing for residual waste as a replacement for volume-based billing is likely to reduce the total amount of collected household waste (Reichenbach (ed.), 2004.; Dahlén, 2008), even though it is not evident whether this is caused by reduction in waste generation or by transfer of waste to other ways of disposal, legal or illegal.

3.2.2 Bulky waste

A material fraction dataset for bulky waste does not exist. Instead, two case studies were performed in order to make inventories of waste fractions and quantities (Larsen & Christensen, I). The study identified 12 main fractions and additionally 8 sub-fractions of bulky waste, which are listed in Table 2 together with the purpose of collecting the given fraction. The waste amounts and distribution of waste fractions were similar in the two case studies, but it is unknown how well they represent the average composition of bulky waste in Denmark. Some sources of uncertainties were identified during data collection. First of all, the definition of bulky waste itself was imprecise, and the waste fractions were locally defined. Secondly, the waste was collected through a combination of property-close collection by truck and a bring scheme with recycling centres, which, combined with the large number of fractions, resulted in a large number of waste flows to keep track of. Finally, there was a risk that the waste from households was mixed with similar waste from other sources during collection, both at the recycling centres and in the kerbside collection schemes. These and other uncertainties are further discussed by Larsen & Christensen (I).

Most of the waste fractions contained mixed materials, and some material compositions were estimated in the study (Larsen & Christensen, I). However, no chemical composition could be assigned to these materials due to lack of data. The chemical composition of the waste fraction called small combustible waste (<1 metre) was measured by Riber (2007), but it was not possible to relate the substances to any specific materials.

Table 2. Waste fractions in bulky waste and purpose of collection (Larsen & Christensen, I).

Waste fractions	Purpose of collection
Glass - *Flat glass* - *Windows with frames* - *Car windows*	Recycling
Cardboard	Recycling
Plastic - *EPS* - *PP*	Recycling
Metal scrap	Recycling
WEEE - *Refrigeration equipment* - *Cables* - *Other WEEE*	Recycling and management of hazardous substances
Tyres	Recycling
Wood	Recycling
Plasterboards	Recycling
Bricks and tile	Recycling
Concrete	Recycling
Combustible waste	Energy recovery
Incombustible waste - *Mixed incombustible* - *Impregnated wood* - *Asbestos* - *PVC*	Landfilling and management of hazardous substances

3.3 Sorting efficiency and recycling potential

3.3.1 Sorting efficiency

The sorting efficiency is a measure of how effectively a recyclable material is routed into a separately collected waste fraction. It is defined as the amount of the material separated at the source and placed in a separate bin or container in relation to the total amount of the material in the generated waste. The sorting efficiency is expressed in weight-%. The non-separated material is included in the residual waste. The concept of sorting efficiencies is used in modelling of waste collection systems for household waste with source-separation of recyclables. It is not yet applicable to bulky waste due to the lack of a material fraction dataset.

The potential amount of recyclable material in the waste is estimated from the material fraction dataset and may comprise more than one material fraction. The sorting efficiency is an average measure of the whole waste collection system and is the product of scheme coverage, participation rate and the individual persons' sorting efficiencies for the given waste fraction. The individual person's willingness to participate might be shaped by factors such as environmental awareness, information, economic incentives, perception of convenience and design of the technical system, but these mechanisms behind the sorting efficiency were not scrutinised in the study. Other terms for sorting efficiency are used in the literature: source-sorting ratio (Dahlén, 2008), recovery rate (Edwards & Schelling, 1999; Heilmann & Winkler, 2005) and capture rate (Tucker & Speirs, 2002).

The figures in Table 3 show sorting efficiencies for dry recyclables from household waste obtained from reporting of various studies. They are not comparable because of differences in waste compositions, definitions of waste fractions, sampling methods, geographic scale, year of reporting etc., but they give an indication of how much the sorting efficiencies vary between different waste collection systems.

The highest sorting efficiencies were achieved through kerbside collection, but the figures were not significantly higher than for bring systems. Property-close collection is more convenient for the citizens and therefore likely to yield the highest sorting efficiencies. For example, Dahlén (2008) found that the amount of recyclables collected in bring systems (drop-off containers and recycling centres) increased with the density of collection points. This indicates that the distance to the collection point is determining for the sorting efficiencies. Edwards & Schilling (1999) proposed a model for forecasting the sorting efficiency of glass as a function of the density of collection points.

In general, the sorting efficiencies were higher for paper and glass than for materials such as cardboard, plastics and other packaging materials, but there was no tendency of significant differences, e.g. the sorting efficiency was higher for plastic bottles than for paper in the Australian study (Grant et al., 2001). The citizens' willingness to sort out a given waste fraction is likely to be influenced by their perceptions of the waste amount, the recyclability of the material and the effort it takes to sort and clean the material (Perrin & Barton, 2001). For example,

Table 3. Literature survey of sorting efficiencies.

Study no.	Collection scheme[a]	Waste fraction	Sorting efficiency
Study 1 *Denmark*	C R B	Paper and cardboard Paper and cardboard Glass	63% 9% 52%
Study 2 *Denmark*	B	Glass	54%
Study 3 *Denmark*	B B	Beverage containers of PET, HDPE, aluminium and steel Glass	4% 41%
Study 4 *Australia*	K K K K K K K	Paper and cardboard Liquid paper board HDPE packaging PET packaging Glass Steel-tin cans Aluminium	68% 42% 73% 76% 77% 39% 56%
Study 5 *Sweden*	K K K B B B	Newsprint Glass packaging Paper, plastic & metal packaging Newsprint Glass packaging Paper, plastic & metal packaging	77%–94% 78%–88% 30%–63% 60% 71–79% 17%
Study 6 *UK*	C C C C C	Newspaper Glass bottles Glass jars, aluminium cans, steel cans Cardboard Plastics beverage bottles	80%–82% 80%–82% 75%–78% 71%–73% 71%–73%
Study 7 *Germany?*	K K K K B B B B	Glass Paper Cardboard Plastics Glass Paper Cardboard Plastics	45%–96% 71%–97% 63%–77% 45%–65% 45%–96% 55%–94% 25%–71% 42%–57%
Study 8 *UK*	K	Paper and cardboard	33%

a: K = Kerbside collection, B= Bring system with drop-off containers, C=Combined K and B, R=Recycling centre

Table continues...

...Table continued

1: (Larsen et al., 2008)
2: (Larsen et al., 2007)
3: (Schmidt, 2005), Results of full-scale experiment
4: (Grant et al., 2001)
5: (Dahlén, 2008), Based on sampling in six municipalities
6: (Tucker & Speirs, 2002), Maximum figures predicted by model
7: (Heilmann & Winkler, 2005), Maximum and minimum figures reported in a literature survey
8: (Harder et al., 2005), Product of coverage rate, participation rate and individual separation efficiency

paper is a large waste fraction, is well-known as recyclable and does not require cleaning; it also had the highest sorting efficiency in several studies.

The figures reported by Tucker & Speirs (2002) are forecasts of the maximum sorting efficiencies that can be achieved through extended kerbside collection schemes and enhanced information. If new schemes were not followed by intensive promotion and education, the expected sorting efficiencies would be approximately 20 percentage points lower. They suggested that the citizens' motivation for participation must be maintained through promotional education and awareness campaigns.

Economic incentives in the form of weight-based billing for residual waste might affect the waste composition, as mentioned before. Furthermore, the Swedish study reported the highest sorting efficiencies in the municipality that had a weight-based billing system (Dahlén, 2008). However, quantification of the effect was not found in the other studies in the literature survey.

3.3.2 Recycling rate

Sorting efficiencies describe the effectiveness of source-separation of individual materials, but the effectiveness of a waste collection system is also often expressed by the overall recycling rate, e.g. as a political target for waste management. The recycling rate is defined as the amount of source-separated waste in relation to the total amount of waste generated; it is expressed in weight-%. The recycling rate applies to the whole waste collection system and is the weighted average of the material-based sorting efficiencies; weighting is done with regard to the materials' relative shares in the generated waste.

Various other terms with a similar definition were found in the literature survey, among others, source-sorting ratio (Dahlén, 2008), separation rate (Calabrò, 2009) and level of source-separated collection (Rigamonti et al., 2009). The term recycling rate was chosen because it indicates that the materials are sorted for the purpose of recycling, no matter if they are separated at source or at a central waste sorting facility. If the recyclables are collected commingled, terms containing word such as source-sorting or source-separation could be misleading. It should be noted that the recycling rate does not take into account that the amount of recovered material is lower due to loss of material and removal of contamination material during reprocessing.

The recycling rate is a system-specific measure, and estimation of likely ranges was not attempted due to the variety of waste management systems. The recycling rate for household waste was at a national level of 18% in Denmark in 2005 (Environmental Protection Agency, 2007), mainly because of collection of paper, glass and bio-waste.

4 Environmental impact

This section illustrates how the individual phases of the waste management system are modelled and how large their environmental impact potentially is. The purpose is to show a consistent way of setting up alternative waste management scenarios by analysing the waste management system step-wise. The impact from the first three phases (collection, pre-treatment and transport) is simply related to the use of energy and materials for moving and sorting the waste. All flows correlate to the mass of the waste processed in the system. Modelling of the treatment phase is more complicated for two reasons. First of all, some flows are related to the waste composition which is where the quality of the waste sorting becomes an important factor. Secondly, the utilisation of the waste is included in the treatment phase by subtraction of the environmental impact avoided in order to make the functional units in different waste management scenarios comparable. This is a somewhat theoretical construction which most likely makes sense only when the life cycle inventory is applied in a life cycle assessment. In general, comparing individual parts of the waste management system makes sense only if they have the same functional unit.

