ENVIRONMENTAL SYSTEMS ANALYSIS OF WASTE MANAGEMENT
- Experiences from Applications of the ORWARE Model

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DOCTORAL THESIS

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ABSTRACT

Waste management has gone through a history of shifting problems, demands, and strategies over the years. In contrast to the long prevailing view that the problem could be solved by hiding or moving it, waste is now viewed as a problem ranging from local to global concern, and as being an integral part of several sectors in society. Decisive for this view has been society's increasing complexity and thus the increasing complexity of waste, together with a general development of environmental consciousness, moving from local focus on point emission sources, to regional and global issues of more complex nature.

This thesis is about the development and application ORWARE; a model for computer aided environmental systems analysis of municipal waste management. Its origin is the hypothesis that widened perspectives are needed in waste management decision-making to avoid severe sub-optimisation of environmental performance. With a strong foundation in life cycle assessment (LCA), ORWARE aims to cover the environmental impacts over the entire life cycle of waste management. It also performs substance flow analysis (SFA) calculations at a rather detailed level of the system.

Applying ORWARE has confirmed the importance of applying systems perspective and of taking into account site specific differences in analysis and planning of waste management, rather than relying on overly simplified solutions. Some findings can be generalised and used as guidelines to reduce environmental impact of waste management. Recovery of material and energy resources from waste generally leads to net reductions in energy use and environmental impact, because of the savings this brings about in other sectors. Waste treatment with low rate of energy and materials recovery should therefore be avoided. The exact choice of technology however depends on what products can be recovered and how they are used.

Despite the complexity of the model and a certain degree of user unfriendliness, involved stakeholders have expressed the value of participating in ORWARE case studies. It provides improved decision-basis, but also wider understanding of the complexity of waste management and of environmental issues in general.

The thesis also contains a first suggestion of a framework to handle uncertainty in ORWARE, based on a review of types of uncertainty in LCA and tools to handle it.

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SVENSK SAMMANFATTNING

Avfallshanteringens problem, behov och strategier har skiftat genom tiderna. Numera har man lämnat det gamla synsättet att det räcker att gömma eller flytta problemet för att bli av med det. Istället betraktas avfall som ett problem av både lokal och global betydelse och som en integrerad del av flera olika sektorer i samhället. Avgörande för den här synen på avfall har varit att samhället och därmed dess avfall blivit allt mer komplext, samt att det allmänna miljömedvetandet vidgats fån lokala frågor till regionala och globala frågor av mer sammansatt slag.

Denna avhandling beskriver utvecklingen och tillämpningen av ORWARE, en modell för datorstödd miljösystemanalys av avfallshantering. Modellen har sitt ursprung i hypotesen att avfallshantering bör styras av ett vidare synsätt än idag för att finna lösningar med liten total miljöpåverkan. ORWARE är till stor del baserad på livscykelanalys (LCA), och täcker därmed miljöeffekter från avfallshanteringens hela livscykel. Dessutom gör modellen en relativt detaljerad substansflödesanalys (SFA), d.v.s. beräkning av flöden av ämnen genom systemet.

Tillämpning av ORWARE har visat på vikten av systemperspektiv och av att ta hänsyn till platsspecifika förhållanden vid analys och planering av avfallshantering, istället för att förlita sig på överdrivet förenklade lösningar. Vissa resultat är så pass generella att de kan användas som vägledning för att minska miljöpåverkan från avfallshantering. Återvinning av material och energi leder i allmänhet till totalt sett minskad miljöpåverkan och energianvändning, genom att det ger resursbesparingar i andra sektorer i samhället. Avfallsbehandling med låg material- och energiåtervinning bör därför undvikas. Exakt vilken behandlingsmetod som är bäst beror på vilka produkter som kan återvinnas och hur de används.

Trots en komplex modell och ett visst mått av användarovänlighet, vittnar de som deltagit i studier med ORWARE om dess värde. Modellen bidrar till att förbättra beslutsunderlaget i avfallsplanering och ger vidgad förståelse för hur komplex avfallshantering och miljöfrågan i allmänhet är.

Avhandlingen innehåller också ett utkast till ramverk för att hantera osäkerhet i ORWARE, som baseras en sammanställning av olika typer av osäkerhet i LCA och metoder för att hantera dessa.

ACKNOWLEDGEMENTS

To me, life often appears as being shaped by a series of coincidences. Now I have completed a doctoral thesis – just by mere chance! I don't feel I planned this, and didn't know as I started where it would lead. But the truth probably is that I know perfectly well what I want, and when the opportunity appears, I make sure to grab it. So that in the end, it just appears as a long row of happy coincidences! But of course I couldn't have grabbed all lucky opportunities that finally brought me here, were it not for a whole bunch of people who helped me along the way in one way or another; family, friends, and colleagues. Thanks to all of you, but in this case especially those who have been important to me for getting along in my research. Thanks to:

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Martin. I wouldn't have done this without him. And Sackarias-i-magen, who although we still haven't met, has already claimed my love and will keep me occupied with worldly matters when I get my degree.

LIST OF APPENDED PAPERS

I. Björklund, A. and Bjuggren, C. (1998) Waste Modelling Using Substance Flow Analysis and Life Cycle Assessment. Paper 98-A431 in proceedings of the *Air & Waste Management Association's Annual Meeting*, June 14-18, 1998, San Diego, CA, USA.

Björklund performed the review of waste management models. Descriptions and discussions about methodology are by Björklund and Bjuggren, who were both responsible for writing the paper.

II. Dalemo, M., Sonesson, U., Björklund, A., Mingarini, K., Frostell, B., Jönsson, H., Nybrant, T., Sundqvist, J.-O., and Thyselius, L. (1997) ORWARE - A Simulation Model for Organic Waste Handling Systems, Part 1: Model Description. *Resources, Conservation and Recycling*, 21, 17-37.

The model concept was developed by Dalemo, Sonesson, Mingarini, Frostell, Nybrant, Sundqvist and Thyselius. Dalemo, Sonesson, Björklund, Mingarini, and Jönsson performed model development. Dalemo, Sonesson, and Björklund were responsible for methodological discussions and writing the paper.

III. Björklund, A., Bjuggren, C., Dalemo, M., and Sonesson, U. (2000) Planning Biodegradable Waste Management in Stockholm. *Journal of Industrial Ecology*, 3(4), 43-58.

Björklund, Bjuggren, Dalemo, and Sonesson designed and performed the case study. Björklund was responsible for writing the paper.

IV. Björklund, A., Dalemo, M., and Sonesson, U. (1999) Evaluating a Municipal Waste Management Plan Using ORWARE. *Journal of Cleaner Production*, 7(4), 271-280.

Björklund, Dalemo, and Sonesson designed and performed the case study. Björklund was responsible for writing the paper.

V. Björklund, A., Jensen, M., and Keoleian, G. (2000) Hydrogen as a Transportation Fuel Produced from Thermal Gasification of Municipal Solid Waste: An Examination of Two Integrated Technologies. Submitted to *International Journal of Hydrogen Energy*.

Björklund, Jensen, and Keoleian designed the study. Jensen was responsible for modelling the transportation sector. Björklund was responsible for waste management modelling and main responsible for writing the paper.

VI. Björklund, A. (2000) Survey of Approaches to Improve Reliability in LCA. Submitted to *International Journal of LCA*.

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1 INTRODUCTION

Waste is by no means a new phenomenon; it has always been a consequence of human life. However, early humans who lead a nomadic life in very sparsely populated regions, must hardly have worried about the few remains left when moving on to another site, although there is actually proof in the Bible of sanitary regulations among early nomads (Deuteronomy 23:10-13). When people settled, getting rid of waste and keeping good hygiene required some kind of waste handling. In the pre-industrial societies wastes mainly consisted of food wastes, human excreta and animal manure. Such wastes were naturally recycled to fertilise farmland. To the limited extent that products such as tools and clothing ended up as waste, these were mainly produced of natural, degradable material. Real problems with waste management appeared when people gathered in larger towns and cities. Without organised solutions to transport waste from the cities, the inhabitants were expected to handle their own waste. It was either dug down in holes in the back yards or simply dumped in the streets or rivers. It is easy to imagine the odour, how it attracted pests, contaminated the ground water and surface water, and spread diseases.

As cities grew, waste gradually became a more and more pressing issue. Common regulations for waste handling in towns and cities were introduced in Sweden in 1869, mainly out of fear for epidemics. Human excreta were composted and sold as fertiliser with animal manure, and food wastes were used as swine feed. This was a way to keep down the costs of waste management, but it was also considered important to return nutrients to agriculture. The industrial revolution brought about cheaper products, which were consequently disposed of more, but materials such as paper and rags were collected and recycled. The remainder was used as filling material or burned.

In the beginning of the 20^{th} century the WC was introduced in Swedish cities. At the same time waste amounts grew and its composition changed so that it was no longer easy to reuse or recycle. With this, the mainly cyclic waste management practices essentially ceased, and were replaced by the main objective to get rid of the waste. This was done by dumping or open air burning at largely uncontrolled sites. Gradually waste management practices were improved to reduce hazardous emissions. Sanitary landfills and waste incinerators with air pollution control and energy recovery were built. The oil crises in the 1970s brought about awareness of the limits of energy and material resources, resulting in attempts to (re)introduce large scale recycling, at that time however with limited success. (Andréasson 1994, SOU 1994, Berg 1989).

Being very visible, waste handling has long since attracted a lot of attention and efforts. The awareness of waste as an environmental problem has gone through a development much similar to environmental consciousness in general, moving from local focus on point emission sources, to regional and global issues of much more complex nature. During the last decade or two, strategies have slowly shifted from focusing on waste as an isolated problem, to being integrated in several different sectors of society. One sign of this is that waste is not treated as a separate issue in the 15 Swedish environmental goals recently outlined by the government, but is integrated as part of other goals. The UN Agenda 21 document declares that the General Assembly has pointed out environmentally sound management of wastes as being of major concern in maintaining the quality of the Earth's environment and in achieving environmentally sound and sustainable development. The official standing of the European Union (EU) is expressed by the guiding principles in the so-called waste hierarchy, which prioritises waste prevention (EU 1999a):

1. Prevention of waste.
2. Recycling and reuse.
3. Energy Recovery.
4. Final disposal.

In Swedish legislation, this is reflected in the Environmental Code prescribing extended producer responsibility for products and municipal waste plans for reduction of waste amounts and waste hazardousness (SFS 1998). However, the true situation is that in spite of the focus on waste minimisation, waste generation is increasing in most parts of the world. The average European generates about 350 kg of municipal waste every year. Total waste generation is about 10 times higher (EU 1999b). Swedish municipal waste generation is somewhat higher than the EU average (RVF 2000). Between 1990 and 1995, municipal waste generation in the EU grew by about 11 %, and forecasts point at continued increase in the future (EU 1999a). Swedish municipal waste generation is however slowly decreasing (RVF 2000).

Despite ambitions and efforts to prevent and minimise waste, the waste problem will not be eliminated within the foreseeable future. All types of waste management inevitably cause environmental impact, and although the waste hierarchy may be a good guiding principle in reducing this impact, it is not clear that applying the hierarchy will always lead to the best solution. Given the complexity of the problem, with variations in waste amounts and composition, different possibilities to recover resources from waste, different waste treatment options, different decision criteria (e.g. cost, energy, environment, convenience, social acceptance), and connections to several other sectors in society, the design of waste management systems must involve different solutions in different places. But due to this complexity, waste management alternatives become difficult to survey and prioritise.

Having acknowledged this difficulty, the EU waste management strategy stresses that there is no blueprint that can be applied in every situationthe need for new and better waste management tools. Such tools should lead to reduced costs and environmental impact of waste management, and help to set the path for development of better waste management strategies in the future. To achieve this, it appears essential to use a systems perspective. That is, develop tools that systematise information about waste flows, treatment options and impacts, and include not only impacts directly caused by waste management, but also indirect effects.

This type of problem is well suited for computer modelling, as it largely concerns a technical system, the components of which can be described mathematically. Computerized waste planning models have existed for over 30 years, but have been of more limited scope than what is now acknowledged as the concerns of waste management. In recent years, a number of waste management models have appeared that are based on, or incorporate important aspects of, life cycle assessment (LCA), which brings systems perspectives into environmental assessments. One such model is ORWARE, which is presented and discussed in this thesis.

1.1 Aim and scope of my research

The general and long-term goals of my research have been to improve understanding of the system-wide impacts of waste management on the environment, to prepare data for decision-making about waste management in certain regions, and to promote systems thinking in general in waste management planning. My research has its origin in the hypothesis that widened perspectives are needed in waste management decision-making to avoid severe sub-optimisation of environmental performance, and that this can be achieved through computer aided environmental systems analysis. This hypothesis has been tested by developing and applying one such model.

In practice, this has involved development and application of ORWARE, a computerised model for environmental systems analysis of municipal waste management. My research was performed from 1996 to 2000 within the scope of a project that has mainly been funded by the Swedish Waste Research Council (AFN) at the Swedish Environmental Protection Agency and by the Swedish Energy Administration (STEM). Since 1993, the project has engaged seven PhD students and several senior researchers.

I joined the project in a phase when much of the basic model development was completed and ORWARE was ready to use on a larger scale. Therefore, my research has been characterised by model application and methodology development. To the extent that I have worked with model development, focus has been on the landfill, incineration, and thermal gasification sub-models. Other participants of the project have developed the other sub-models.

1.2 Aim and scope of this thesis

The aim of my thesis is to prove, to the degree that such things can be proved, the usefulness of ORWARE in improving understanding of the system-wide environmental impacts of waste management, preparing data for decision-making about waste management, and promoting systems thinking in general in waste management planning. This is done by presenting and discussing different applications of ORWARE, user experiences, limitations of the model, and reliability. Summaries of different areas of my research form the basis for this. Through chapters 2 to 5, this summary:

- defines environmental systems analysis in general and in the context of this thesis,
- describes environmental systems analysis of waste management in general and ORWARE in particular,
- summarises three case studies with different aims, and
- describes reliability issues in life cycle assessment.

Details about sub-model development are not covered. This was thoroughly documented in my Licentiate thesis (Björklund 1998).

This thesis is mainly a description and discussion about ORWARE, its methodological context, modelling issues, applications, reliability, and usefulness. This is of interest to others working with ORWARE, but should also be of interest to the growing number of researchers working with waste management models and similar environmental systems analysis tools. Although partly theoretical, I also wish that this thesis will find its way to and be read by non-researchers interested in waste management.

1.3 Outline of this thesis

Chapter 2 "Methods and concepts" introduces some fundamental concepts of the ORWARE model. The meaning of environmental systems analysis, life cycle assessment (LCA), and substance flow analysis (SFA) is explained.

Chapter 3 "Systems analysis of waste management" gives an overview of waste management models based on Paper I, particularly those with significant similarities to ORWARE. Some insight is given into problematic methodological aspects that may be encountered in this type of waste management modelling. The design and methodology of the ORWARE model are presented, based on Paper II, but also complemented with more recent material.

Chapter 4 "Summary of case studies" briefly summarises the scope, objectives, and main results of three case studies with ORWARE (Papers III, IV, and V). This is not primarily to describe specific quantitative results but to illustrate different possible model applications.

Chapter 5 "Reliability" is based on a survey of tools for handling uncertainty in LCA in general (Paper VI). Because of the ORWARE model's close resemblance to LCA, this is of relevance for interpretation of model results and for further developments of the model.

The thesis is closed by **chapter 6 "Discussion and conclusions"**, in which reliability, different applications, and user experiences of ORWARE are discussed, and concluding comments are made about the usefulness of systems analysis of waste management.

A number of terms that are used throughout the thesis are explained in the **"Glossary"**.

"Other ORWARE publications" than those appended to the thesis are listed at the end.

2 METHODS AND CONCEPTS

This chapter introduces four concepts of fundamental significance to the ORWARE model: environmental systems analysis, life cycle assessment (LCA), substance flow analysis (SFA), and system boundaries. Environmental systems analysis is a collective term encompassing a range of tools that have been developed based on a systems oriented approach to addressing environmental problems. LCA and SFA are two such tools that are applied in the ORWARE model. They have both been classified as tools for integrated chain analysis (Udo de Haes et al. 1997), which means that they analyse chains of processes, including aspects from both the society and the environment. System boundaries are crucial in both LCA and SFA, and are described in a separate section.

2.1 Environmental systems analysis

The term "environmental systems analysis" in the thesis title indicates the context of my research. A *system* is a set of related components, sub-systems, that interact with each other in some way. The properties of a system are defined by the whole of the sub-systems, their characteristics, and the relationships between them. Anything in society or nature may be described as a system consisting of sub-systems, and itself acting as a sub-system in a larger context, forming a sort of hierarchical structure (Figure 1). For instance, a landfill consists of technical equipment and the landfilled material that is degraded by biological, chemical and physical processes; the sub-systems of the landfill system. On a higher level, the landfill is linked to incineration, transportation, electricity production etc., and thereby acts as a sub-system of the waste management system. Studies of systems should focus on the hierarchical level that is most appropriate for the purpose of the study (Gustavsson et al. 1995).

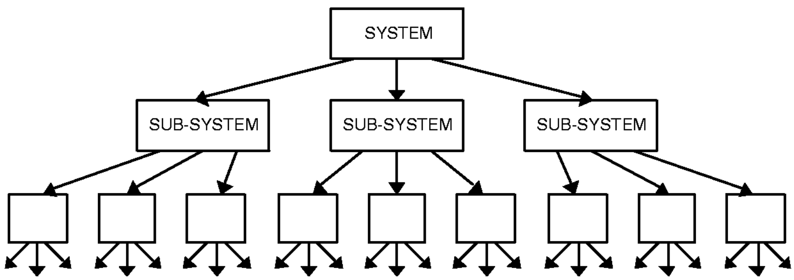

Figure 1 *A system can be viewed as a hierarchical structure of more and more detailed sub-systems. Based on Gustavsson et al. 1995.*

Systems analysis is a systematic investigation of a real or planned system, its components, relations between components, and connections to other systems. The term systems analysis is often encountered in the context of commercial software programming, but is also used by enfineers as a synonym to systems engineering of technical systems, and it is used by ecologists, social scientists and others. Obviously, it is not a specific methodology, but can mean very different things in different contexts. Despite significant differences, these applications have in common the focus on complex systems rather than its isolated components. Characteristic is also that the system components and their interlinkages are represented in some kind of model, a simplified abstraction of the system. Often, but not necessarily, a mathematical computer model of the system is constructed. A basic introduction to systems, models and modelling can be found in for example Gustavsson et al. (1995).

In the context of this thesis, systems analysis refers to a process the aim of which is to help in decision-making, planning, and policy making about complex technical, natural, and social systems. By understanding the behaviour of the sub-systems and the linkages between them, the effects of new decisions can be assessed, and severe sub-optimisations can be avoided. This understanding of the meaning of systems analysis is wider than in many other fields, and corresponds to that brought forward by the International Institute of Applied Systems Analysis (IIASA) in Austria. The theories and methods developed at IIASA are described in Handbook of Systems Analysis (Miser and Quade 1995). Despite IIASA's long tradition in this field, it does not define exactly what systems analysis is, but chooses to rather describe what it does:

> *"A systems analysis commonly focuses on a problem arising from interaction among elements in society, enterprises and the environment, considers various responses to this problem, and supplies evidence about the consequences."*

With this scope systems analysis is inherently interdisciplinary. It is often necessary to engage experts from many different fields to adequately address a problem in a systems analysis. Miser and Quade (1995) again:

> *"Systems analysis brings to bear the knowledge and methods of modern science and technology, in combination with concepts of social goals and equities, elements of judgement and taste, and appropriate consideration of the larger contexts and uncertainties that inevitably attend such problems."*

Miser and Quade also make an important point that, while systems analysis may contain many scientific components and is based on a scientific approach, it is not itself a science. It rather resembles engineering, in that it applies and combines knowledge gained from studies of various sciences.

Finally, the attribute *environmental* emphasises the main purpose of environmental systems analysis. It is no easier to define than the wider "systems analysis", although it is obviously a systems analysis of some kind of environmental relevance. In a survey of environmental systems analysis tools, Moberg (1999) touches on a definition when describing environmental systems analysis tools as facilitating the assessment of environmental impacts and/or natural resource use caused by the studied system (a product, service, economy, or project) through some sort of analysis. An extended version of this survey identified 18 tools that fit into this description (Moberg et al. 1999). An even more extensive list of 80 tools was presented by the International Council for Local Environmental Initiatives (Erdmenger 1998a and 1998b, as cited by Burström 2000). Although not described as environmental systems analysis tools, but environmental management instruments, there is significant overlap between these and the tools presented by Moberg et al. (1999). The research plan that defines the scope of the research at the division of Industrial Ecology at KTH points out environmental systems analysis as its main focus area, and defines it as:

> *"... models and methods for integrated quantification and presentation of material and energy flows in different subsystems of nature and society and the evaluation of the future sustainability of different alternatives of action."*

This reflects a common, but not necessary focus of environmental systems analysis tools on material and energy flow studies.

2.1.1 Life cycle assessment

Life cycle assessment (LCA) was described as an environmental systems analysis tool in the survey by Moberg et al. (1999). During the last decade, it has become an increasingly common tool in environmental decision making. Its basic idea is to evaluate the potential environmental impact associated with a product over its entire life cycle (ISO 1997). A product may be either a material product or a service, with focus on the function provided. It does this by identifying, quantifying and assessing the impact of energy and material use related to a product, from raw materials acquisition through production, use and disposal, commonly known as "from cradle to grave". This wide scope is applied to ensure that both direct and indirect effects of a product are accounted for. LCA is a tool for comparative assessments, either between different products providing similar functions, or between different life cycle stages of a product in an improvement analysis. A standardised framework for LCA is being developed by the International Organisation for Standardisation (ISO 1997, ISO 1998, ISO 2000). It outlines four different steps in an iterative procedure, as illustrated in Figure 2.

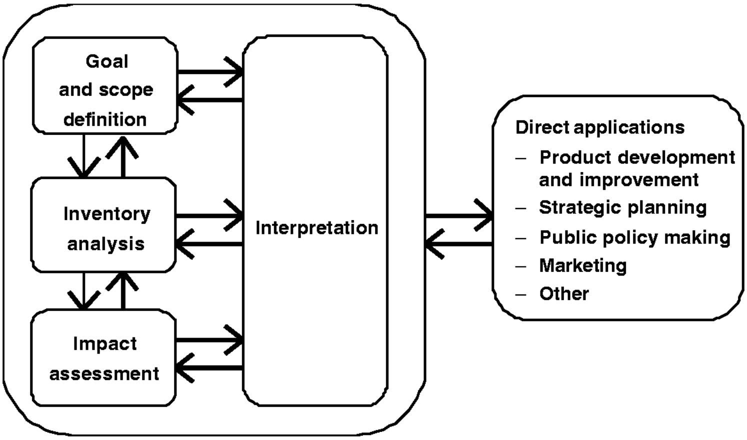

Figure 2 Phases of an LCA (ISO 1997).

The goals may be as diverse as product improvement and development, strategic planning by industry, public policy making by authorities, or marketing purposes. When setting the scope of a study, data requirements, assumptions and system boundaries are defined in accordance with the defined goal (c.f. section 2.2 "System boundaries in LCA and SFA").

In the inventory the inputs and outputs (resources and emissions) associated with the processes of the product throughout its life cycle are compiled and quantified.

In impact assessment, which is done in several steps, the inventory results are used to assess the total environmental impact of the system. In classification the inventory results are classified, or grouped, in environmental impact categories, such as global warming or eutrophication. In characterisation, emissions in the same impact category are aggregated by means of weighting factors that reflect the relative contribution of each emission to the impact category. There are several different methods for doing this, with different degrees of aggregation or specificity (SETAC 1997). Valuation is an optional step, in which results are further aggregated to a single index by weighting of impact categories based on e.g. political or ethical considerations. Normalisation may be used to relate results from the characterisation to the total magnitude of the given impact category in some given area and time.

In the interpretation, findings from the inventory and impact assessment are analysed to reach conclusions, explain limitations and provide recommendations based on the findings.

2.1.2 Substance flow analysis

Substance flow analysis (SFA) is also included in the survey of environmental systems analysis tools by Moberg et al. (1999). It is one of a number of different tools for material flow analysis (MFA), the scope of which is more limited than LCA. It is based on the thermodynamic law of mass conservation, and accounts in physical units the flows of selected materials through a certain area. The scope of different MFA tools differs with regard to level of aggregation of materials and studied areas. For instance the Material Intensity per Unit Service (MIPS) measures total mass flows related to a service, divided in abiotic or biotic material, soil, water, and air (Wuppertal Institute 1999 and Bringezu et al. 1997, as cited in Moberg et al. 1999). The Total Material Requirement (TMR) concept also measures total mass flows, but through regions or nations (Wuppertal Institute 1999 and Bringezu et al. 1997, as cited in Moberg et al. 1999). SFA on the other hand focuses on flows of selected substances, usually through a region (van der Voet 1996, as cited in Moberg et al. 1999).

The basic idea of SFA is to describe exchanges of substances between the lithosphere, biosphere and technosphere. It can be used to trace sources of environmental problems, discover potential future problems, or form a basis for regulations in substance handling. Research in this area has been ongoing since the seventies, and is now in use in environmental statistics and modelling of substance flows in society. SFA does not have the status of a well-established tool with a standardised framework. General rules have however been identified and formulated by van der Voet et al. (1995) and Udo de Haes et al. (1997). The suggested framework, which resembles that of LCA, is divided in three basic steps:

1. Goal and system definition
2. Inventory and modelling
3. Interpretation

SFA may serve goals such as error check of inventory data, identification of missing flows or hidden leaks in society, identification of problem flows and causes of environmental problems, monitoring, prediction of effectiveness of pollution abatement measures, possible shifting of problems caused by redirected substance flows, or screening to identify issues for further investigation with other analytical tools. The system boundaries are defined in accordance with the specified goals (c.f. section 2.2 “System boundaries in LCA and SFA”).