4.1 Environmental impact from collection

The direct environmental impact from collection stems from combustion of fuel in the collection vehicle. A conceptual model that allows modelling of the fuel used for transport to the facility and the fuel used in the collection area separately was described in Larsen et al. (II). As illustrated in Figure 2, the collection vehicle is assumed to drive directly between garage, collection area and point of unloading. The consumption of diesel on these routes is calculated as a linear function of the covered distance and the total mass of truck and payload and thus expressed in the unit litres/tonne/km. Data for preparation of life cycle inventories are obtained from life cycle assessment databases and transportation simulation software. This approach is further described in Section 4.3 about transport. Driving in the collection area is modelled differently because linear fuel consumption cannot be assumed when the vehicle has many stops and the payload increases during collection. Diesel used for driving, idling and compacting is aggregated into one fuel consumption factor and given in the unit litres/tonne.

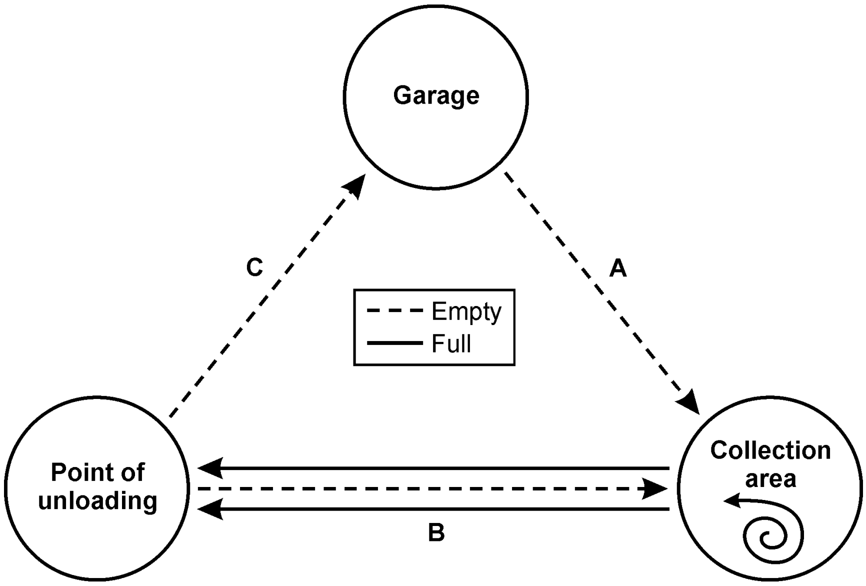

Figure 2. Conceptual model for modelling of the collection phase (Larsen et al., II)

Fuel consumption factors for driving in the collection area were estimated in a study performed in two municipalities in order to provide data needed for environmental assessments of waste collection systems (Larsen et al., II). The studied collection schemes were grouped according to waste type, collection method and type of residential area. The waste types included were residual waste, paper, glass and bulky waste. For kerbside collection, the catchment areas were categorised as city centre, multi-family housing, single-family housing, small towns and rural areas; here listed after decreasing population density. Bring schemes with drop-off containers cut across all types of area. The results are summarised in Table 4 together with information about standard deviation, number of measurements and collection frequency. It was found that the diesel consumption varied between 1.4 and 10.1 litres/tonne of waste collected, both extremes found for residual waste. In general, the fuel consumption factors increased when the population density in the catchment area decreased. This showed that there is a significant different between collection schemes, which would be relevant to consider in an environmental assessment. The diesel consumption for collection of paper was higher than for residual waste, though not significantly. This finding indicated that collection of recyclables could increase the fuel consumption because less waste is picked up per stop. The study also showed that the amount of fuel spent in the collection area and the amount of fuel spent on other routes became equally important for the total fuel consumption when the distance from the collection area to the point of unloading was approximately 20–50 km, depending on the type of collection scheme.

Table 4: Diesel consumption observed for collection of waste (Larsen et al., II)

		Diesel consumption [litre/tonne]	Standard deviation	Number of measure-ments	Collection frequency [times/month]
Residual household waste	City centre[1]	3.1	1.1	9	>4
	City centre[2]	3.0	1.6	38	>4
	Multi-family[1]	1.6	0.5	6	>4
	Multi-family[2]	1.7	0.5	15	>4
	Single-family[1]	3.3	1.5	21	2
	Single-family[2]	3.6	1.3	28	2
	Single-/multi-family[3]	1.4	0.4	4	2
	Small towns[3]	2.4	0.3	4	2
	Small towns[2]	5.7	0.8	6	2
	Rural areas[3]	10.1	2.6	4	2
	Rural areas[1]	6.3	1.3	11	2
	Rural areas[2]	6.3	1.2	19	2
Paper	Multi-family[1]	3.5	1.7	8	2
	Multi-family[2]	2.2	1.0	17	2
	Single-family[1]	6.6	2.5	8	1
	Single-family[2]	4.1	0.8	4	1
	Single-/multi-family[3]	3.4	0.3	4	1
	Drop-off containers[1]	3.7	0.8	12	-
	Drop-off containers[2]	4.9	1.9	15	-
Glass, Drop-off containers[2]		4.9	1.4	6	-
Bulky waste, City centre[1]		2.6	0.7	6	1
Bulky waste, Outside city[1]		9.1	3.3	9	-

1: Municipality of Aarhus, 2006-2007, 2: Municipality of Aarhus, 2002-2003, 3: Municipality of Herning, 2006.

The fuel consumption can also be predicted by other modelling approaches using, e.g. number of bins, number of stops, distance between stops and idling time as input parameters (den Boer et al., 2005; Sonesson, 2000; Tanskanen & Kaila, 2001; Tavares et al., 2009; Wang, 2001). Fuel consumption factors for delivery of waste to drop-off containers or recycling centres by car were not measured and the data found in literature were sparse. An important question is whether a car trip is undertaken especially to deliver waste or is combined with other purposes. In the latter case, the fuel consumption should not be allocated to waste collection only.

When the total diesel consumption for the collection phase has been estimated, the environmental impact is calculated as the emissions and resource consumption related to production and combustion of diesel. However, the emissions of exhaust gases are also depended on the truck engine technology. For instance, certain substances (CO, HC, NO_X and particulate matter) are regulated by exhaust emission standards that set limit values for emissions from new trucks. The potential effect of implementing successive European exhaust emission standards (Euro II in 1996, Euro III 2000, Euro IV in 2005, Euro V in 2008) is shown in Figure 3. The impact from combustion has decreased considerably in three of the four impact categories; however, GW was barely affected. The impact in the GW impact category was mainly caused by emission of carbon dioxide from combustion of the fuel; thus more energy-efficient collection is needed if the impact of GW should be minimised.

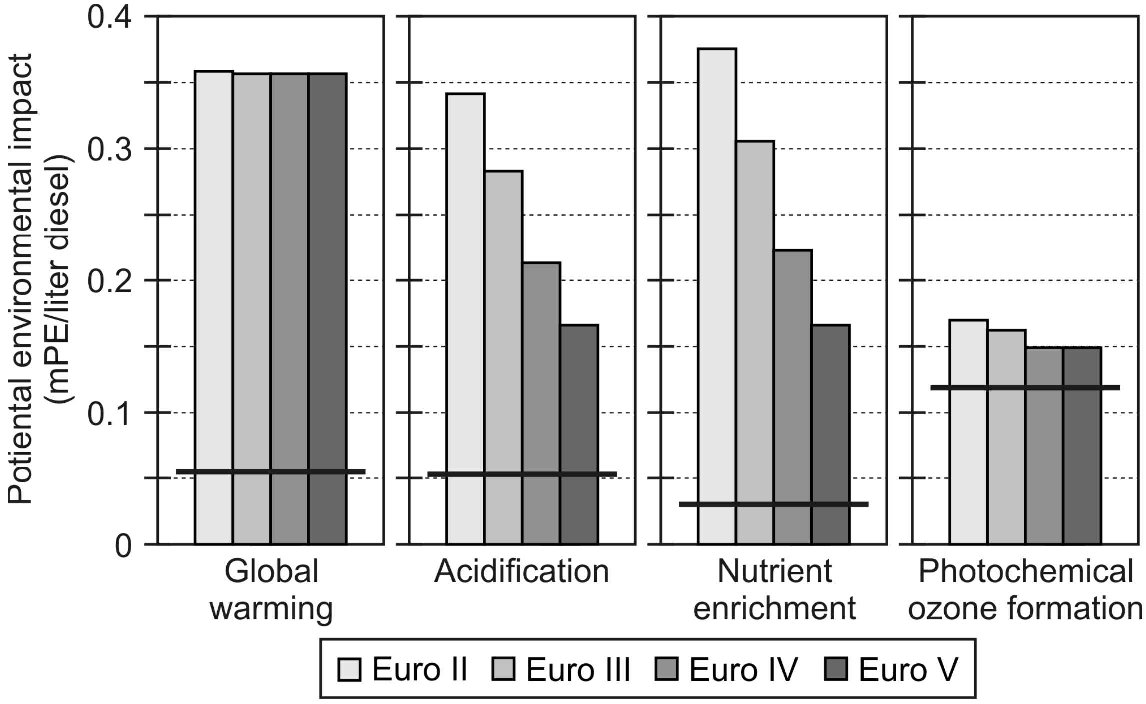

Figure 3. Potential environmental impact from production and combustion of 1 litre diesel. The share below the line illustrates the impact related to production only (Larsen et al., II).