When the substance flows have been quantified according to the system definition, they are incorporated in either of three types of models:

- Bookkeeping: data are organised according to the structure of the system.
- Static modelling: output flows are related to input flows by transfer equations, giving a steady state description of the system.
- Dynamic modelling: changes over time are included.

In SFA of single substances, no further interpretation may be needed. Results from complex systems may however need to be interpreted by selecting indicator flows or evaluating against policy targets or standards. If several substances are analysed, interpretation may be facilitated by translating flows of different substances to comparable measures, for example by aggregating in environmental impact categories, as is done in LCA.

2.2 System boundaries in LCA and SFA

System boundaries delimit the system under study from its surroundings. Selecting system boundaries is crucial in both LCA and SFA, as they determine what should or should not be included in the analysis, and thereby in essence govern the results and conclusions. For system boundaries in SFA, see for example Udo de Haes et al. (1997), and in LCA Tillman et al. (1994), Büchel (1996) or ISO (1998). System boundaries define the processes to be included in the modelled system, and must agree with the scope definition. There are different dimensions of system boundaries, here divided in function, time, and space.

2.2.1 Function

Functional system boundaries define what function (product or service) should be provided by the system. This is of more relevance in LCA than SFA. Two systems are comparable from a life cycle perspective only if they provide the same function to the same degree. Therefore the functional unit, a quantified measure of the functional output, forms a basis for comparative assessments in LCA. Its purpose is to provide a reference to which input and output data are normalised, and the functional unit should be clearly defined and measurable (ISO 1998). In the case of waste management, the functional unit could be defined as treatment of x tonnes of waste of a certain composition.

Some systems generate by-products in addition to their main function. Taking waste management as an example again, the main function would be waste treatment and a by-product could be electricity recovered from waste incineration. This obviously reduces the need for electricity produced by other means, which should somehow be accounted for. Finnveden (1994) reviewed different techniques by which systems with different and multiple functional output can be compared on an equal basis. In allocation some causality (natural, political, social or arbitrary) is used to allocate (partition) the burden of resource use and emissions between different functions. Another means is to define multiple functional units and broaden the system boundaries, by either adding or subtracting processes. Broadened system boundaries using the added system approach is illustrated in Figure 3, in which two similar systems (1 and 2) are compared. System 1 provides two functions (A and B), while System 2 only provides one function (A). The two systems can be made comparable by complementing System 2 with the impact of producing function B by some other means (here called compensatory production). In this manner Systems 1 and 2 have the same functional output, and are thus comparable from a life cycle perspective.

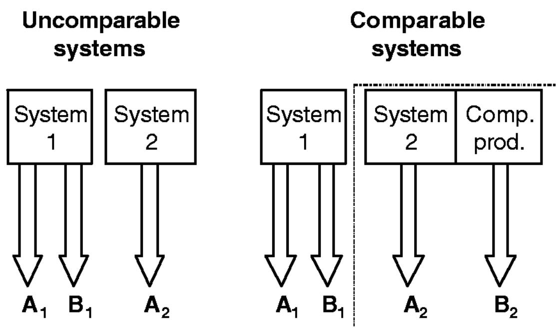

Figure 3 *Added systems to make scenarios comparable. Based on Finnveden (1994).*

Another aspect of functional system boundaries is to what extent the process chains connected to the analysed system are included. The process chains may de divided in core system, up-stream processes, and down-stream processes, as illustrated by Figure 4.

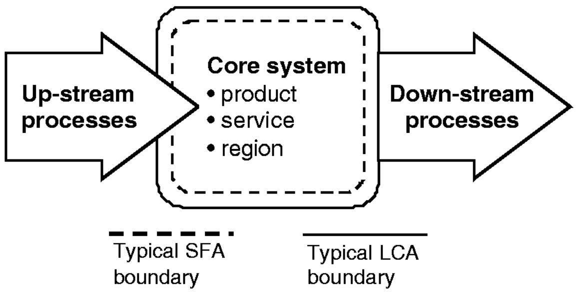

Figure 4 *The core system relies on up-stream processes and causes down-stream processes. Based on Paper II.*

The core system encompasses activities directly related to the defined function (in LCA) or region (in SFA). It includes those activities that may be directly affected by decisions based on the study (Tillman et al. 1998). Up-stream processes provide necessary inputs to the core system. Down-stream processes take place as a result of activities in the core system. Using LCA of waste as an example once again, waste transports and treatment constitute the core system, production of fuels and electricity used in waste management constitute up-stream processes, and use of products recovered from waste constitute down-stream processes. As illustrated in Figure 4, SFA typically covers the core system, while LCA encompasses all process stages, so that energy and material flows are traced "from cradle to grave". At a first glance the up-stream and down-stream processes may be "less visible" than the core system, as they may occur in geographically distant places. Sometimes the expressions foreground and background system (Huppes and

Frischknecht 1995) are used instead of core system and up-stream/down-stream processes, respectively. The up-stream, down-stream, and compensatory processes constitute the so-called enlarged system as defined by Tillman et al. (1998).

2.2.2 Time

The period of the analysis must be delimited to define the time span (years, centuries or other) for which inputs and outputs of the system should be included. This causes difficulties if processes proceed over extended time periods, e.g. emissions from landfills. It must also be determined what time period the inventory should represent, whether to analyse a past, current, or future system. Past or current systems are easier to model due to data availability, but future systems may be of more interest in a planning situation.

2.2.3 Space

The geographical borders of the analysis may be determined by for instance political boundaries (e.g. a municipality, county, or nation) or natural boundaries (e.g. an ecosystem, lake or watershed). This is of more relevance in SFA than LCA. In LCA, where function is the central issue and the analysis extends over the entire life cycle, the geographical boundaries of processes and impacts are in essence unlimited.

3 SYSTEMS ANALYSIS OF WASTE MANAGEMENT

3.1 Review of waste management models

ORWARE and similar waste models that have been developed during the last decade are part of the currently fast growing number of environmental systems analysis tools that address environmental issues from a systems perspective. But waste models have a history beginning by the end of the 1960s, when the first computerised waste planning models were developed. In the following, these early waste management models are briefly reviewed, followed by an overview of LCA based waste models and case studies, and a discussion of important methodological considerations. This chapter is partly based on Paper I, but has been complemented with more recent information.

3.1.1 Early waste management models

The early development of waste management models came about when newly developed methods in operations research and systems analysis, combined with growing access to high speed computing devices, enabled optimisation of large systems. Many of these tools were intended for planning the practical operation of waste management systems. Attention was given to specific problem areas, e.g. routing of vehicles and location of treatment and disposal facilities (Deininger 1974). Cost was then the main decision variable in urban planning and early models were aimed at minimising costs of parts of or entire waste management systems.

Environmental considerations appeared in waste models in the beginning of the 1980s. One category of models analyses different recycling schemes (Jenkins 1982, Clapham 1986, Vigil et al. 1987, Barlishen and Baetz 1996, Everett and Modak 1996). The objective is however cost minimisation, and the environmental benefits or drawbacks of recycling are not included. Other models analyse the cost of technical solutions that meet environmental restrictions, i.e. cost minimisation with environmental constraints (Chang et al. 1996a, Chang et al. 1996b). A third category explicitly calculates environmental parameters, either in optimisation, scenario analysis or information management.

Optimisation models are generally multi-criteria optimisation (MCO) models, i.e. simultaneous optimisation of two or more objectives (Periack and Willis 1985, Caruso et al. 1993, MacDonald 1996, Chang and Lu 1997, Sushil 1993). Scenario models evaluate pre-defined scenarios, instead of optimising to identify one best scenario. The consequences of each scenario are calculated, but not automatically prioritised (Wang et al. 1988, MacDonald 1996). Yet another category are multiple criteria analysis (MCA) models, a decision-making procedure for simultaneous consideration of quantitative and qualitative evaluation criteria. By means of a weighting procedure, alternative scenarios are evaluated against each other (Sobral et al. 1981, Maimone 1985, Chung and Poon 1996, MacDonald 1996). Input-output analysis is used by Huang et al. (1994) as a means of reporting on land use, air quality, water quality and waste from industry, service and waste management.

The above models have similar scope with regard to what processes and wastes are included, while environmental impact calculations vary largely among the models. Approaches range from extremely simple to very detailed. For instance, Chang et al. (1996a) assume that air pollution and leachate impacts can be controlled by engineering actions, and their model only evaluates noise and traffic. Wang et al. (1988) calculate CO_2 emissions from vehicles. Caruso et al. (1993) combine air emissions, soil impoverishment, negative impacts on the landscape and public opposition in a so-called "ecological unit", which depends on coefficients based on advice from experts and the amount of waste treated at a certain facility.

3.1.2 LCA of waste management

During the last decade, LCA has appeared as a new approach to analyse environmental impacts of waste management. LCA is typically used to analyse products, but services may just as well be addressed, as long as the function provided by the service can be clearly defined. A waste management system can be described as a service, the function of which is to collect, transport, and treat waste from a certain area in an adequate manner. A limited number of LCA-based models of waste management have been developed. In this context "model" refers to a computerised model intended to be used repetitively in different studies. LCA has also been used in several case studies of waste management systems or certain parts of waste management.

To my knowledge, there are five models with similar scope as ORWARE. The model MIMES/Waste has been developed in Sweden (Sundberg and Ljunggren 1997), and mainly funded by the same financiers as ORWARE. Two models have been developed in the UK; the ISWM (Integrated Solid Waste Management) model by Procter & Gamble (White et al. 1995), and WISARD (Waste Integrated Systems Assessment for Recovery and Disposal) developed by the Ecobilan Group, commissioned by the UK Environment Agency (Aumônier and Coleman 1997). The ISWM model forms the basis for a Canadian model, which has been funded by the Environment and Plastics Industry Council and the Corporations Supporting Recycling (Mirza 1998). In the US, the Environmental Protection Agency has developed a model, with co-funding from the Department of Energy (Weitz et al. 1999).

The objectives of these models are similar, to go beyond limited local perspectives and evaluate environmental effects of waste management from a systems perspective. In doing this, the models have one functional unit in common; to handle and treat the waste generated in a certain area and time. All models describe input flows of waste in terms of waste fractions, mainly including organic wastes, metal, glass, plastic, paper, and incineration ashes. Investment and running costs are also calculated. The system boundaries differ somewhat with regard to the degree of inclusion of up-stream and down-stream processes, and whether multiple functional units are applied for comparative studies. The level of detail in the modelling of waste management processes also differs between the models, so that different degree of site-specificity is allowed, different amounts of data is required, and results of different level of detail can be retrieved from simulations. In addition, the models are developed for different regional characteristics, and will not easily allow adjustments to other regions.

Apart from these models, many case studies have been done applying LCA to address different questions related to waste management. An assessment of the effects, with main focus on energy and climate change, of different strategic choices about the management of combustible, recyclable, and compostable wastes was performed by Finnveden et al. (2000). The analysis focused on Swedish conditions, but was expected to be of interest to other countries as well. Hassan et al. (1999) performed a life cycle comparison of four Malaysian cities. The implications of introducing incineration instead of the current landfilling were also evaluated. Denison (1996) reviewed four major North American LCA-based studies of waste management, comparing landfilling, incineration, and recycling of municipal solid waste

In some studies, specific waste treatment processes have been analysed in detail. Rieradevall et al. (1997) performed a case study of the life cycle impacts of landfilling of household solid wastes. The computer tool LCA-Land was developed for modelling landfilling of waste in LCA studies (Nielsen and Hauschild 1998, Nielsen et al. 1998). Bez et al. (1998) presented a model of a domestic waste landfill, specifically developed to calculate the environmental effects of individual products. This is necessary if the model is intended to be used in product specific LCAs. Product specific effects of waste incineration are calculated in a model developed by Kremer et al. (1998). Waste incineration with different technologies for nitrogen oxide reduction were compared by Hellweg (1997) as part of a Swiss project comparing different waste treatment technologies. A review of different models for LCA of anaerobic digestion was performed by Aumônier (1997).

Some case studies have focused on analysing specific waste fractions. Sewage was the focus of Tillman et al. (1998), who performed an LCA of municipal waste water systems in two Swedish municipalities. The existing, conventional wastewater treatment was compared to two alternative, small-scale solutions. Recyclable paper and plastics have been the focus of several case studies. An example is Hunt (1995) who compared landfilling, composting, and burning of paper and plastics. In a study by Finnveden and Ekvall (1998) recycling of paper packaging materials was compared to incineration with energy recovery, based on the results of seven different case studies. Heyde et al. (1999) presented a comparison of feedstock recycling, energy recovery, and mechanical recycling of plastics. The results were derived from five different projects.

Important methodological considerations

Certain problematic methodological issues are typically encountered in LCA of waste management. These have been discussed among model developers, but have no definite solutions. A crucial first question is related to the important definition of the functional unit. Waste management systems with some kind of resource recovery provide other functions than merely managing waste. Recycled paper and plastics, organic fertiliser, electricity, district heating and fuels are products that may be recovered depending on the design of the waste management system. Two systems that treat the same amount of waste, but do not recover the same resources, will provide different functions. Because systems in comparative LCAs must provide the same functions, either allocation or broadened system boundaries with compensatory production as described above (chapter 2.2.1, "Function"), must be applied.