The main conclusion of the study of diesel consumption and its environmental impact was that the following three parameters all were important for the resulting environmental impact from collection: the fuel consumption in the collection area, the distance to the pre-treatment plant and the truck engine technology. Thus both optimisation of collection routes, planning of waste facilities and legislative requirements are important instruments in relation to reduction of environmental impact from collection.

Based on the data reported in Larsen et al. (II), the environmental impact of the collection phase (collection and up to 100 km transport in collection truck to pre-treatment facility, including return of empty truck) is expected to be in the order of 1–10 mPE per tonne of waste in each of the impact categories (GW, AC, NE and POF). 100 km was considered to be a maximum distance for transport in a collection vehicle without transfer to a more fuel-efficient means of transport. Transfer and transport of waste is further described in Section 4.2 and Section 4.3.

4.2 Environmental impact from pre-treatment

Pre-treatment here refers to waste management activities, such as initial sorting, separation, baling, compaction and reloading of collected waste, that take place at material recovery facilities (MRFs) and transfer stations. Pre-treatment is often an important part of the waste management system because the purpose of it is optimisation of the following transport and treatment, for example, by increasing the bulk density of the waste and removing foreign items from the waste. The total energy consumption and the type of fuel used depend on the type of equipment and machinery used at the facility. The types of facility considered for pre-treatment of recyclables in Denmark were relatively simple facilities that upgraded a single material stream by semi-manual removal of foreign items and compaction. In order to estimate the magnitude of the environmental impact related to pre-treatment, Merrild et al. (IV) performed a literature survey of reported energy consumptions. As a result, they modelled a MRF with an electricity use of 25 kWh/tonne and a diesel use of 3.4 litres/tonne and a transfer station with an electricity use of 1 kWh/tonne and a diesel use of 0.4 litres/tonne. The environmental impact of GW, AC, NE and POF was in the order of 1–4 mPE/tonne at the MRF and 0.1–0.3 mPE/tonne at the transfer station, and thus lower than impact from collection. Advanced mechanical sorting of commingled waste involving shredders, air classifiers, magnet separation etc. and mechanical-biological-treatment (MBT) plants were not assessed, but their energy consumptions are expected to be higher than the aforementioned figures.

4.3 Environmental impact from transport

Waste in terms of recyclable materials is often treated in regions other than where it is generated and therefore has to be transported over considerable distances. The following means of transport, which all are used for long-distance transport, were compared: trucks, trains and ships. The energy consumption is expressed as the amount of fuel used on transport of one tonne one kilometre. Large means of transport are in general more fuel-efficient than smaller ones, but the efficiency also depends on how well the waste is compacted and how well the payload capacity is utilised. A comparison of different means of transportation showed that typical fuel consumption factors given in litres/tonne/km varied between 0.15 for a collection truck and 0.0005 for a large bulk carrier (Merrild et al., IV). In these two extreme cases, the bulk carrier was 300 times more fuel-efficient than the collection truck. Because of this great variation, it seems important to make appropriate choices about the means of transport in environmental assessments, even though it might be difficult to get information about the type actually used. However, the interval of a minimum and maximum distance, in which the given means of transport is economically optimal to use, also varies. Figure 4 shows the environmental impact from transport of one tonne of waste as a function of the transport distances for five different means of transport. Realistic ranges of transport distances were chosen for each means of transport, e.g. 150–4800 km for a long-haul truck and 4800–19200 km for a large bulk carrier. The environmental impact from transport rarely exceeded 50 mPE/tonne, except for the modelled container ship. Eisted et al. (II) used data from different sources to show the variation of the impact in the GW impact category. They found that energy consumption typically varied a factor two or three for each of the means of transport, depending on data source. Even though many databases provide data for transport, the underlying assumption about payload capacity, degree of utilisation and bulk density should be considered carefully in order to choose the most appropriate dataset.

4.4 Environmental impact from treatment

When the impact from treatment is assessed, the waste management system is expanded to include the downstream effect of avoided virgin production. Due to the large variety of waste treatment technologies and virgin production technologies available, use of general estimates of the environmental impact is not recommendable. Data should always be chosen based on a thorough analysis of the treatment options for the waste and preferable obtained from the actual

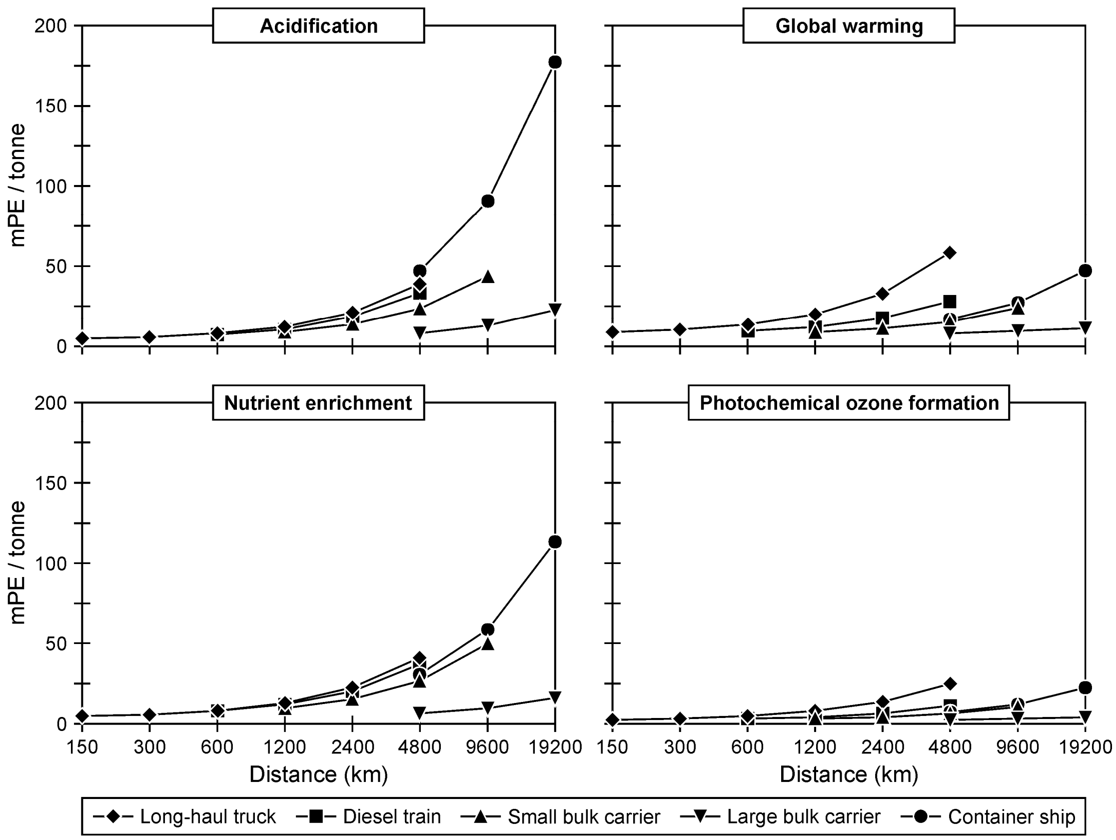

Figure 4. Environmental impact for five means of transport (incl. collection and pre-treatment) as a function of the transport distance (Merrild et al., IV).

treatment facilities. The issue of variation between available data sources was illustrated in several studies with focus on the GW impact category. The impact related to recycling and material substitution were calculated to vary between -500 to -450 kg CO_2-eq./tonne for glass remelting (Larsen et al., V); -1500 to -600 kg CO_2-eq./tonne for reuse of glass bottles (Larsen et al., V); -19300 to -5000 kg CO_2-eq./tonne for aluminium recycling (Damgaard et al., VI); -2400 to -600 kg CO_2-eq./tonne for steel recycling (Damgaard et al., VI) and -1600 to -800 kg CO_2-eq./tonne for plastic recycling (Astrup et al., 2009). Merrild et al. (2008) showed in more detail how different combinations of waste treatment technologies and virgin production technologies could lead to very different profiles for paper and cardboard recycling, e.g. turning a net saving into a net impact by combining one recycling technology with different virgin production technologies. The variation in global warming impact was mainly caused by differences in energy efficiency and energy sources, but for other impact categories emission abatement systems and use of chemicals in the production process play an important role.

Incineration is the alternative to recycling of materials from household waste in Denmark. The impact from incineration is greatly related to the technological level of flue gas cleaning, residue management and energy recovery at the incinerator. On the substitution side, the interaction between the incinerator and the surrounding energy system must be analysed thoroughly. As for recycling technologies, the variation in impact is large between different incinerators, but magnitudes and causes are not further described here. Details about impact from different waste types, impact from different types of incinerators and modelling of incineration in EASEWASTE are found in the PhD thesis by Riber (2007) and its related papers.

While much research has focused on environmental issues related to treatment of household waste, only few studies are concerned with bulky waste. A screening of the environmental impact from treatment of bulky waste was therefore performed, and the results were reported in Larsen & Christensen (VI). Ten waste fractions were included in the assessment, but five others were omitted due to lack of data. The environmental profiles of the waste fractions were, as expected, very different. Recycling of flat glass, windows, cardboard, metal scrap, refrigeration equipment and wood resulted in avoided environmental impact in most of the impact categories, up to -463 mPE/tonne for refrigeration equipment in the PT impact category, whereas tile, concrete and incombustible waste had a relative low net environmental impact, less than 2 mPE/tonne, in all impact categories. The impact from combustible waste depended highly on the modelled energy system, e.g. the impact of GW was in two cases estimated to -111 and +8 mPE/tonne (or -960 and +70 kg CO_2-eq./tonne), respectively.

In the few examples referred to here, the environmental impact from treatment of selected materials was found to vary greatly between different types of material and also within a given treatment option. The probable magnitude of environmental impact ranged from -1000 to +100 mPE/tonne for the most extreme cases. This is significantly more than the magnitude of the impact from the preceding phases: collection, pre-treatment and transport. However, the purpose was not to evaluate the significance of each phases, but to report the environmental impact in a transparent way in order to assess the environmental performance of the whole waste management system. Section 5 addresses situations where the connection between the phases is determining for the total environmental impact from the system.

5 Waste collection in a system perspective

The potential benefits from collection of dry recyclables from household waste were studied closely. To date, the effort in Denmark has been concentrated on collection of paper and glass, but collection schemes for other types of materials, e.g. different types of packaging waste, are emerging. Material recycling is expected to be more environmentally beneficial than incineration, which is the alternative treatment option if the recyclables are not sorted out and collected separately. However, this assumption might not hold in all cases, and three central issues were identified in Merrild et al. (IV). Incinerators in Denmark are effective waste-to-energy plants with high energy recovery rates, and that makes incineration a favourable alternative to recycling of high-calorific materials such as paper and plastic. It is also possible to recover at least some magnetic iron and aluminium for recycling after incineration. Finally, the benefit could be undermined by a higher energy consumption needed for collection, pre-treatment and transport of the recyclables. Many recyclables are traded on a world market and subject to long transport distances, whereas residual waste is incinerated locally.

The first part in this section shows whether the environmental impact from collection, pre-treatment and transport of six recyclables is limiting for recycling. The next part shows the significance of the six recyclables when the potential quantities are taken into account. The final part shows how important the choice of waste collection system is for the environmental performance of a waste management system when organisational and technical limitations are respected.

5.1 Environmental capacity for recycling

The concept of environmental capacity was introduced in order to assess the importance of increased energy consumption caused by separate collection of recyclables. The environmental capacity is defined as the difference between the environmental impact from the residual waste treatment system (collection, pre-treatment, transport and treatment) and the environmental impact from material recycling (treatment). It expresses a potential environmental saving that can be used for extra collection, pre-treatment and transport when source-separation and recycling is introduced as an alternative to incineration of the materials. Recycling will not be environmentally feasible if the impact from collection, pre-treatment and transport of recyclables exceeds the environmental capacity. The recyclables included were paper, cardboard, glass, plastic, steel and aluminium. The scenario setup is further described in Merrild et al. (IV). The results showed positive environmental capacities for paper, glass, steel and aluminium in all impact categories (GW, AC, NE and POF). Thus the environmental impact from recycling was potentially lower than the impact from incineration for these four materials. The environmental capacity in the GW impact category was negative for cardboard and plastic when recycling was compared with incineration with high energy recovery rate but positive if the energy recovery rate was low. Furthermore, there was a negative environmental impact for plastic in the POF impact category. The findings indicate that recycling is preferable to incineration due to lower environmental impact, but exceptions exist for incineration of high-calorific materials such as cardboard and plastic if the energy recovery rate is high at the incinerator. It is also important to consider if increased impact in one category can be accepted if the other impact categories show an advantage of recycling over incineration. Aluminium had the largest environmental capacity in all four impact categories; the largest was 992 mPE/tonne for AC. Besides this, the results did not show any consistent ranking of the other materials. A graphical presentation of the results and a thorough interpretation are given in Merrild et al. (IV).

After the environmental capacities were established, it was investigated if the impact from collection and pre-treatment could exceed them and thereby undermine the potential benefit from recycling. In the modelling, the impact from collection and pre-treatment was for the four impact categories estimated to 2–7 mPE/tonne, in line with the magnitudes of impact estimated in Section 4. These figures were far from exceeding the environmental capacities. Thus the additional energy consumption for collection and pre-treatment is not a decisive factor for comparison of recycling and incineration for the six chosen materials. This means that new collection schemes for recyclables from household waste and simple pre-treatment technologies could be implemented without compromising the benefits of recycling.

In the next step, the environmental capacities were compared with the impact from transport (including collection and pre-treatment). Transport in five means of transport: a long-haul truck, a diesel train, a small bulk carrier, a large bulk carrier and a container ship, with different distance ranges was modelled as shown in Figure 4 on page 27. Break-even transport distances where the total impact from collection, pre-treatment and transport equaled the environmental capacity were calculated. Two clear tendencies were found: transport of aluminium did not exceed the environmental capacity for any of the five means of transport, and transport in a large bulk carrier did not exceed the environmental capacity for any of the materials. For all other combinations of materials and means of transport, one or several impact categories were limiting for the benefit of recycling over incineration. All the four impact categories were at least in one combination the limiting factor. The longest transport distances could be justified for aluminium, and in descending order, steel, glass, paper and plastic/cardboard. The shortest distance calculated was 600 km in the GW impact category for transport of cardboard in a truck when compared with incineration with low energy recovery rate. An overview of all break-even distances is presented in Table 5 in Merrild et al. (IV). It should be noted that the break-even distance for transport of paper, cardboard, glass and plastic in a container ship was less than 4800 km, which was assumed to be the minimum distance for use of the container ship. It should also be noted that in three cases there was a negative environmental capacity, aforementioned.

In conclusion, the materials paper, glass, steel and aluminium can be transported several thousand kilometres to recycling facilities without compromising the benefit of recycling, even when compared with incineration with high energy recovery rate, providing appropriate means of transport are used. In some situations, incineration would be a better solution for cardboard and plastic, especially if the energy recovery rate at the incinerator is high. In cases of doubt, waste management planners should take the efficiency of energy recovery from incineration, the transport distances and the means of transport into consideration.

In practice, export of waste is done for reasons other than the environmental benefits. For instance, export might be economically beneficial if the costs of treating the waste locally are high, or it might be necessary to export the waste if local treatment options do not exist. Some recyclable waste from Europe and North America is today exported to Asia where the demand for raw materials is high. The calculations of break-even distances showed that such transports scenarios do not lead to an environmental deterioration if fuel-efficient ships are used. Furthermore, the fuel used for transporting the waste might be marginal if the ships return partly empty to Asia after delivering their goods to the European and American markets, but it is recommended that this assertion is studied further.

5.2 Potentials for collection of recyclables in Denmark

The aforementioned analysis was made for treatment of one tonne of each material. In the next step, the real amounts of the materials in household waste were taken into consideration. The amount of recyclables in average Danish household waste was estimated to 23% paper, 4.8% cardboard, 8.8% glass, 1.0% hard plastic packaging, 0.7% steel packaging and 0.3% aluminium packaging. The potential amount of recyclables in one tonne of household waste was then combined with the tonne-based environmental capacities. The environmental capacities for the content of recyclables in one tonne of Danish household waste are presented in Figure 5. The numbers I and II denote variants of the scenarios, but only scenarios marked I are considered here, see Merrild et al. (IV) for further explanations.

Paper had the largest environmental capacity in all impact categories. It was followed by aluminium, cardboard and glass, while the environmental capacities for plastic and steel were even lower. This means that paper is potentially the most beneficial material to sort out for recycling. Even though the environmental capacity per tonne material was relatively low, the actual amount of paper in household waste was large. Aluminium, the second most beneficial material, had the highest environmental capacity per tonne, but the amount found in household waste was low. The waste amounts are important because it probably would not be economically feasible to initiate a collection scheme for one of the small fractions only. Collection of paper, cardboard and glass is already the standard in Danish municipalities, meaning that the potential environmental benefits from recycling to a large extent are realised for these materials. The environmental capacities could be used for estimating the remaining potentials and comparing this with the unrealised benefits from collection of plastic, steel and aluminium. The concept then becomes a tool that can identify focus areas for optimisation of the environmental performance of waste management systems. However, the potentials cannot be fully utilised in reality and realistic sorting efficiencies should also be considered. The case study presented in the following section, Section 5.3, was based on an analysis of expected sorting efficiencies when limitations in the waste management system were taken into account.