Another important consideration is how to define the "cradle" of waste management. In LCA, energy and resource flows are followed from the point of extraction from nature, through production and use, to final disposal and eventually complete dispersal in nature. This is rather straightforward in a product LCA. As waste consists of products, the actual "cradle" of waste is the same as that of products. But modelling production and use of all products that constitute the waste is practically impossible. The range of products in ordinary household waste is enormous, as are their individual use phases. This problem is avoided by regarding the "cradle" of waste to be at the point where products become waste and are disposed of in a waste bin. Thus, all up-stream processes are cut-off, i.e. excluded from the analysis, and the analysis starts with waste collection (Figure 5). This approach is compatible with the LCA framework if all processes up-stream of waste collection are assumed to be equal, disregarding the design of the waste management system. In practice, it implies that waste is treated as a "zero burden" input. That is, material and energy in waste are not associated with any up-stream burdens. These system boundaries significantly simplify the LCA, but limits the range of waste strategies that can be analysed. Waste minimisation strategies cannot be analysed, as they influence the waste generation, which is excluded.

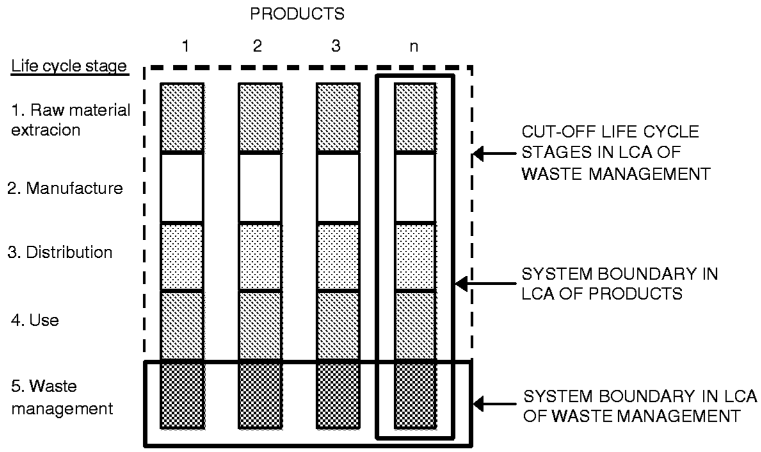

Figure 5 *In LCA of waste management, all life cycle stages up-stream of waste management are cut-off. Based on White (1999).*

Likewise, defining the "grave" of waste management may be difficult. One aspect is waste disposal in landfills. Landfilled material clearly goes through a series of reactions that cause emissions, which should be included. But these processes are not known in detail, and it is a more or less subjective choice whether to model complete dispersal of landfilled material, cut-off emissions after a certain time period, or view landfills as completely stabilised after a certain time. For further discussion on this topic, see

Finnveden (1999). Defining the "grave" of recycled materials is another complicated matter, as they will go through another use phase.

Materials recycling requires certain consideration. One aspect is the quality of recycled vs. virgin materials. The compensatory production of recycled materials is usually assumed to be material production from virgin raw materials. In case of a 1:1 replacement ratio, the processes down-stream of production of recycled or virgin materials may be cut-off. But this is fair only if recycled and virgin materials have equivalent quality and function, which is not necessarily the case. Some studies assume that recycled materials replace a smaller amount of the same virgin material. For instance cardboard containers may be less rigid if made of recycled rather than virgin material (Sundqvist et al. 2000a). In other studies, recycled materials are assumed to replace entirely different materials. For instance recycled plastic may replace wood (Finnveden et al. 2000). In these cases, the down-stream process of using and disposing of these materials will differ, and should not be cut-off.

An issue that may be more important in LCA of waste management than in other LCA, is carbon balances. One of the main issues of carbon is the impact on global warming. Carbon dioxide (CO_2) from combustion adds to the global warming impact, while growing biomass has the opposite effect by reducing the amount of CO_2 in the atmosphere. To give a fair picture of the net impact, both emissions and absorption of CO_2 should be accounted for. But if an LCA of waste management excludes all up-stream processes of waste generation, absorption by growing biomass will not be not accounted for. The prevalent approach in LCA is to set the impact CO_2 from carbon in biogenic material to be zero. This presupposes that forests are maintained sustainably, so that new biomass grows to absorb CO_2 at the same rate as biogenic CO_2 is released (IPCC 1996). But if for instance paper is made of biomass from forests that are not sustainably maintained, burning that paper would result in net emissions of CO_2. Another problem arises in comparisons of landfilling and for instance incineration. Landfills are sometimes assumed to act as carbon sinks, that is, to sequester carbon in a form that is never released. If emissions of biogenic CO_2 are counted as having zero impact, the benefit of this permanent withdrawal of biogenic carbon will be realised only if accounted for as "negative emissions" of CO_2.

3.2 The ORWARE model

3.2.1 Objectives of the model

Initially ORWARE was intended as a tool for assessment of environmental impact of organic (biodegradable) waste handling in municipal waste management systems, hence the acronym ORWARE (ORganic WAste REsearch). The aim was to enable quantified and systematic comparisons of the environmental impacts of different means to handle biodegradable waste, both solid and liquid (sewage). This was done by modelling waste flows in total amounts and as specific substances, and its related energy turnover, through the system in scenarios of different system designs. The system boundaries of the model were limited to the waste management core system and its up-stream processes of for instance diesel production. For practical reasons the tool, which was then essentially an SFA of biodegradable waste management, was implemented as a computer model. This development is described in Paper II. Since then, ORWARE has gradually been further developed to apply the wider system boundaries of LCA, to cover also non-biodegradable fractions of municipal solid waste (MSW), and to calculate the costs of waste management. Separate development has also been made of models of wastewater systems. The following model presentation is based on Paper II, but complemented with more recent references to give a comprehensive picture of the current model. Neither the economic sub-models, nor the wastewater sub-models in ORWARE are considered here.

3.2.2 System boundaries

Today ORWARE can be characterised as an LCA model because of its system boundaries. But it still has a strong foundation in SFA, due to its tracing of substance flows, which is more thorough than what is usually encountered in LCA models. As was described in chapter 2.2 "System boundaries in LCA and SFA", LCA and SFA models should be delimited with regard to function, time, and space. In the following, ORWARE is described according to the terminology in this chapter.

Function: As in comparative LCA, functional units form the basis for comparative assessments between scenarios in ORWARE. This means that all scenarios in a comparison provide the same function (product or service). Waste management can serve several different functions at the same time. Its primary function is to manage waste. Depending on the system design different valuable resources may be recovered from waste, a kind of by-products from waste management. To account for the fact that this reduces the need for other production of these products and to make different scenarios comparable, multiple functional units and broadened system boundaries are applied in ORWARE. The following is a list of possible functional units, of which only the first must always be included, as it forms the basis for the rest of the study.

- Manage one year's waste generation from a selected area.
- Produce a certain amount of district heating.
- Produce a certain amount of electricity.
- Provide a certain amount of transport work.
- Deliver a certain amount of plant-available nitrogen fertiliser.
- Deliver a certain amount of phosphorus fertiliser.

When a functional unit is not sufficiently provided by the waste management system in some scenario, the system boundary is broadened to include compensatory processes to provide this function. For compensatory processes, the entire life cycle except production and disposal of capital goods and disposal of residuals such as coal combustion ashes are included.

The core system of ORWARE consists of the waste management system, including collection, treatment, and final disposal of waste generated within a defined area and time period. These are the processes that can be controlled by waste management decisions. Production of electricity and fuels used in waste management is included as up-stream processes to the core system. All up-stream processes related to waste generation are assumed equal regardless of chosen waste treatment alternative and are cut-off, as is production of capital goods. The down-stream processes of using recovered products are included if they are thought to have different impact than using the equivalent product from compensatory production. For instance, use of organic fertiliser differs from use of mineral fertiliser with regard to emissions from spreading and leaching of nutrients, and emissions from use of waste-derived fuels differs from use of other fuels, and are therefore included. However, use of recovered plastic or paper is assumed to have equal impact as use of virgin materials produced, and is excluded. Demolition and disposal of capital goods also is excluded.

Figure 6 illustrates the waste management core system as it is modelled in ORWARE. The solid line encloses the core system. Waste sources, which are up-stream of waste management, are indicated outside the system boundary. Other linkages to up-stream processes, down-stream processes, and the compensatory system are indicated by the input and output flows of products and energy.

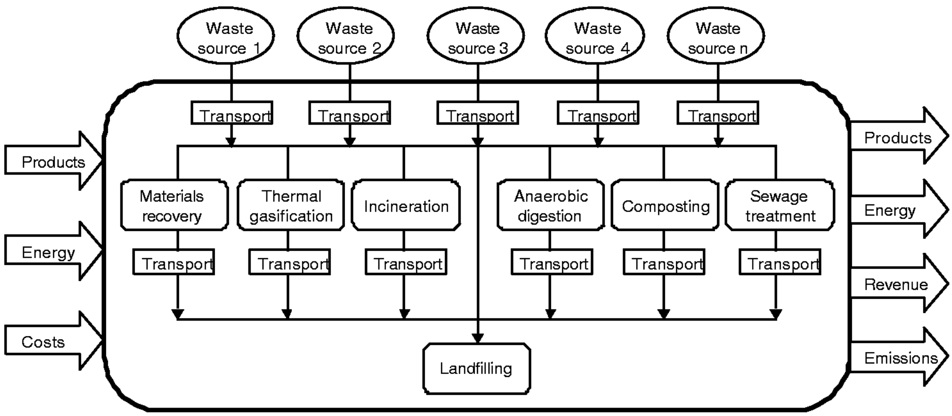

Figure 6 *Conceptual model illustrating the core system of waste management as modelled in ORWARE. (Modified from Eriksson et al. 2000).*

Next, Figure 7 illustrates the system boundaries as defined in ORWARE when evaluating waste management from an LCA perspective, including the core system and the enlarged system, consisting of up-stream processes, down-stream processes, and compensatory processes.

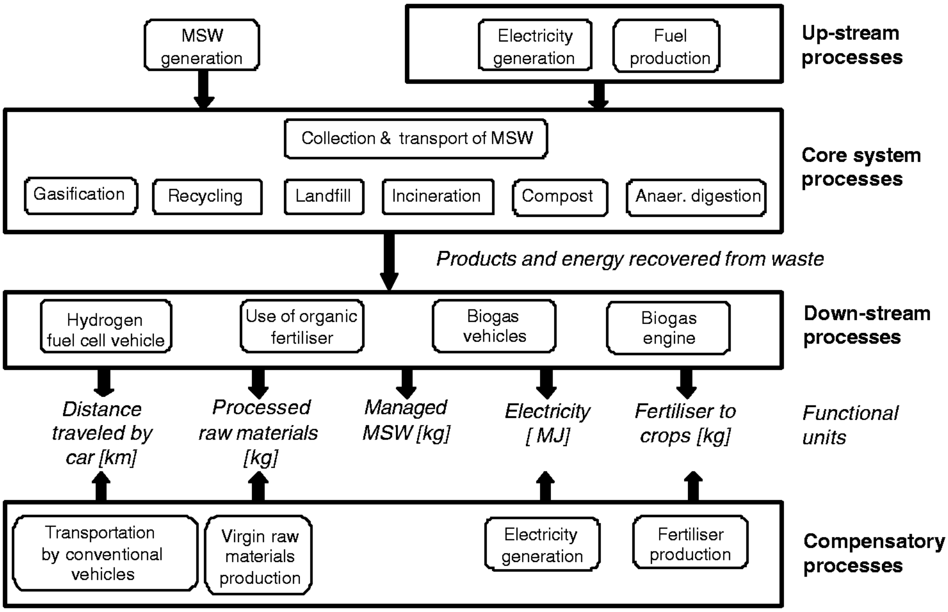

Figure 7 *Conceptual model illustrating system boundaries of ORWARE, including examples of up-stream, down-stream, and compensatory processes.*

Time: ORWARE calculates the impact caused by handling and treating waste generated during one year in a selected area. The emissions mainly occur during that same year, but in the case of landfilling, long-term emissions are included. Generally, scenarios are designed to mirror a not too distant future, from present to 10 - 15 years from today.

Space: The selected area, which is usually a municipality, defines what waste is included in the analysis, whereas emissions and resource depletion are included regardless of where they occur.

3.2.3 Substance flows and energy turnover

ORWARE calculates both environmental impact and energy turnover related to waste management. Modelling of substance flows through the processes of the waste management core system and the enlarged system constitutes the basis for this. Emissions to air, water, and soil are calculated based on the substance flows through the process submodels. Energy turnover, consisting of process energy input and recovered energy from waste is calculated based on the amounts and composition of waste treated by different means. A uniform framework for all calculations has been defined by identifying substances or substance groups that should be traced through all sub-models. Naturally, not all are relevant to all process sub-models and in all emissions, and are then simply left as blanks in the model. The substances were chosen according to three criteria, they should be:

- of importance for the performance of some process
- environmentally hazardous, or
- of economic value.