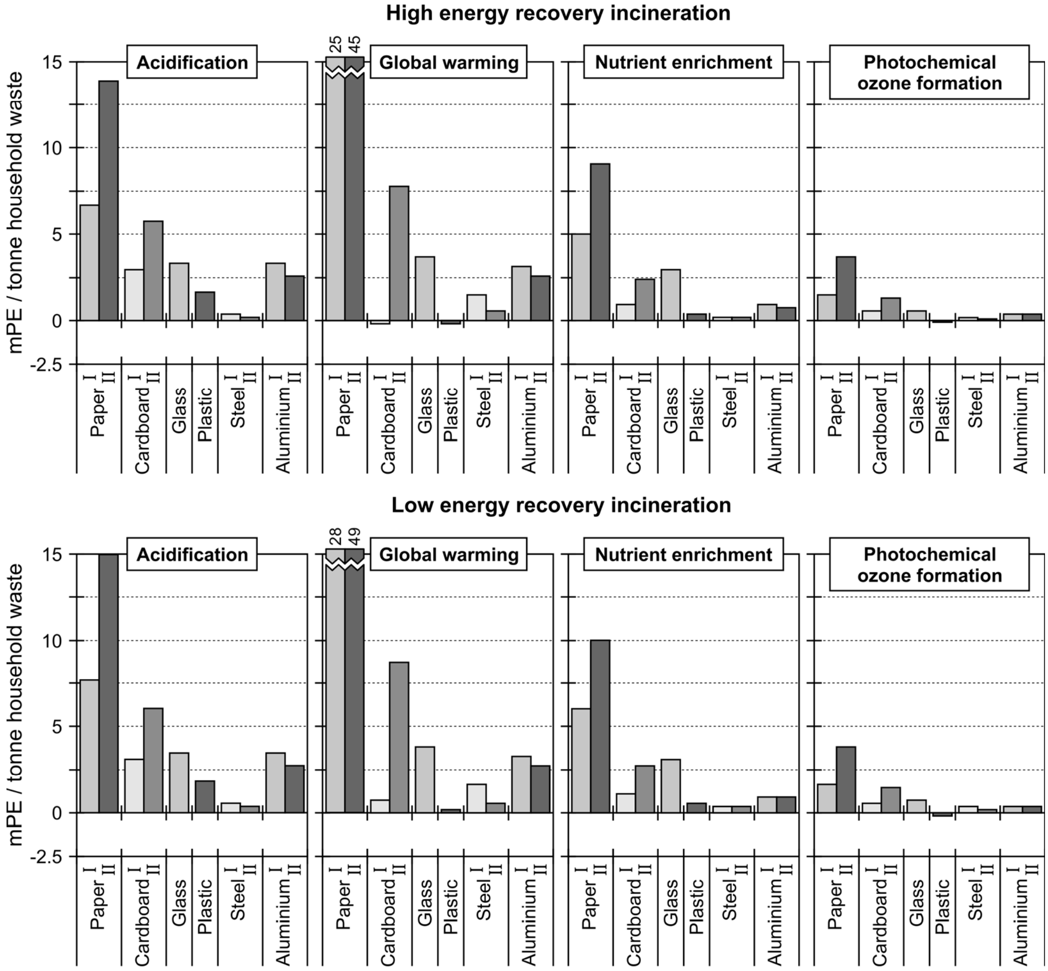

Figure 5. Environmental capacity for the content of recyclables in one tonne of Danish household waste when recycling is compared with incineration with a high or low energy recovery rate (Merrild et al., IV).

5.3 Case study: collection of recyclables

5.3.1 Purpose of the case study

The environmental consequences of modifying a waste collection system for the intention of increasing the recycling rate were examined thoroughly in a case study (Larsen et al., VIII). Even though the results in Section 5.2 showed that there was an environmental capacity available for recycling instead of incinerating certain materials, the full potentials can never be realised due to organisational or technical limitations. The case study was performed for the municipality of Aarhus, which helped with the detailed description of its waste collection system.

The purpose of the case study was to assess the differences between alternative waste collection systems when the effects downstream of collection were included and when organisational and technical limitations were respected. Secondly, the results could be used for recommendations regarding which collection schemes and waste fractions were the most beneficial for the environmental performance of the waste management system. The central question for the municipality was how much it could improve the environmental performance of the waste management system without fundamentally changing the waste collection system.

5.3.2 The waste collection system and its limitations

The municipality of Aarhus has nearly 300,000 citizens and covers the city of Aarhus and its surrounding areas. The waste management system (modelled for year 2005) had collection of paper, glass and residual waste. The source-separated recyclables were primarily collected in a bring scheme with centrally placed drop-off containers with a density of 1 per 600 citizens, and to a lesser extent at recycling centres with a density of 1 per 60,000 citizens. Additionally, approximately 40% of the source-separated paper was collected in a kerbside collection scheme with bins, mainly from apartment blocks, which in many cases had established small collection points with shared containers. Kerbside collection of residual waste in bins was mandatory for all households. In the city centre, a system with underground containers for paper, glass and residual waste was recently introduced in order to save space above ground. This system was not as property-close as a kerbside collection scheme but closer than a bring scheme.

The existing waste collection system was the foundation of new recycling initiatives, but its organisational and technical structure limited the possibilities. First of all, the legislation require collection of packaging waste made of plastic and metal (the Danish Government, 2004), and, the municipality is obliged to establish collection of paper, glass, metal and plastic by 2015 and reuse or recycle 50% of the recyclable materials (at least paper, glass, metal and plastic) from households by 2020 (European Parliament and Council Directive, 2008). However, collection of plastic and metals was not strongly promoted by the municipality. Therefore, new initiatives should include collection of metal and plastic packaging, whereas bio-waste was not on the agenda. The municipality must also offer collection of all waste fractions to all citizens, even though the technical possibilities and costs would differ among the different types of residential area. In Aarhus, three characteristic types of residential area were identified: suburban single-family houses, suburban apartment blocks and apartment blocks in the city centre. This division was also necessary because the waste composition depended on the dominating type of housing in the area; however, the differences were small. Most of the limitations were related to the configuration of collection schemes. Introducing new collection methods was not an option for several reasons: it would be too costly; replacing bins with bags would deteriorate the working environment etc. Therefore, only modification of existing kerbside collection and bring systems in the suburban areas could be considered. However, the collection points at apartment blocks were a popular solution that should be retained and possibly supplemented with more fractions. The collection points fulfil a need for property-close collection because those living in apartment blocks on average are less mobile than those living in single-family houses. In the city centre, the new underground collection system could not be altered. Paper was the largest recyclable fraction and high sorting efficiency was required if the amount of residual waste was not to increase drastically. Therefore, voluntary or mandatory kerbside collection and collection at recycling centres should be included in future waste collection systems. The predicted amounts of plastic, aluminium and steel were so small that it would be most feasible to collect these as one commingled fraction.

5.3.3 Defining scenarios

Based on the analysis of the waste collection system and its limitations, five scenarios with alternative waste collection systems were formulated. The existing waste collection system served as the Baseline scenario. The titles of the alternative scenarios were: Kerbside collection only (K); Kerbside collection limited to two bins (K-limit); Voluntary participation in kerbside collection (K-volun); Bring scheme with drop-off containers only (B) and Recycling centres only (RC). The waste collection systems described in the scenarios did to some extent deviate from those indicated by the titles due to the aforementioned limitations. An overview of the configuration of collection schemes the scenarios is provided in Table 5, but the reasoning for the configurations is further described in Larsen et al. (VIII).

Table 5. Overview of collection schemes in the scenarios (Larsen et al., VIII)

Collection schemes in the scenarios	Suburban single-family houses	Suburban apartment blocks	Apartment blocks in city centre
Baseline			
Paper#	k+b	k+b	u
Glass	b	b	u
Packaging waste	-	-	-
K			
Paper#	k	k	u
Glass	k	k	u
Packaging waste	k	k	m
K-limit			
Paper#	k	k	u
Glass	b	b, k*	u
Packaging waste	b	b, k*	m
K-volun			
Paper#	k*, b	k*, b	u
Glass	k*, b	k*, b	u
Packaging waste	k*, b	k*, b	m
B			
Paper#	b	b, k*	u
Glass	b	b	u
Packaging waste	b	b	m
RC			
Paper	r, k*	r, k*	u
Glass	r	r	u
Packaging waste	r	r	r

k = kerbside collection
b = bring scheme with drop-off containers
r = recycling centres
u = underground containers in city centre
m = monthly kerbside collection in city centre
# collection schemes for paper including collection at recycling centres.
* voluntary participation in kerbside collection.

5.3.4 Waste amounts, sorting efficiencies and recycling rates

The mass flows in the Baseline scenario were analysed and the sorting efficiencies for paper and glass were calculated from modelled waste composition, which was based on the material fraction dataset from EASEWASTE. Sorting efficiencies in new collection schemes were estimated from the literature survey presented in Section 3.3.1. It was assumed that the order of sorting efficiencies would always be paper > glass > packaging waste, kerbside collection > bring system > recycling centres; and suburban single-family houses > suburban apartment blocks > apartment blocks in the city centre.

The recycling rate, sorting efficiencies at system level and waste amounts in each scenario were calculated, see Table 6. The amounts summed up to 312 kg household waste per capita per year. The recycling rate increased to 31% in Scenario K with intensified kerbside collection, compared with 25% in the Baseline scenario. Using recycling centres as the primary collection method would result in a recycling rate of only 20% in Scenario RC. The theoretical recycling potential, i.e. based on theoretical sorting efficiencies of 100%, was estimated to 40% of the amount of household waste. This meant that 51–78% of the recycling potential was realised in the scenarios, compared with 62% in the Baseline scenario. All scenarios met the national target of 20% recycling of household waste (the Danish Government, 2004) and the EU target of 50% reuse or recycling of dry recyclables in 2020 (European Parliament and Council Directive, 2008), but the Baseline scenario did not have the required collection of metal and plastic.

Table 6. Recycling rates, sorting efficiencies (SE) and waste amounts (A) [kg/capita/year] of the recyclable waste fractions in the five scenarios, compared with the baseline scenario and the theoretical recycling potential (Larsen et al., VIII).