To mention some, different carbonaceous compounds in organic material are important for calculation of degradation products and energy output, heavy metals are significant pollutants, and nutrients are economically valuable (Table 1). Since the model was developed to include non-biodegradable fractions in MSW, total carbon has been divided in carbon of biogenic and fossil origin, and different fractions of paper, plastic and metal have been added to this list, although their elemental composition is also described in terms of the substances in Table 1.

Table 1 Substances that are traced through the waste management system in ORWARE.

Dry matter	BOD_7	Dioxins	NO_3^-	Pb
Volatile substance	COD	PCB	NO_x	Cu
Total biogenic C	Bigenic CO_2	PAH	N_2O	Cr
Total fossil C	Fossil CO_2	Phenols	S total	Ni
Slowly degradable carbohydrates	CO	O total	SO_x	Zn
Moderately degradable carbohydrates	CH_4	H total	Cl total	Hg
Rapidly degradable carbohydrates	VOC	H_2O	P	Cd
Fat	AOX	N total	K	Particles
Protein	CHX	NH_3/NH_4^+	Ca	

3.2.4 Sub-models of the core system and down-stream processes

To date, the sub-models listed below have been developed for core system and down-stream processes. These sub-models are unique to ORWARE, and calculate substance flows at a detailed level. They can be run in somewhat different modes depending on site-specific circumstances, and may always be tailored to match a specific case. The sub-models are not described in any further detail in this thesis, but reference is made to other publications.

- Waste fractions (Sundqvist et al. 2000b)
- Waste collection (Sonesson 1996, Sonesson 1998)
- Waste and material transports (Sonesson 1996)
- Incineration (Björklund 1998)
- Anaerobic digestion (Dalemo 1996)
- Composting (Sonesson 1996)
- Landfill (Björklund 1998)

- Thermal gasification (Paper V)
- Sewage treatment plant (Dalemo1996)
- Other waste water systems (Kärrman 2000, Ramírez et al. 1999)
- Plastics recycling (Sundqvist et al. 2000b)
- Cardboard recycling (Sundqvist et al. 2000b)
- Spreading of organic residues on farmland (Dalemo et al. 1998)
- Biogas utilisation (gas engine, vehicle fuel) (Sundqvist et al. 2000b)
- Synthesis gas utilisation (hydrogen production and fuel cell vehicle) (Paper V)
- Economic sub-models linked to all process sub-models (Carlsson 1997, Sundqvist et al. 2000b)

In reality the processes represented in ORWARE have dynamic properties, with factors varying over time. Despite this, the process sub-models are static and work with one-year averages. This is partly because data on waste generation and process performance is most easily available as yearly averages, but mainly because the dynamic properties of the system are seldom important to the analysis.

Figure 3 shows a screen dump of the computer implementation of ORWARE to illustrate how sub-models can be linked to model a waste management system. The computer implementation is done in the software MATLAB® with the graphical interface Simulink® (The Mathworks, Inc.). Calculations in Matlab are based on matrix algebra, which is very convenient to support substance flow modelling.

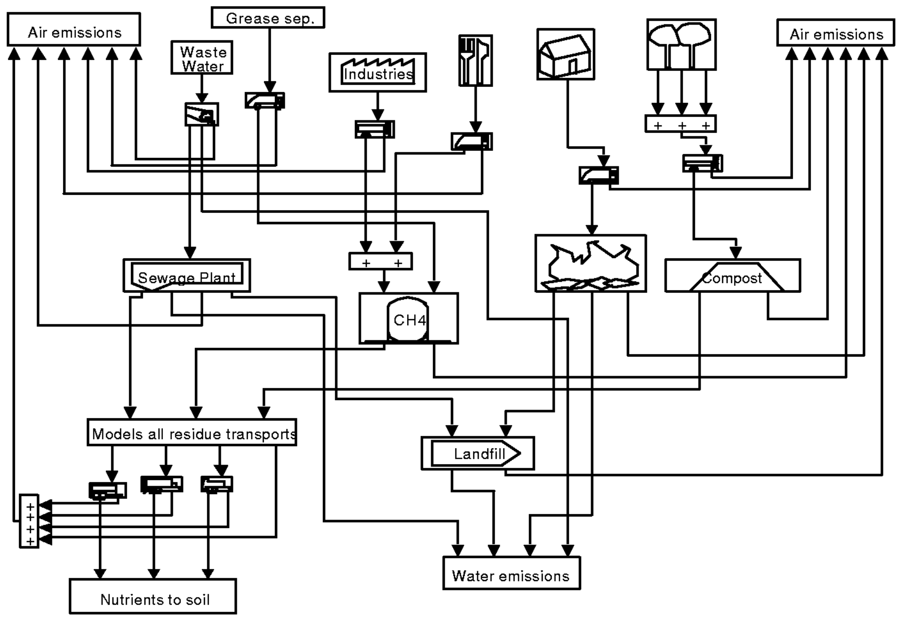

Figure 8 *Example of sub-models linked to model a waste management system in ORWARE. Not all available sub-models are represented in this figure.*

Waste is collected from various sources in the upper part of the figure, transported to different treatment facilities, and finally treated. Some waste treatments generate residues that are landfilled, while some generate products that may be further utilised by down-stream processes. All processes generate emissions.

3.2.5 Sub-models of the compensatory and up-stream processes

Up-stream and compensatory processes are included in the enlarged system of ORWARE to give a complete picture of the systems impacts of waste management.

Up-stream processes supply resources needed to operate the waste management system, for instance electricity and vehicle fuels. Data used to model the full life cycle impacts of these processes is collected various from LCA databases (Sundqvist et al. 2000b), and are not unique to ORWARE. The impact of production of capital equipment or process additives has not yet been included in the model.

Compensatory processes are needed to deliver the products or services of the multiple functional units in ORWARE. The compensatory processes are generally modelled as being either the average or the marginal means of producing these products or services, when not produced by the waste management system. They can however be selected as found appropriate for the objectives of each specific study. Examples are generation of district heating from oil or biofuels, production of electricity from coal or hydropower, transportation by petrol or diesel powered vehicles, or mineral fertiliser production. To some extent, these processes coincide with up-stream processes. Data used to model the full life cycle impacts of compensatory processes is collected from various LCA databases (Sundqvist et al. 2000b), and are not unique to ORWARE.

3.2.6 Impact assessment

The result of a simulation is a complete inventory of substance flows through the system, energy use and recovery, resource consumption, and financial and environmental costs. The substance flows can be displayed without further processing as in SFA, which may be of interest for the analysis of e.g. nutrient flows or heavy metal flows. Usually the substance flows are however aggregated in environmental impact categories. The impact categories are calculated using weighting factors developed for LCA purposes (Sundqvist et al. 2000a).

3.2.7 Running the model

Depending on how the waste streams are directed through the model, different scenarios can be simulated. The analysis may be performed either as a comparison of pre-defined scenarios, or as an optimisation. In the case of optimisation, one optimisation parameter must be selected, e.g. minimise non-renewable energy use or global warming impact, and possible solutions may be restricted by applying constraints on input variables. No valuation by weighting impact categories is done in ORWARE.

4 SUMMARY OF CASE STUDIES

Up to date, ORWARE has been applied in more than 15 case studies of municipal waste management systems. This chapter summarises briefly the scope, objectives, and main results of three case studies. It illustrates that although similar in most aspects of the modelling, the objectives of these three projects were quite different.

4.1 Waste management planning in Stockholm

This section summarises briefly the contents of Paper III, which describes a case study of organic waste management in Stockholm.

The Environment and Health Protection Administration in Stockholm (EHPAS) sets up long-term goals for the local environment in Stockholm, with sustainable development as guiding principle. One specific goal in the proposed waste management plan of 1997 (EHPAS 1997) was to increase recycling of nutrients from waste, including sewage, while also striving to reduce environmental impact from waste management and to reduce resource consumption. The EHPAS was interested in finding guiding principles for how these goals could be achieved without counteracting each other. This coincided with a need for large-scale testing and refinement of the ORWARE model.

Thus, the project “Systems Analysis of Waste Management in Stockholm” was initiated. A project group was formed including the ORWARE research group, representatives from the EHPAS, Stockholm Energi (now Birka Energi, local energy distributor and owner of waste incineration facility), Stockholm Water Company (responsible for sewage treatment), SKAFAB (responsible for waste management in Stockholm), and the city planning office. Throughout the project, the local representatives played an important role in defining the scope of the study, providing data, and reviewing the results.

Three scenarios of future handling of biodegradable wastes were evaluated with regard to resource consumption, environmental impact, and organic fertiliser quality:

- large-scale composting,
- anaerobic digestion, and
- urine separation.

For comparison, a reference scenario mirroring the current situation with mainly incineration was also included.

The most striking outcome of the analysis was actually the complexity of the results. Because of the existing waste management infrastructure, changes in the treatment of biodegradable wastes caused changes in the treatment of other waste fractions. As less biodegradable waste was incinerated, mixed wastes with higher energy content were diverted from landfill to incineration. This reduced landfill impacts, but primarily lead to increased energy recovery, which had a significant impact by reducing the need for oil-based district heating. The net environmental impacts of this complex series of events were not easily foreseeable.

The objective of introducing biological treatment was to increase nutrient recycling. As it turned out, the major part of phosphorus was in the sewage sludge. Thus, the potential to increase recycling of phosphorus by changing the treatment of solid waste was limited. The potential to increase nitrogen recycling was better, although it too was mainly found in sewage, and the most efficient alternative was urine separation.

An unexpected finding of the study was the very limited importance of transports. As Stockholm is rather densely populated with a lack of farmland in its immediate surroundings, it was expected that long distance transports of organic fertiliser might significantly increase the overall environmental impact of the system. Despite 25 to 100 % increased transport labour compared to the reference scenario, the impact on total emissions and energy use was minor.

Overall environmental impacts were largely unaffected by choice of waste treatment Large-scale composting and anaerobic digestion would reduce greenhouse gas emissions and emissions of VOCs. Urine separation would reduce eutrophication, but increase acidifying emissions like NH_3 and NO_x. However, probably the most crucial question when recycling nutrients from waste is the quality of the biological fertiliser product. An analysis of the heavy metal content showed that only urine would be accepted by Swedish standards, spreading of compost and digester sludge would be limited by their metal content. Obviously, this problem must be solved before recycling of nutrients from waste is introduced on a large scale.

4.2 Evaluation of Uppsala's waste management plan

This section summarises briefly the contents of Paper IV, which describes a case study of waste management in Uppsala.

All Swedish municipalities are required by law to formulate a local waste management plan, a document containing data on current waste generation and management, and strategies for reducing waste amounts and harmfulness (SFS 1998). The responsibility for Uppsala's waste management plan is on the Technical Office, who in 1998 revised its old plan. Among other things, a three-step strategy to increase biological treatment of biodegradable wastes and recycling of materials was outlined. Although in line with political goals, the actual environmental impacts of this strategy were uncertain. Since the ORWARE model had been used earlier in Uppsala (Sonesson et al. 1997), it was close at hand to use the model to evaluate whether the strategy would successively reduce, as intended, the environmental impact of waste management in Uppsala. At this time, the ORWARE model had also been expanded to include treatment of non-biodegradable waste fractions, which could suitably be tested during the analysis.

The study was performed primarily as a research project, but still in close co-operation with the Technical Office, the Environment Administration, and Uppsala Energi (local energy distributor and owner of waste incineration facility). These contacts were important to ensure a relevant scope of the study, get insight in the structure of waste management in Uppsala, and get access to site-specific data.

The future scenarios in the analysis represented the stages of successive increase of biological treatment and materials recycling:

- Stage 1: Large-scale composting of all collected household waste and anaerobic digestion of biodegradable waste from restaurants, trade, hotels, and offal.
- Stage 2: Anaerobic digestion of all collected biodegradable waste.
- Stage 3: Anaerobic digestion of all collected biodegradable waste, and increased materials recycling compared to current levels.

A reference scenario mirroring the original situation, mainly incineration, some landfilling, and materials recycling, was also included.

Like in the Stockholm study (Paper III), changes in the treatment of biodegradable waste caused changes in the treatment of other wastes. Reduced incineration of biodegradable waste was compensated by increased incineration of industrial waste that was otherwise landfilled. Thereby, net heat recovery from waste was not largely affected. Biogas from anaerobic digestion was used as vehicle fuel, which reduced the need for diesel. This significantly reduced greenhouse gas emissions and fossil fuel consumption.

It was found that Stage 2, anaerobic digestion, would reduce environmental impact and fossil fuel consumption. Stage 1, large-scale composting, would however lead to an initial increase of environmental impact. It thus seems that this stage would do more harm than good. It may however be motivated during a transitional period, before all parts of the source separation infrastructure are functioning well. The only significant effects of increased materials recycling was a large increase in biofuels consumption, and reduced greenhouse gas emissions. Other impact categories were left largely unaffected.

Similar to the Stockholm study, the heavy metal content in biological fertiliser would limit the use of these products. Sewage sludge was too contaminated by copper to be used at all in agriculture, and the use of compost would be limited by its lead content. Only digester sludge had acceptable heavy metal content.

As a means to evaluate the importance of the environmental impacts of waste management, the impacts were normalised by relating them to the total impacts in Uppsala. All impacts were in the range 1 to 5 % of local totals, global warming and eutrophication being the most important.

4.3 Strategic analysis of hydrogen from waste

This section summarises briefly the contents of Paper V, which describes a case study of a system linking hydrogen production from waste to fuel cell vehicles.

During recent years, thermal waste gasification has become an increasingly interesting alternative waste treatment technology. It is often claimed to be advantageous in comparison to incineration concerning energy recovery and environmental performance. Although the technology cannot yet be considered as commercially practicable, there are a number of large-scale demonstration facilities. A comparable emerging technology within the transportation sector is the fuel cell vehicle (FCV). Several of the world's big car manufacturers are developing fuel cells and FCVs. Some applications of fuel cells are already commercially available, but FCVs are still in the prototype and research phase. The main advantages of FCVs would be higher energy conversion efficiencies than cars with internal combustion engines, and near-zero emission levels.

This case study considered the possible integration of MSW management and transportation, by fuelling FCVs with hydrogen produced from gasified MSW. Linking these two emerging technologies would be favourable if the resulting reduction in environmental impacts were greater in combination than either technology would be capable of achieving in isolation, and greater than what could be attained using conventional technologies. This possible link was investigated by e.g. Thorsness (1995) and Wallman et al. (1998). The cost of MSW-derived hydrogen was shown to be similar to that of coal-derived hydrogen. Another study concluded that gasification of all MSW generated in New York City could provide enough hydrogen to cover over 40 % of all car and light-duty truck transportation in New York City (Larsen et al. 1996). In combination with the likely improvements in energy efficiency and environmental performance, this suggests that it should be a both desirable and viable solution. Because the consequences of combining these two technologies are far-reaching and difficult to get an overall picture of, ORWARE was thought to be an excellent tool for evaluating the impacts on energy use and emissions. The study was based on U.S. conditions.

The analysis covered four MSW management scenarios:

- A: Thermal gasification of MSW, conversion of syngas to hydrogen.
- B: Thermal gasification of sorted MSW, materials recycling at current levels, conversion of syngas to hydrogen.
- C: Landfilling of MSW, recovery of landfill gas for electricity generation in a gas engine.
- D: Combustion of MSW, energy recovered as electricity.

Linked to these were four different transportation scenarios, of which scenario I was linked to gasification, and scenarios II, III, and IV constituted compensatory transportation in the other scenarios:

- I: Direct hydrogen FCVs, hydrogen produced from MSW gasification.
- II: Direct hydrogen FCVs, hydrogen produced from steam reforming of natural gas.
- III: Reformer-based FCVs fuelled by methanol.
- IV: Hybrid gasoline-electric vehicles.

If only energy use in the MSW management and transportation sectors are considered, gasification apperas very favourable. Combining MSW gasification with direct hydrogen FCVs (scenarios A and I) is almost twice as energy efficient as incineration combined with direct hydrogen FCVs using hydrogen from natural gas (scenarios D and II), and would be a significant improvement in comparison with the other alternatives. This perspective is, however, too limited to account for the total system impacts. If the other functions of waste management (recovery of electricity and materials) are taken into account as well, gasified MSW as a source of hydrogen for FCVs is about as energy efficient as incinerating MSW while relying on natural gas as a source of hydrogen. Landfilling however stands out as the least energy efficient alternative. Regarding materials recycling vs. gasification, it appears to be equally energy efficient to recycle combustible materials and produce vehicle fuels from other sources.

In comparison to the current situation in transportation and waste management (mainly gasoline internal combustion engines and landfilling, respectively), MSW gasification and FCVs would significantly enhance overall system energy efficiency and reduce greenhouse gas emissions. But if MSW can be incinerated with efficient recovery of electricity, both natural gas and methanol appear to be about as energy efficient hydrogen sources as MSW, but with lower greenhouse gas emissions. The hybrid gasoline-electric vehicle shows comparable impact on both energy use and greenhouse gas emissions. However, if MSW were incinerated without electricity recovery, non-renewable energy use and GWP would be lower in the gasification scenario than the incineration scenario.

5 RELIABILITY IN LCA

An important experience from performing case studies with ORWARE is the importance of acceptance by the involved authorities and companies. Essential to gain acceptance is credibility, of which one important aspect is model reliability. The level of requested model reliability depends on the intended use of the results. Reliability of mathematical models is traditionally assessed by statistical analysis of model data and calibration of the model. But classical statistical analysis requires several measurements of each data point, whereas ORWARE frequently relies on one single measurement or even estimated values. Further, calibration requires that model results can be compared to real data, which is not possible when hypothetical large-scale technical systems are modelled.

These problems are by and large the same as those encountered in LCA models. Therefore, as a first step to develop an approach to formally handle reliability in ORWARE, a survey was performed of the literature on LCA and reliability (Paper VI), which forms the basis for this section. Different types of uncertainties relevant to LCA were identified, as well as tools that address them. Addressing a certain type of uncertainty does not necessarily mean reducing it to a minimum or assessing the extent of it. Sometimes this is just not possible. Other approaches are then needed that allow communicating the importance of that uncertainty. It was expected that the survey would be able to identify one or a number of tools that can be used regularly in ORWARE case studies, to improve data quality and assess the uncertainty of the final results. Although not covered in the paper, this is discussed in section 6.1 "

The problems associated with reliability in LCA are long since acknowledged. Vigon and Jensen (1992, as cited in USEPA 1995) noted that LCA practitioners lack systematic approaches for determining the quality of data, and that there is a need for improved techniques for sensitivity analysis and uncertainty analysis. Despite this, the state of the matter is that data quality and uncertainty are often discussed, but there is still a lack of consensus about methodology, and real assessments are rarely done. The survey however identified a wide range of tools and approaches, from the early mainly qualitative tools, to an increasing amount of quantitative methods.

Strictly, uncertainty arises due to lack of knowledge about the true value of a quantity. Eleven different types of uncertainty in LCA were identified:

- Data inaccuracy
- Data gaps
- Unrepresentative data
- Model uncertainty
- Uncertainty due to choices
- Spatial variability
- Temporal variability
- Variability between sources and objects
- Epistemological uncertainty (caused by lack of knowledge)
- Mistakes
- Estimation of uncertainty

The different tools that were identified to address these uncertainties were divided in three different categories, tools for:

- improvement of data quality and availability,
- sensitivity analysis, and
- uncertainty analysis.

Table 2 summarises what types of uncertainty can be addressed by the different tools. It is quite clear that not one method alone is enough to handle data quality and uncertainty. Thus, the range of methods appears quite necessary to cover all possible needs.

Standardisation of the LCA methodology, such as the ISO standards (ISO 1997, ISO 1998, ISO 2000), and development of standardised databases, such as the SPINE and SPOLD database formats (Pålsson 1999, Weidema 1999) may improve data quality and availability. These approaches require consensus among LCA practitioners, which makes them time and resource demanding long-term solutions. Data quality goals (DQG) and data quality indicators (DQI) are simpler and straightforward approaches that can be tailored to the specific needs in each case, which makes them flexible. DQGs specify in general terms the desirable characteristics of the data needed for the study (SETAC 1997). DQIs relate the quality of data to the DQGs (e.g. SETAC 1997, Weidema and Wesnæs 1996). Making additional measurements of inventory data or using higher resolution are seemingly simple approaches, but often too time consuming and costly.

Sensitivity analysis is a systematic procedure for estimating the effects on the outcome of a study of the chosen methods and data (ISO 1998). It is a means to acquire better knowledge and understanding of a model and its behaviour. This may sometimes be more valuable for the overall credibility of a model than using the most elaborate uncertainty assessment techniques or spending more resources to improve data quality. Closely related is uncertainty importance analysis, which focuses on how the uncertainty of different parameters contributes to the total uncertainty of the result (SETAC 2000). This is a good screening methodology, which can help in prioritising model improvements.

Among tools for uncertainty analysis, classical statistical analysis was the first quantitative tool to be proposed, but has not been very successful in LCA. The reason is the difficulty of statistically deriving uncertainty distributions. Bayesian statistical analysis solves this by making use of uncertainty distributions based on expert judgement. Probabilistic, or stochastic, simulation estimates uncertainty by repetitive model simulation with parameter values randomly sampled from uncertainty distributions. It is especially promising for uncertainty analysis in LCA, because it allows for the use of any type of uncertainty distribution, and can be used with all kinds of operations (Heijungs 1996, Huijbregts 1998, Maurice et al. 2000).

Table 2 *Overview of tools available to address (reduce and/or illustrate) different types of uncertainty in LCA. Modified from Huijbregts (1998).*

	Data inaccuracy	Data gaps	Unrepresentative data	Model uncertainty	Uncertainty due to choices	Spatial variability	Temporal variability	Variability in objects/sources	Epistemological uncertainty	Mistakes	Estimation of uncertainty
Standardisation					x					x	
Data bases		x	x								x
Data quality goals	x		x								
Data quality indicators	x		x								
Validation of data										x	
Parameter estimation		x									
Additional measurements	x	x	x					x			
Higher resolution models				x		x	x				
Critical review		x	x		x				x	x	x
Sensitivity analysis	x		x	x	x	x	x	x			
Uncertainty importance analysis	x		x	x	x	x	x	x			
Classical statistical analysis	x					x	x	x			
Bayesian statistical analysis	x					x	x	x			
Interval arithmetic	x										
Vague error intervals	x										
Probabilistic simulation	x							x			
Scenario modelling			x	x	x	x	x	x			
Rules of thumb	x										

Some kind of tools to address data quality and uncertainty are needed, but they cannot be too complex. Not only because it would be very difficult to collect the necessary data. In most cases it would not be practically feasible to spend the necessary time and resources, and thus the tools would not be applied. A good tool must lead to actual improvement of data inventory routines, model insight and results presentation, as well as be of help to decision makers. Simple tools may be dismissed as not being accurate enough, but may still be used most in the long run, simply by being practically usable.

The amount of extra work associated with data quality management and uncertainty analysis can be limited if efforts are focused on the most important areas, and areas where large improvements can be gained at limited efforts. Key issues can be identified by uncertainty importance analysis, but also based on experience of what types of uncertainty are usually most important. Selection of system boundaries and allocations methods tends to have large influence, which may well override many other types of uncertainty. This type of uncertainty cannot be eliminated, but can be illustrated by identifying the relevant alternatives and performing sensitivity analysis by scenario modelling.

The best way to help practitioners and ensure a comparable standard of LCA studies would be to agree on a framework for data quality management and uncertainty analysis. A good framework should:

- point out the important aspects of data quality and uncertainty in LCA,
- guide through the considerations one must make regarding for instance desired results, time and resources,
- describe what one can do to address different issues, and
- describe how to do it.

6 DISCUSSION AND CONCLUSIONS

6.1 Conclusions about waste management design - Don't waste waste

Although the main focus of this thesis is on the usefulness and methodological aspects of ORWARE, of most general interest are probably findings regarding how waste management systems should be designed. In the end, being able to draw such conclusions is what makes the model useful. It must always be kept in mind though, that results from one area are not directly applicable to other areas. Due to site specific conditions and assumptions made to reflect the questions in a particular study, overly simplified generalisations should be avoided.

However careful one should be about generalising site-specific results, there are findings of wider relevance. This section summarises some results that have come out repeatedly of ORWARE case studies (the ones presented in this thesis and others), but is no comprehensive compilation of such conclusions. Even in these cases, objections to any generalisation may of course be made, as most results can be altered if the technical performance of the modelled processes is considerably altered. Thus, results should actually be interpreted in their real context.

Reducing environmental impact of waste management is a matter of recovering resources from waste to the extent possible. This is so because the impacts of compensatory processes, which account for burdens that are avoided when resources are recovered from waste rather than produced from virgin sources, tend to be of the same magnitude or larger than that of the waste management core system. Thus, landfilling of waste should be avoided because it is a waste of resources. Although some energy may be recovered from landfills through landfill gas recovery, it is much less efficient than other energy recovery technologies. In addition, the environmental impact of landfill emissions is significant in comparison to other treatment options. Composting, which allows nutrient recovery but generally no energy recovery, is in many ways as wasteful a treatment method as landfilling. Its emissions are however less significant, mainly because composts are aerated, which leads to much less emissions of methane, which is a potent greenhouse, gas.

Thus, incineration, anaerobic digestion (provided heat, electricity, or biogas are recovered), or materials recycling are preferable solutions. However, the possibility to choose among these technologies may be restrained by different reasons. For instance, contaminated waste fractions may limit the possibilities of resource recovery. Heavy metal contamination has often turned out to be a decisive obstacle to nutrient recovery by utilisation of sewage sludge, anaerobic digestion residue, and compost in agriculture. If contamination limits the possibility to apply otherwise beneficial technologies, this should be dealt with upstream of the waste management system, so as to avoid contamination in the first place. Cost is another important limitation. However, cost as experienced by waste managers is not necessarily the actual long-term cost to society, so that decision based solely on this cost may be misleading.

A conclusion that tends to surprise decision-makers is the modest impact of transports. Emissions from transports often play an important role in the debate. This is not surprising, since transportation is one of the most important environmental concerns of society in general. Locally impacts of waste transports can be serious, and it is one of the more expensive operations in waste management. But when viewing waste management from a life cycle perspective, transports cause but a minor part of the total impact. Once collected, waste can be transported far without significant impact.