		Potential amount	Baseline scenario	Scenario K	Scenario K-limit	Scenario K-volun	Scenario B	Scenario RC
Recycling rate		40%	25%	31%	30%	27%	26%	20%
Residual waste	A	188.1	234.6	215.5	219.9	228.6	231.7	248.3
Paper waste	A	87.6	63.2	73.5	73.5	64.0	62.2	55.9
	SE	100%	72%	84%	84%	73%	71%	64%
Glass waste	A	27.3	14.2	19.3	16.2	16.8	15.9	6.8
	SE	100%	52%	71%	59%	61%	58%	25%
Packaging waste	A	9.0	0.0	3.7	2.4	2.6	2.2	1.0
	SE	100%	0%	41%	26%	29%	25%	11%

The largest potential amounts were found for paper waste; furthermore it had the highest sorting efficiency in all scenarios. Glass waste was the second largest recyclable and had the second highest sorting efficiency. Finally, packaging waste was the least collected waste fraction, in relative as well as absolute numbers, in all scenarios.

5.3.5 Environmental impact

Figure 6 shows the results of the life cycle assessment for the six environmental impact categories. A negative figure means that the environmental impact in the scenario was lower than in the Baseline scenario. Graphs in the left-side panes show the contributions from collection and transport as one phase and pre-treatment and treatment as one phase. Graphs in the right-side panes show the net change in environmental impact.

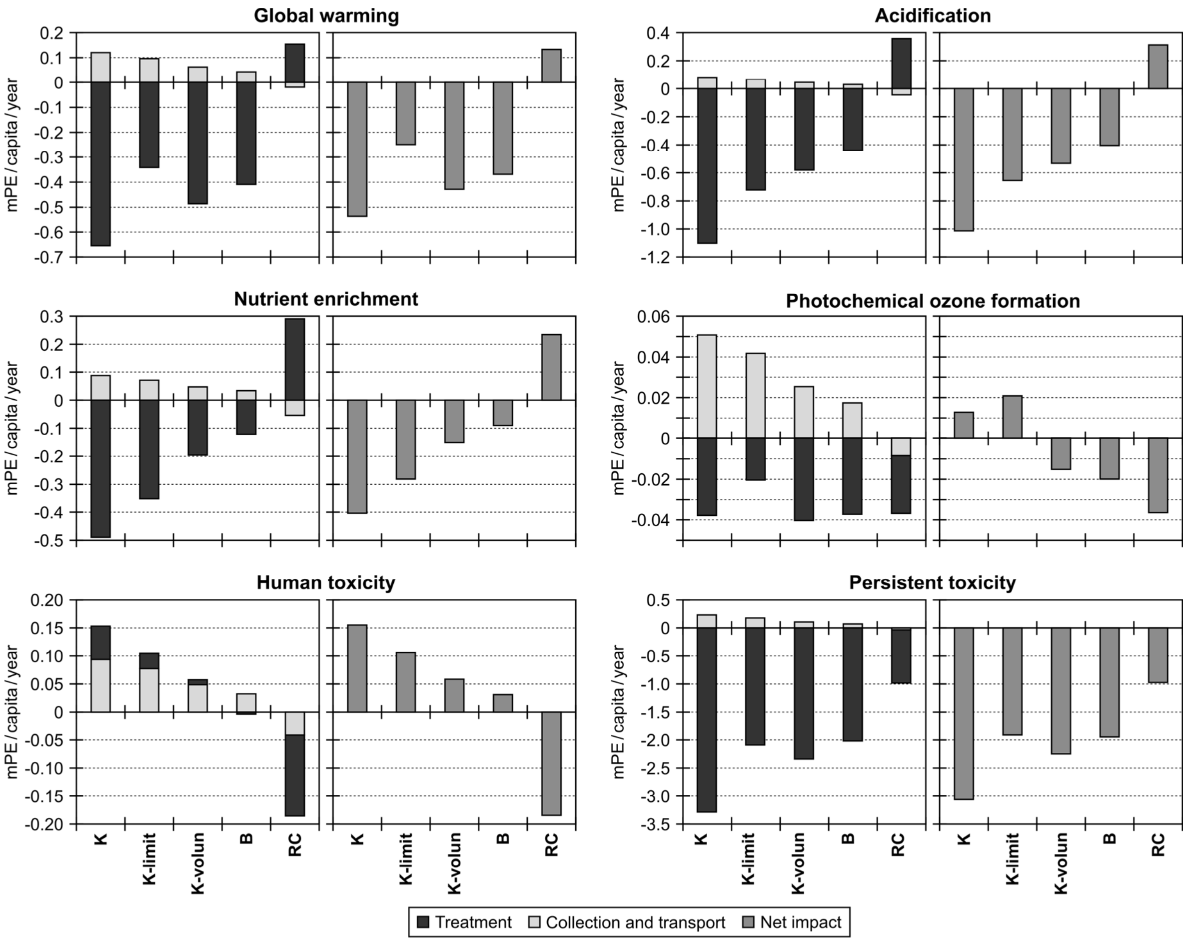

Figure 6. Changes in environmental impact [mPE/capita/year] for the five scenarios compared to the baseline scenario, left-side pane shows the changes in contributions from collection and transport as one phase and treatment as one phase, right-side pane shows the net change in impact (Larsen et al., VIII).

The environmental impact from collection and transport increased in the scenarios K, K-limit, K-volun and B because more waste was separated for recycling and thus transported longer. Less waste was recycled in Scenario RC, which resulted in reduced impact from collection and transport. It was expected, based on the environmental capacities, that the increased impact from collection and transport would not compromise the benefit from increased recycling. That was the case for GW, AC, NE and PT but not for POF and HT. The change in the impact from treatment was relatively low in the latter two impact categories, meaning that the changes in impact from collection and transport influenced the results. Overall, the net impact in the impact categories GW, AC, NE and PT decreased with increasing recycling rate, whereas the opposite tendency was observed for POF and HT, although with some exceptions for Scenario K-limit. Scenario K-volun and Scenario B were in some cases better than Scenario K-limit, even though their recycling rates were lower, because the net impact depended not only on recycling rate but also on the types of material recycled.

The net impact in the POF and HT impact categories could be reduced and perhaps turned to net savings either by improving the recycling technologies or by reducing collection and transport. Some of the suggestions for transport optimisation are use of better engine technology, which would reduce the amount of toxic and ozone-forming exhaust gases; use of more fuel-efficient means of transport; or use of treatment facilities closer to the waste generation area. For instance, changing from the Euro III emission standard, which was used in the modelling, to the Euro IV emission standard would decrease the impact of HT by 30% and the impact of POF by 8%. The impact from collection was of minor importance, but similar solutions could be sought in order to minimise the impact from this phase also. For example, collection routes could be optimised with regard to driven distance and utilisation of payload capacity, or new types of trucks could be considered. Tanskanen & Kaila (2001) demonstrated that introduction of additional source-separated fractions in property-close collection schemes increased the fuel consumption, but this was to some extent mitigated by more fuel-efficient methods such as combined or commingled collection.

The life cycle assessment also included resource consumptions (figures shown in Larsen et al. (VIII)). The results for fossil fuels were ambiguous and could not be used for ranking of the scenarios. Net saving for one type of fossil fuel was counteracted by net increase for another type. However, there was a correlation between higher recycling rate and reduced consumption of crude oil, except in scenario K-limit. Even though more crude oil was used for collection and transport, a larger amount was saved elsewhere in the waste management system due to substitution of virgin material production. All scenarios showed saved metal resources proportional to the sorting efficiency for metal packaging.

5.3.6 Conclusions of the case study

Three collection methods: kerbside collection, bring scheme with drop-off containers and recycling centres, were suggested, but the difference between them was relatively low. The downstream consequences for the transport and treatment phases had more influence on the changes in environmental performance. Thus the most important difference between the waste collection systems was the assumptions made about obtainable sorting efficiencies. Even though the recycling rate could potentially be increased 15 percentage points, it increased only 6 percentage points in the best scenario with kerbside collection. The case study showed that the potential benefits from recycling might be difficult to realise when limitations in a real waste collection system were respected. Conversely, much had already been done as 62% of the recycling potential was realised in the Baseline scenario. The calculation of the waste amounts in each scenario showed that it was necessary to consider collection of all materials at the same time because the potential amounts of packaging waste were relatively small. For instance, the environmental capacity for collection of aluminium was large, but the amount was so small that it would be realistic to collect it only when commingled with other materials.

It was recommended that the municipality should enhance the recycling rate of dry recyclables by establishing new collection schemes for packaging waste and improving the existing collection schemes for paper and glass as recycling resulted in improved environmental performance in several impact categories. Based on the conditions in the scenarios, kerbside collection would provide the highest recycling rate, but bring schemes with drop-off containers would also be a reasonable solution. Collection of recyclables at recycling centres only was not recommendable because the recycling rate assumingly would decrease. However, the municipality should also seek solutions for mitigation of air pollution caused by enhanced collection and transport.

6 Discussion

This section contains a discussion of some issues found to be important for modelling of waste collection systems and environmental assessment of waste management systems. It elaborates on the results presented in the previous sections.