Thus far, the case studies agree. Less clear are the conclusions regarding what exact method of resource recovery is to prefer. It depends primarily on what exact products are recovered and what virgin products they replace. Results come out quite differently when using heat from incineration to replace heat from either biofuels or oil, or when using biogas either to generate electricity replacing hydro generated electricity or to run biogas cars. At this level, results can no longer be generalised, but the specific circumstances must be specified in detail.

6.2 Model limitations

By definition, models are simplified representations of reality. When working with a model and interpreting its results, it is important to be aware of its limitations by knowing *how* simplified, i.e. what aspects of reality are included and how realistically they are modelled. This determines what questions the model can be used to address. In all models, it is a matter of course that the model is no better than the data used to build it. Thus, the sub-models of ORWARE are limited by the data of the information sources used.

Although rather extensive, the list of substances modelled in ORWARE (Table 1) does not cover all substances of environmental relevance in waste. The list of substances was determined according to current knowledge and what was thought feasible to model. Despite this, there are still data gaps in primarily the modelling of organic pollutants. There is lack of knowledge about some organic substances/substance groups in Table 1, which thus are not satisfactorily modelled. Other substances that may be of relevance, but are even less known, are left out of the model. It is also likely that important substances have not yet have been identified, which thus could not possibly be included. This is however not a limitation of the model, but rather a limitation of scientific knowledge as such.

As was mentioned previously, ORWARE is a static model, working with one-year averages. Consequently, the model describes fairly well the average yearly impacts of waste management, but does not capture for instance differences between summer and winter in waste composition, peak demands for district heating, or variations in emission levels from waste incineration. Nor does it have any means of predicting and including process disturbances or other unforeseen events. If disturbances occur regularly and affect the average measures on which the model is built, they are however included implicitly.

ORWARE does not include all impact categories recommended for life cycle assessments. Among those included are only categories that are possible to determine based on quantification of substance flows. For instance, biological diversity and non-toxicological health impacts are not included. Other impacts, which in theory could be quantified based on substance flows, have been excluded do to lack of data or irrelevance. Ecotoxicological and toxicological health impacts depend to a great extent on organic pollutants, for which there are severe data gaps in ORWARE. Depletion of stratospheric ozone was estimated to insignificantly affected by municipal waste management.

6.3 Reliability of ORWARE

Reliability of the ORWARE model was addressed qualitatively to a limited extent in Paper I. Model equations were characterised as:

- mechanistic, with known mechanisms ruling the modelled phenomenon,
- empirical, with parameters based in experimental data and statistical methods,
- measurements, based only on single point estimates, or
- plausible assumptions, based on expert judgement or estimates.

The characterisation of data quality was taken one step further in Bjuggren et al. (1998), in which all sub-models were described with a few simple DQI. This communicates some quality issues of the model. In addition, uncertainties due to choices have been analysed to some extent in all ORWARE case studies by scenario analysis. This is a start, but much more remains to be done.

A long-term aim of compiling the tools in Paper VI was to identify one or a few methodologies for improvement of reliability suitable for regular use in the ORWARE model. These methodologies could be incorporated in the form of calculation tools in the computer model, but also in the form of guidelines for routines to follow during the data inventory phase, and possibly also in the results presentation. This is yet to be done, but in the following the findings in Paper VI are used to discuss a proper selection of suitable methodologies. Although specific to the ORWARE model, this should be of general interest as an example to LCA and waste modelling practitioners.

Choice of methodology should depend on:

- what uncertainties are present in the ORWARE model,
- what uncertainties dominate the total uncertainty,
- what tools are available to address these uncertainties, and
- what is practically feasible.

6.3.1 Uncertainties in ORWARE

All different types of uncertainties that were identified in the survey are present in ORWARE. Some examples are given below. A much more thorough review should be done in order to identify in more detail the uncertainties of each specific sub-model.

Data inaccuracy. Data inaccuracy due to measurement errors can never be entirely avoided. It is an issue for any type of data in the model; waste characterisation, process parameters, transport distances, fuel consumption etc. As the data used in ORWARE are seldom measured for the specific purpose of waste modelling, but is collected from other data sources, measures of data inaccuracy are generally missing. Inaccuracy of measured data is not necessarily a big problem in ORWARE, but this is difficult to conclude if measures of uncertainty cannot be obtained.

Data gaps. Missing data is a common problem. Site specific adjustments of the model may be difficult because of for instance incomplete statistics of waste amounts or incomplete measurement of process parameters. Non-site specific parameters may also be missing because of lacking knowledge about for instance compost or landfill degradation processes. Data gaps are especially severe if not recognised in the final model calculations and noted in the results. Complete data gaps in a model may be avoided by using more or less unrepresentative data or estimated data.

Unrepresentative data. Because of data gaps, unrepresentative data must sometimes be used as a substitute. Data from foreign databases can be a source of unrepresentative data, but this may often be better than leaving the model with a complete data gap. Use of unrepresentative data may also be due to difficulties of knowing what is actually representative, for instance when choosing to model marginal or average electricity production. Unrepresentative data may often be a good enough substitute, but also at times severely misleading.

Model uncertainty. By definition, a model is a simplified representation of reality. Therefore model uncertainty naturally cannot be eliminated. Some phenomena are however more difficult than others to model in an adequately realistic way. An example of a considerable simplification in ORWARE is the landfill sub-model, which does not take into account for instance different liner systems or variations in precipitation, and calculates the total emissions during two time horizons, but not their spread over time. The ambition is to avoid severe simplifications that tend to have significant impact on the results.

Uncertainty due to choices. Choices are unavoidable in systems analysis. For instance, ORWARE could in theory include all links between all affected processes, but in practice a system boundary is drawn that excludes parts that are thought to be less important. One example is excluding production of capital equipment, which may constitute a noticeable part of the total system impact. Another type of choice is selection of compensatory processes. It is not always certain what the compensatory processes of for instance electricity production is, or one may want to show the impacts if it were produced from biofuels, hydropower, or something else. As a result, entirely different processes may be modelled, resulting sometimes in totally different results.

Spatial variability. Spatial variability is important especially in the impact assessment, as the same emission may cause different impact in different places due to spatial variability in e.g. background concentration. This is not taken into consideration in the ORWARE model.

Temporal variability. All calculations in ORWARE are done using yearly averages. This precludes the inclusion of variations over time, but is in most cases adequate for the purpose of the model.

Variability between sources and objects. Inherent variations between sources and objects are not captured in a model like ORWARE, which is based on average values. An example of variation between sources is the fuel efficiencies of collection vehicles, depending on how they are driven. Like spatial variability, variability between objects may affect the impact of an emission, depending on the sensitivity of the exposed organisms. It can be expected however that averages give a fairly good picture of the system, although the extremes will not be recognised.

Epistemological uncertainty. There is always a risk that lack of knowledge about individual processes or the system design causes errors in the model. This is hopefully minimised by consulting specialists in the different fields that are covered by the model. When modelling a hypothetical future system, it is in practice impossible to know the exact performance of processes and system, and one must rely on forecasts, predictions, and guesses.

Mistakes. Mistakes are difficult to entirely avoid, and may appear in data collection, implementation of the computer model, data processing, and results presentation. Peer review and double-checking are good, but not water proof means to avoid mistakes.

Estimation of uncertainty. If one tries to assess the total uncertainty of model results, assessment of the uncertainty of individual parameters is in itself a source of uncertainty. This has not yet been done in the ORWARE model.

As no quantitative assessment has been done of these and other uncertainties in ORWARE, it is not possible to say what the range of uncertainty may be in specific case studies. However, although certain parameters may be highly uncertain, it is likely that the overall uncertainty is generally dominated by a few discrete choices. As was clearly expressed by the views of participants of several ORWARE case studies, quantitative results were not the only important outcome of the projects. Just as important, or even more important, was the sense of getting a wider perspective of waste management and environmental problems in general. In this case, the range of uncertainty of the results is of no real importance.

6.3.2 Outlining an approach to improve reliability in ORWARE

Usefulness and feasibility are decisive when choosing methodology to improve reliability. The required extra efforts must be reasonable, and the outcome must contribute to the usefulness and credibility of the model. Efforts should be focused on the dominating uncertainties. To identify these, a more detailed survey should be done of the uncertainties of sub-models and system design than the examples listed in the preceding section. Based on experience from ORWARE case studies and other LCA studies, the seemingly most important uncertainties should then be selected for more detailed analysis by sensitivity or uncertainty importance analysis to identify key issues. Depending on the findings of the sensitivity and uncertainty importance analyses, efforts should be made to improve the quality of key data. Alternatively, if uncertainty cannot be reduced, the results of some sensitivity analyses may be included in the final results.

If uncertainty analysis should at all be performed, the necessary data must be accessible. As pointed out in Paper VI, many uncertainty analysis tools are not practically feasible in LCA, because they require too much of statistical information. In ORWARE, data is collected from existing sources, such as environmental reports, official statistics, and the general literature. Very seldom do these data sources provide any information on uncertainty. For an uncertainty assessment of ORWARE, it must therefore be sufficient to use estimated uncertainty ranges. Because of the size and complexity of the model, analytical propagation of uncertainties is not feasible. Stochastic simulation appears to be the most appealing choice. However, this too will be time consuming, and not necessarily more valuable than other approaches. A simplified alternative would be to perform uncertainty analysis only of key data, or to analyse only a few model scenarios and rely on these results in future case studies.

Disregarding what uncertainties dominate, if they are quantified, and if total uncertainty is assessed, a number of measures that require limited extra effort should be applied at a minimum. They will not quantify uncertainties, but will improve the quality of data, make a good basis for further analysis of sensitivity and uncertainty, and may contribute to credibility quite significantly.

Data quality goals (DQG) and data quality indicators (DQI). DQGs can be formulated so that they can be used also as DQIs. The ISO standard (ISO 1998) includes a range of data quality requirements, and many more have been suggested elsewhere. Striving for feasibility though, the DQI suggested by Weidema and Wesnæs (1996) appear useful and manageable for the ORWARE model: temporal, geographical, and technological correlation, reliability, and completeness.

Compile discrete choices. Not all information in ORWARE can be described by DQIs. Discrete model choices, such as system boundaries or functional units, are non-quantitative but often uncertain parameters. An overview of discrete choices, along with the identified alternatives, provides important insight in the model.

Validation of data. An effective approach of validating data by checking data consistency is already implemented in the ORWARE model. Registration of all material flows over all process sub-models ensures that material balances are maintained for all elements.

Critical review. External experts should always be engaged for critical review. The individual sub-models need only be reviewed once, but case specific data should be reviewed in each new case study.

These measures should give a good picture of the overall quality of data in the model, as well as being of good help to narrow down on key issues in the sensitivity analysis, and providing information to the uncertainty analysis described above.

Table 3 is an attempt to summarise the suggested approach, showing what types of uncertainty are introduced in the different phases of modelling in an ORWARE case study, and what the suggested measures are to deal with them.

Table 3 *Overview of suggested approaches to address different types of uncertainty introduced in different phases of modelling in an ORWARE case study. Approaches in italics suggested as a minimum.*

Modelling phase	Data inaccuracy	Data gaps	Unrepresentative data	Model uncertainty	Uncertainty due to choices	Spatial variability	Temporal variability	Variability in objects/sources	Epistemological uncertainty	Mistakes	Estimation of uncertainty	**Approach to address uncertainty**
1. Sub-model development	x	x	x	x		x	x	x	x	x		*Decide DQG. Assess DQI. Critical review of sub-models.*
2. Site specific adjustment of sub-models	x	x	x	x		x	x	x	x	x		*Assess DQI. Critical review of adjustments.*
3. System model implementation					x					x		*Compile choices and alternatives. Critical review of system design.* Sensitivity and uncertainty importance analysis. Refine data quality of key issues. Simplified uncertainty analysis.
4. Simulation												
5. Data processing										x		*Check material balances.*
6. Characterisation	x	x	x	x	x	x	x	x	x	x		
7. Results presentation										x		Present findings from uncertainty assessment.

Although characterisation contributes to overall uncertainty, no suggestions are made to address it in an uncertainty assessment of ORWARE, simply because the additional complexity of an uncertainty assessment if it were included. Partly because additional data would need to be treated, and partly because the uncertainties are best assessed by those experts by whom the methods were developed.

6.4 On the usefulness of ORWARE

6.4.1 Different applications

The three case studies presented above (Papers III, IV, and V) illustrate different areas of application of the ORWARE model. They all aim to produce results relevant in decision making, either operative or strategic. The practical implementation of the model in each case was in essence the same, but the underlying questions were quite different.

The objective in Stockholm (Paper III) was to find guiding principles for biodegradable waste treatment that would not counteract the Environment and Health Protection Administration's goals of reduced environmental impact and resource consumption. This involved investigating both likely and less likely alternatives, to understand the system, and in search for good alternatives. Although not an explicit objective in this case, this type of analysis can serve as a basis for decision when making strategies for future waste management.

In Uppsala (Paper IV), the objective was clearly limited to evaluating a waste management strategy that had already been decided upon. Other, possibly advantageous alternatives, were not investigated. The results served as feedback to the municipality about the impacts of implementing the strategy, but were of no real importance as a decision basis.