6.1 The importance of waste collection systems

The environmental impact from the collection and pre-treatment phases was relatively low compared with the other phases of the waste management system and thus of minor importance when seen in a life cycle perspective. The study of environmental capacities demonstrated that the impact from collection and pre-treatment did not exceed the environmental capacities for six chosen recyclables. Waste collection was, however, in other ways a key factor for the life cycle assessments. The case study of the municipality of Aarhus showed that waste composition, expected sorting efficiencies and possible collection methods should be analysed carefully in order to make realistic estimates of the waste flows in alternative waste collection systems. Furthermore, the case study revealed some organisational and technical limitations in the waste collection system. When these limitations were respected, only 51–78% of the potential amount of recyclables was collected (Larsen et al., VIII). The improvements that could be made in a well-functioning waste collection system might be limited to a relatively narrow interval. Definition of waste fractions should also take other aspects of waste management into consideration. For instance, collection of very small waste fractions might not be feasible in practice if the collection costs become too high.

The transport and treatment phases were important for the outcome of the environmental assessments, but the data basis was more uncertain for these parts. The case study showed that more knowledge about the disposal routes for recyclables is needed. The collected waste materials were traded on global markets, which made it difficult to track the actual treatment facilities. Transport distances, recycling technologies and substituted materials were therefore modelled based on assumptions about disposal routes and market behaviour of sale of recyclable materials.

As the PhD project considered only recycling compared with incineration of dry recyclables in Denmark, it was not demonstrated if similar conclusions about the relevance of waste collection systems could be drawn for other waste types and treatment technologies. Both recycling and incineration technologies have large potentials for energy savings due to utilisation of the energy content in the waste. Collection, pre-treatment and transport would assumingly be more important for treatment technologies with a low energy utilisation rate, such as composting and landfilling.

6.2 Break-even distances

Break-even distances for transport of recyclables, where the environmental impact from recycling and incineration was of equal size, were calculated in the study of environmental capacities (Merrild et al., IV). The results showed that dry recyclables in general can be transported over long distances before the benefit of recycling is undermined. Recycling was in this case compared with incineration with energy recovery. This conclusion applied to the materials aluminium, steel, glass and paper, but exceptions existed for high-calorific materials, such as cardboard and plastics, according to the results presented in Section 5.1.

The relevance of transport has been assessed in a few other studies. Beigl & Salhofer (2004) compared recycling of source-separated waste with mechanical-biological-treatment of mixed waste. They concluded that the favoured treatment option was sensitive to the modelling of transport for source-separated metal packaging (in the GW impact category) and glass (in the GW and AC impact categories). This is contrary to the conclusions drawn by Merrild et al. (IV), who found that aluminium, steel and glass can be transported very long distances for the purpose of recycling, and that the NE and POF impact categories would be the limiting factors. Beigl & Salhofer (2004) also concluded that modelling of transport had no or low relevance for the benefit of recycling of paper and plastic packaging. To some extent this is in line with Merrild et al. (IV), but the conclusions for plastic in that study were sensitive to the energy recovery rate at the incinerator.

Salhofer et al. (2007) compared recycling of different waste fractions with landfilling. They estimated the breakeven distances for recycling of paper and plastic films to be several thousand kilometres; the shortest distance was 4400 km for plastic films in the HT impact category. These long distances were obtained because the energy content of the materials was not utilised by landfilling. The breakeven distance for a lightweight material, such as expanded polystyrene (EPS), was only 288 km in the NE category. The study concluded that introduction of more complex collection schemes, for example kerbside collection, would not reduce the environmental benefit of recycling. These findings are in line with those from Merrild et al. (IV).

Comparison with these two studies supports the conclusions that dry recyclables in practice can be transported long distances without compromising the benefits of recycling. However, collection and transport of lightweight materials, i.e. materials with low bulk densities, would be relevant to study more thoroughly. Furthermore, the limiting impact categories varied among the studies. Estimation of break-even distances should then include as many impact categories as possible because focus on only one impact category could lead to wrong conclusions.

6.3 Linearity in life cycle assessments

The life cycle assessments were based on the assumption of a linear relationship between waste quantities and environmental burden. It was assumed that the fuel consumption factor for collection was independent of the sorting efficiency providing the collection scheme was not significantly modified. For example, it was assumed that collection would be performed only when all waste bins were nearly full in order to sustain rational fuel consumption; i.e. the collection frequency would have to be adjusted according to the sorting efficiency. Edwards & Schelling (1999) showed that the assumption held for sorting efficiencies between 5%–90% in a bring scheme for glass waste. The interval shrunk to approximately 20%–80% when consumer transport to the bring site and production of bins were included. Their results indicated that linearity might be a reasonable assumption over a large interval.

Ekvall et al. (2007) pointed out another dilemma. The range of probable sorting efficiencies for a certain type of collection scheme is not known, and very high sorting efficiencies can possibly only be achieved through collection schemes with a high environmental burden. The case study of the municipality of Aarhus took into account that the sorting efficiencies would vary among different types of collection schemes, but a range for each type could not be established (Larsen et al., VIII). More knowledge about the correlation between types of collection schemes and achievable sorting efficiencies would improve assessment of waste collection systems. Notably, many life cycle assessments found in literature have not considered the sorting efficiencies in the compared collection and treatment alternatives.

Intervals for linearity between input and output should be estimated not only for collection but for all technologies in a life cycle assessment. For instance, a treatment technology might be sensitive to changes in the composition of the incoming waste. Such information is, however, rarely available in databases. In the case study, the changes in lower heating value of the residual waste caused by source-separation of more recyclables were found not to be critical for the functioning of the incinerator. In contrast, contamination in terms of unwanted materials in the recyclable waste fraction was not accounted for in the case study due to lack of data.

6.4 Impact categories and interpretation

The life cycle assessments in this project focused mainly on the energy-related impact categories, but the significance of collection and transport in other impact categories should be assessed as well. The case study of the municipality of Aarhus showed that collection and transport contributed significantly to air pollution, expressed by the impact categories POF and HT (Larsen et al., VIII). Emissions of volatile organic compounds (VOC) and polycyclic aromatic hydrocarbons (PAH) from production and combustion of fuels were the main contributors. Characterisation of these and other groups of substances is more uncertain than characterisation of a single substance, which, in general, makes the results for POF, HT and PT more uncertain than the results for GW, AC and NE. This discrepancy between impact categories is difficult to deal with and could lead decision makers to put the most weight on the most certain results. Furthermore, the magnitude of the normalised results for the POF and HT impact categories was smaller than in the other impact categories in the case study and thereby easier to neglect. In this way, the importance of collection and transport could easily be underestimated.

The contributions from the collection and transport phases to resource consumption were insignificant. Only crude oil used for fuel production gave a noticeable contribution, but this was offset by larger savings from the utilisation of waste in the case study. Even though resource consumption in the waste collection system was insignificant, the waste management system's importance for resource recovery should be included in life cycle assessments. The results for energy-related resources were ambiguous, but there were some clear benefits in terms of savings of metals and minerals, e.g. approximately 735 kg of raw materials was recovered per tonne of bulky waste treated (Larsen & Christensen, VI). However, comparing consumptions of fossil fuels, metals and renewable resources with each other was difficult because properties such as energy content, accessibility, substitutability, scarcity and regeneration rate could be used as assessment criteria. Comparing resource consumptions with environmental impact categories was even more difficult because the applied life cycle assessment method did not offer guidelines for comparison and weighting of the different types of categories. Improving the method for assessment of resource consumptions would make life cycle assessments a stronger tool for environmental assessments of waste management systems.

Another issue regarding interpretation was that no consistent ranking could be made of the scenarios in the case study (Larsen et al., VIII) because the ranking varied between the twelve environmental impact categories and resource consumption. Furthermore, no scenario could be implemented without trade-offs because they all caused an increased impact in at least one category. Recommendations to the municipality were then made based on some clear tendencies observed in the results. It is important to keep in mind that life cycle assessment is a decision-support tool that does not always provide unambiguous answers to the examined issues.

Despite these shortcomings of the method, a life cycle assessment condenses a very large amount of data to a manageable number of indicators in terms of impact categories; nevertheless, it leaves decision-makers with many possibilities regarding interpretation of the results.

6.5 Environmental impact from capital goods

Even though the use of energy and materials at the operational level was the central issue in the life cycle assessment of waste collection, some final comments are made on the significance of the impact from capital goods in the waste management system.

So far only the impact related to energy consumption in the collection phase has been considered; however, production, maintenance and disposal of capital goods, such as bins, containers, collection trucks and road infrastructure, could also be included in the collection phase. Hartling (2008) estimated the environmental impact from production of a 240-litre HDPE bin for residual waste and a 2.5 m^3 glass fibre container for glass waste used for waste collection for ten years. The environmental impact in the energy-related impact categories was in the order of 0.05–0.30 mPE/tonne of waste. The impact from production and use of a collection truck for ten years was in the order of 0.02–0.10 mPE/tonne of waste under the assumption that 90% of the steel was recycled. According to Hartling (2008), construction of the waste collection system contributed with 3–14% of the total impact in the energy-related impact categories. The impact in the toxic impact categories was in the order of 10–100 times larger but was very uncertain. The contribution from construction of the waste collection system here varied from 1% to 90% of the total impact.

Other studies have investigated the importance of capital goods for transport services. Frischknecht et al. (2007) concluded that production of capital goods in terms of vehicles and road infrastructure contributed substantially (10–90%) to the impact in the energy-related and toxic impact categories and in energy demand, while it had a major contribution (>90%) in land use and mineral resources. Studies that considered specific air emissions, such as CO_2, NO_X, SO_2, CO, NMHC and particulate matter, support these findings (Facanha & Hovarth, 2007; Spielmann & Scholz, 2005; Eriksson et al., 1996). The impact from construction of waste treatment facilities is poorly studied. The findings of Hartling (2008) and Frischknecht et al. (2007) indicate that the impact is probably less than the impact from capital goods in the collection and transport phases.