If ORWARE is to contribute to the decision basis in waste management planning, it is important to apply the model at the right time in the decision making process. If applied too soon or too late, the results might not be of any practical use. In Stockholm, where the model was used when there was no actual ongoing decision making process, the questions asked by the decision makers were vague and difficult to be meaningfully linked to the model results. In Uppsala on the other hand, the major decisions had already been taken and were not likely to be changed because of the model results. It is important that clear questions are formulated before or during the course of the study, because the design of the study and presentation of results should be tailored to answer these.

Waste management planning however is not the only possible application of ORWARE. In the study of waste gasification and fuel cell vehicles (Paper V), the aim was to evaluate the feasibility of a new technical system. This is a type of technology assessment[1], something that is further investigated in Assefa et al. (2000). The evaluated future

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[1] Technology assessment has been defined as a category of policy studies, intended to provide decision-makers with information about the possible impacts and consequences of a new technology or a significant change in an old technology (UNEP 1992, as cited by CEFIC 1992).

scenarios would be practically feasible at the earliest within 10 to 20 years, which added to the uncertainty the data sets used. Besides, there was no real orderer or client to the study, which was conducted merely for research purposes. The expectation though, was that albeit rough in its calculations, a study of this type may serve to guide future R&D of these technologies.

6.4.2 User experiences

ORWARE has been developed mainly as a research tool, but is also used for waste management strategies, planning and evaluation. The model is a powerful research tool, its flexibility giving great freedom to the researcher to design new applications to investigate new questions. But practitioners, planners, and decision-makers are likely to have other requirements than researchers on a tool like ORWARE. How useful is it to practitioners as a planning tool? What are the experiences of stakeholders from municipalities and companies that have been involved in such studies? To get an idea of the experiences and opinions of non-researcher participants of ORWARE projects, a minor inquiry was made among some of those who were involved in ORWARE case studies between 1995 and 1999[2]. On the whole, the opinions of those asked were very positive.

Case study results have come to practical use by almost all involved organisations. In many cases the results were used directly as decision basis in development of waste management strategies, planning, or purchasing of waste management services. In other cases project documentation was used as a source of information in general discussions.

Several participants mentioned that they appreciated how the model revealed the complexity of waste management, and as a consequence improved their understanding of how complex environmental issues in general are. All participants mentioned the importance of the systems perspective, and felt that working with ORWARE was a good way of learning this way of thinking. In some cases only they personally benefited from this, while in other cases the project had a wider impact on their organisations. Some participants mentioned that these perspectives were already part of their work, and were their reason to initiate a case study with ORWARE to begin with.

Although a widened systems perspective appears to be the most lasting experience, several participants also pointed at insights in specific questions, such as highlighting of technical barriers of some technologies, and revealing of some significant issues that had not been acknowledged earlier.

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[2] Answers to the inquiry were received from: Göran Albjär, Uppsala Environment Office; Johan Ericson, Uppsala Energi; Ingela Hammerfeldt, Stockholm Waste Management Administration; Avtar Jasser, Hydro Agri Europe; Leif Lundin, Värmdö Waste Management Department; Ulf Molander, Stockholm Environment and Health Protection Agency; Per-Erik Persson, Vafab; Bo Twengström, Stockholm Water Company; Ulf Wikström, Stockholm Environment and Health Protection Administration, now with Birka Energi; Lars Erik Wretblad, Stockholm City Planning Administration.

Several participants pointed at the difficulties for other groups than specialists to understand and interpret the results of ORWARE case studies, and asked for a simpler reporting format. Also, the model, its structure, sub-models, and data were difficult to penetrate. Some participants spent much time and effort to understand and critically review the model, while those who did not were uncomfortable with the feeling of working with a black-box. Some pointed at the importance of being aware that the model does not deal with all important aspects, but still thought it was a good way of getting the important questions on the table and then deal with them by other means. Likewise, although valuation and prioritisation was difficult, the results were considered useful to gather different stakeholders for discussions.

Regarding the feasibility of using ORWARE or similar tools on a more frequent basis, the opinions diverged. While some considered such tools too complex and time consuming to use on a daily basis, others worked with this type of analyses regularly already before participating in the ORWARE case study, or had come to do so afterwards.

6.5 Is systems perspective in waste management important?

Decisions based on a systems perspective are often pointed out as absolutely necessary in waste management and environmental issues in general. Meanwhile, and somewhat paradoxical, authorities tend to want to find simple solutions to complex problems, such as the waste hierarchy. ORWARE and similar tools improve the possibilities to bring systems perspectives into the decision-making process on a regular basis. Important though, as pointed out by Wilson (1998), life cycle tools for waste planning cannot on their own create well running waste management systems, but hopefully help regions and municipalities in planning. In interviews with decision-makers about LCA in environmental decision-making (Huybrechts et al. 1996), LCA was considered potentially useful by providing objective information, increasing participation in environmental decision-making, and identifying improvement options. On the other hand, long-term strategic use was questioned because of the controversy of the questions addressed, and the controversy caused by the case studies themselves.

The dominating experiences of participants in ORWARE projects were more positive, and the complexity revealed in the analyses was appreciated rather than considered an obstacle. Findings from the projects had come to practical use, and the perspectives in waste management and other environmental issues of the participants and their organisations had been widened. An obstacle, though, to its usefulness and spread as a decision-support tool, is the complexity of the tool itself. Although scenario formulation and data collection can largely be done by different actors involved in waste management, simulation and interpretation are almost exclusively done by researchers. However, a more simplified model is no guarantee for more wide spread use by practitioners. McDougall and White (1998) reviewed case studies performed with the model by White et al. (1995), which is distributed in a rather simple spreadsheet format. Despite its user-friendly format, it was concluded that the main users so far had been academics and consultants.

The aim of ORWARE however is not only that of a planning tool, it is also a research tool. As such, it rather benefits from this complexity, which also makes it flexible. In research applications, the degrees of freedom are naturally larger than in waste management planning and evaluation. Scenario design is not limited by short-term technological constraints on the waste management system, hypothetical solutions can be analysed, and links between waste management and other systems, which are not realistic today, can be modelled. Such analyses are not primarily intended for decision-making, but may serve to reveal new interesting technological research areas, support or question ongoing research, identify knowledge gaps, and illustrate the systems impacts of waste management in general.

To me, there is no doubt that systems perspective in waste management is important. The results show the importance of systems thinking, of being aware of how decisions in waste management may affect other systems, and of being able to separate important issues from the less important. But this does not necessarily require mathematical models like ORWARE, at least not to be used regularly by planners. Working with ORWARE is a good way to learn systems thinking, because it opens up new perspectives and forces one to systematically resolve the problem. Once acquired though, this "systems analytical skill" can be practised quite successfully at a general level without computer models. Thus, to a great extent ORWARE finds its usefulness as an educational tool. However, when it comes to quantifying impacts, as is needed in certain phases of waste management planning and in research, computer models are of course the most convenient.

6.6 Future research

Since the beginning of the first ORWARE project in 1993, the model has been subject to continual development. Practically every case study has included new methodological components and development and testing of new process sub-models. As I see it, research efforts with ORWARE should now focus on two general areas; further refinement of the existing model and development of its application.

Refinement of the existing model should partly proceed as it has done so far, by including new data and new sub-models. New data need to be incorporated in the existing sub-models when made available, to improve data quality and fill in data gaps. New sub-models should be developed as new questions arise and new technologies emerge. I however do not believe in increasing the level of detail of the sub-models. Increasing the complexity would not be to the benefit of the purpose of the model, but rather make it more difficult to overview, more difficult to use and adjust to site-specific conditions, and more difficult to interpret the results. Actually, even the opposite may be needed in some sub-models. Refining the model may involve simplifications of sub-models, but assuring that the most significant parameters are realistic.

As a direct continuation of some of the material presented in this thesis, further work should be done to implement the findings from the survey of uncertainty in LCA. It should be possible to develop a framework for handling data quality and assessing sensitivity and uncertainty in ORWARE.

Different things can be done to develop the applications of ORWARE. If the model is to be used as a waste planning tool, it is necessary that its design be adjusted to the needs of planners. In particular the presentation of results needs to reflect the questions relevant to decision-making. To a large extent this would not involve remodelling, but rather understanding how to use and present the results. An analysis of the needs of planners should be made to identify important decision parameters.

The model would also be more suitable for planning if it were designed in such a way as to facilitate rapid screening analyses. In many instances, the level of detail offered in ORWARE may lead to unnecessarily detailed analyses. By providing reasonable cut-off suggestions for less important processes and suggested default data, the project time could be reduced when a rather crude analysis is acceptable. Another solution to this idea is underway in an ongoing project. By means of a decision guide based on findings from earlier scenario simulations, a more or less qualitative description of the waste management and energy situation in a municipality should be sufficient to point out the impacts of different scenarios. This would reduce the need for full-scale studies, while still giving rather valuable information.

After improving the current modes of application of ORWARE, the next step would be to seek new application areas. One that was touched on earlier in the thesis is to explore ORWARE, or rather the methodology of ORWARE, as a tool for technology assessment, to help understand the likely impact of the use of new technologies in terms of environmental effects. The model could provide a systematic framework for assessing the systems impact of emerging technologies and technical systems.

In light of the current trend of bookkeeping of substance and material flows at corporate, local, and national levels, ORWARE could fit into a wide framework of material flow accounting systems. Applying the methodology of ORWARE to systems of wider scope would allow for more comprehensive assessments of possible paths to reduce environmental impact. Because waste is a relatively visible environmental problem, it is also perceived as important. Analysing waste management in an even wider context than in ORWARE, relating it to other sectors in society such as energy and transportation may give some perspectives on the relative importance of different sectors. However, if accounting is the only objective, working with the type of process models that are now incorporated in ORWARE does not seem motivated.

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GLOSSARY

allocation: partitioning the input or output flows of a process to the system under study

biodegradable waste: solid and liquid organic wastes from human activity or animals, which is readily biodegradable in biological treatment such as composting or anaerobic digestion

broadened system boundaries: when compensatory production of a functional unit is added to or subtracted from a system

characterisation: weighting of the contribution of individual inputs and outputs to different impact category, according to the classification, and aggregating the total contribution to the impact categories

classification: assigning input and output data to a number of impact categories, based on the type of impact they cause on the environment

compensatory process: process of conventional production of a function, which is added to a system as means to circumvent the problem of different functional output of systems in a comparative study

core system: part of analysed system that is directly related to the function of a system, includes those activities that may be directly affected by decis ions based on the study

down-stream process: part of analysed system that takes place as a consequence of activities in the core system

enlarged system: consists of the up-stream, down-stream, and compensatory processes

environmental systems analysis: systems analysis for assessment of environmental impacts and/or natural resource use caused by the studied system (a product, service, economy, or project), often focused on quantification of material and energy flows in subsystems of nature and society and the evaluation of the future sustainability of different alternatives of action

function: product, process or service delivered by a system

functional unit: quantified measure of functional output from a system for use as a reference unit in a life cycle assessment

input: material or energy that enters a system

life cycle assessment (LCA): a method to evaluate the environmental burdens associated with a function by identifying, quantifying and evaluating the environmental impact of inputs and outputs over its entire life cycle

life cycle inventory: inventory of inputs and outputs associated with a function in LCA

material flow analysis (MFA): accounts in physical units the flows of selected materials through a certain area

model: simplified representation of reality, in the context of this thesis generally meaning a computerized mathematical model

multiple functional units: two or more functional units defined when systems in a comparative LCA deliver more than one function

non-biodegradable waste: waste fractions that normally would not be suitable for biological treatment, in the context of this thesis restricted to non-hazardous waste

normalisation: optional step of LCA in which data from the characterisation are related to the total magnitude of that impact for the relevant area and time

output: material and energy that exits a system

scenario: description of a possible future situation, based on assumptions about the future, and are characterised by choice of system boundaries, allocation methods, technology, time, and space

sub-model: smaller, detachable entities of an entire model, i.e. landfill and incineration may be sub-models of a model of a waste management system

substance flow analysis (SFA): description and modelling of flows and stocks of substances in a region, accounting in physical units exchanges of substances between the lithosphere, biosphere and technosphere

system: a set of related entities that interact with each other in some way

system boundary: delimitation in time, space and function between a system and its surroundings

up-stream process: part of analysed system that provides necessary input to the core system, e. g. extracting and processing resources used by the core system

valuation: calculation of a single index of total environmental impact by weighting impact categories against each other, based on e.g. political, ethical or administrative considerations

OTHER ORWARE PUBLICATIONS

In addition to the papers appended to this thesis, the following ORWARE publications are available. Analyses of wastewater treatment systems are only marginally represented in this list. For further references in this field, see Kärrman (2000) and Ramírez et al. (1999).

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14. Eriksson, O., Baky, A., Björklund, A., Carlsson, M., Granath, J., Sundqvist, J.-O., Thyselius, L., and Frostell, B. (2000) Systemanalys för förbättrade beslut avseende energi, miljö och ekonomi i ett regionalt perspektiv. Exemplet energi från avfall. In proceedings of *Sveriges Energiting 2000*, March 14-15, Eskilstuna, Sweden.

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