Based on these studies it seems relevant to examine the importance of capital goods in waste management more thoroughly, especially because it seems to contribute significantly in several impact categories. For waste collection systems, the use of collection equipment could be an important factor. Construction of new facilities and demolition of old ones are likely consequences of new treatment options and should be accounted for. However, the net impact might become relatively low because much of the construction and demolition waste is recyclable, as indicated in the abovementioned studies.

6.6 Other aspects of waste collection

When performing a life cycle assessment of alternative waste collection systems, it should be kept in mind that decision makers, for example waste planners and politicians, are likely to emphasise aspects other than the environmental burden of waste management. It is therefore necessary to consider also the effects on working environment, economy, service level etc. in the scenario descriptions. Other types of decision-support assessment could supplement the life cycle assessment.

The case study of the municipality of Aarhus included an economic assessment of the municipal expenses for waste collection and treatment (Larsen et al., VIII). This assessment showed that collection of recyclables was not more expensive than collection of residual waste, but the costs for treatment of recyclables were considerably lower than the cost for incineration. Taxation on incineration made it the most expensive treatment option (527 DKK/tonne), whereas the municipality generated revenue from the sale of most of the recyclable materials (up to 1223 DKK/tonne). Thus there was an economic incentive to reduce the amount of waste going to incineration. However, the prices on the recycling market depend on the demand for raw materials and may vary a lot. The municipal expenses in the waste collection systems examined were mainly correlated to the achieved recycling rates and not the collection methods, similar to that concluded in the environmental assessment.

In such a case where recycling to a great extent is preferable to incineration with regard to environmental and economic performance, the decision makers would obviously emphasise other aspects of waste collection. The municipality should then seek to encourage citizens to participate in source-separation of recyclables, e.g. through providing sufficient information and keeping a high service level in order to achieve a high recycling rate. Other social aspects, such as job generation and working environment, and environmental impact in terms of noise and traffic would also be relevant to include in the assessment.

Applying an approach with assessment of multiple aspects creates a wide basis for decision-making and clarifies advantages and disadvantages of different solutions, but it also requires that decision-makers have the ability to assess the relative importance of each aspect and are willing to accept trade-offs between different aspects. Otherwise, the effort of making decision-supporting assessments might be useless.

Despite the development of some integrated assessment models (den Boer et al., 2005; Klang et al. 2008), multi-criteria assessments of waste management are not widely used in research contexts and probably not in political contexts either. Application of multi-criteria assessment methods in waste management should be researched more in order to provide robust and consistent tools for decision-makers.

7 Conclusions

The aim of this PhD project was to study how important waste collection was for the environmental performance of the overall waste management system. Collection of recyclables from household waste was thoroughly examined with focus on how much waste collection systems could potentially be improved. A central question was whether extra energy needed for collection, pre-treatment and transport of recyclables could compromise the benefits of recycling.

A consistent way of modelling waste collection systems in life cycle assessments was suggested. Collection schemes should be characterised by the following parameters: waste type/fraction, equipment for temporary storage, collection vehicle, collection method and type of residential area, because these were determining for the energy and material flows in the waste collection system. Defining the waste composition in terms of material fractions, amounts and chemical composition and describing the degree of source-separation by so-called ‘sorting efficiencies’ were necessary input data for modelling of mass flows through the waste management systems. A literature survey showed that the sorting efficiencies varied considerably in real cases; the reported figures ranged from 4% to 96%. Property-close collection was likely to yield the highest sorting efficiency but not significantly. There was a tendency towards higher sorting efficiencies for paper and glass than for cardboard, plastics and metals. The term ‘recycling rate’ was used to express the overall rate of source-separation.

A thorough study of diesel consumption and its environmental impact showed that the following three parameters all were important for the resulting environmental impact from collection: the fuel consumption in the collection area, the distance to the pre-treatment plant and the truck engine technology. Thus both optimisation of collection routes, planning of waste facilities and legislative requirements were important instruments in relation to reduction of environmental impact from collection. Fuel consumption factors for driving in the collection area were estimated in a study performed in two municipalities. The diesel consumption ranged from 1.4 to 10.1 litres/tonne of waste and, in general, increased with decreasing population or waste density in the catchment area. The study also showed that implementation of successive European exhaust emission standards had significantly reduced the environmental impact in terms of acidification, nutrient enrichment and photochemical ozone formation.

The concept of environmental capacity was introduced to demonstrate whether the extra energy needed for collection, pre-treatment and transport of recyclables could undermine the potential benefit of recycling compared with incineration with energy recovery. Additional energy consumption for collection and pre-treatment was far from exceeding the environmental capacity for recycling of six materials from household waste (paper, cardboard, glass, plastic, steel and aluminium). This meant that new collection schemes for recyclables and simple pre-treatment technologies could be implemented without compromising the benefits of recycling. In some cases, transport was a limiting factor which was illustrated by calculation of break-even distances for transport of waste; however, the calculated distances were typically more than a thousand kilometres. Two clear tendencies were found: transport of aluminium did not exceed the environmental capacity for any of the five means of transport examined, and transport in a large bulk carrier, which had the lowest fuel consumption factor, did not exceed the environmental capacity for any of the materials. In practice, the materials paper, glass, steel and aluminium could be transported several thousand kilometres to recycling facilities without compromising the benefit of recycling, providing appropriate means of transport were used. In some situations, incineration would be a better solution for cardboard and plastic, especially if the energy recovery rate at the incinerator was high. In cases of doubt, waste management planners should take the efficiency of energy recovery from incineration, the transport distances and the means of transport into consideration.

The potential quantities of recyclables should also be taken into account, which was shown by calculating the environmental capacities for six recyclable fractions in Danish household waste. Paper was potentially the most beneficial material to sort out for recycling. It was followed by aluminium, cardboard and glass, while the environmental capacities for plastic and steel were even lower. Even though the environmental capacity per tonne of paper was relatively low, the actual amount in household waste was large. Aluminium, the second most beneficial material, had the highest environmental capacity per tonne, but the amount found in household waste was low. The waste amounts were important because it probably would not be economically feasible to initiate a collection scheme for one of the small fractions only.

The recycling rate in the case study of a municipal waste collection system varied from 20% to 31% in the outlined scenarios compared with 25% in the existing system when limitations in the organisational and technical structure were respected. This showed that improvements of a well-functioning waste collection system might be limited to a relatively narrow interval. Enhanced recycling resulted in improved environmental performance in several impact categories, but increased collection and transport worsened air pollution in terms of photochemical ozone formation and human toxicity.

It was recommended that the municipality should enhance the recycling rate of dry recyclables by establishing new collection schemes for packaging waste and improving the existing collection schemes for paper and glass. Based on the conditions in the scenarios, kerbside collection would provide the highest recycling rate, but bring schemes with drop-off containers would also be a reasonable solution. Collection of recyclables at recycling centres only was not recommendable because the recycling rate assumingly would decrease. However, the municipality should also seek solutions for mitigation of air pollution caused by enhanced collection and transport.

In conclusion, defining the waste collection system was a key factor for the life cycle assessments of waste management systems because describing parameters, such as collection schemes, waste composition and sorting efficiencies, influenced the waste flows. Thus waste collection had a significant influence on the environmental impact of the waste management system, even though its own environmental impact was of minor importance in a life cycle perspective.

8 Further research

This PhD project dealt with life cycle assessment of waste management systems with focus on Danish waste collection systems for recyclable materials. Some shortcomings with regard to data and method were identified, and further research of these is recommended.

The first type of shortcoming concerned data used for modelling of waste management systems. The modelling approach used in this project could be applied to various other types of waste, but better databases are needed. For instance, more datasets for fuel consumption and sorting efficiencies for different types of collection scheme would make it easier to establish new modelling scenarios. A material fraction dataset for bulky waste, especially the WEEE fractions, is also needed in order to perform better environmental assessments of this waste type. This is a relevant research area because relatively little is known about the content of potentially harmful substances in bulky waste, the potential for resource recovery and suitable treatment options. Finally, the importance of including capital goods in life cycle assessments of waste management systems should be researched because these are often excluded.

Another relevant research area is estimation of break-even distances where the benefit of recycling is undermined because of the impact from long-distance transport. Export of six recyclable materials was examined, but the concept could be applied to other waste fractions as well, e.g. lightweight materials and recyclable materials from bulky waste. Furthermore, there is a need for more knowledge about where and how exported waste is treated because modelling of recycling was based on assumptions about likely ways of disposal. This would include information about transport distances, means of transport used, recycling technologies, substituted products and other market responses.

The applied life cycle assessment method was deficient in several ways and could be developed to be more suited for environmental assessments of waste management systems. Assessment of resource consumption is highly relevant in waste management, but the results were difficult to compare and interpret because the resources included had very different qualities and applications. Characterisation of toxic substances and substance groups was sometimes uncertain, which made the results of these less reliable than those of other impact categories. Resolving these issues will make life cycle assessment a more reliable tool for decision-support.

Finally, environmental assessments could be supplemented with assessments of economic and social aspects of waste management in order to create a wider basis for decision-support. Methods for multi-criteria assessments exist, but their application in waste management has not been thoroughly studied. This should be researched more in order to provide robust and consistent tools for decision-makers

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10 Appendices

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ISBN 978-87-91855-72-6