Doctoral Thesis

Novel Approach for optimizing Waste Management Systems based on Material Flow Analysis

submitted in satisfaction of the requirements for the degree of Doctor of Science in Civil Engineering of the Vienna University of Technology, Faculty of Civil Engineering

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Dissertation

Eine neue Methode zur Optimierung abfallwirtschaftlicher Systeme auf Basis der Materialflussanalyse

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Doktors der technischen Wissenschaft eingereicht an der Technischen Universität Wien, Fakultät für Bauingenieurwesen von

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Wien, Mai 2017

ACKNOWLEDGMENTS

Firstly, I would like to express my great appreciation and thanks to my supervisor, Prof. Paul H. Brunner (Vienna University of Technology), for his encouragement and continuous support during the last years. His constructive criticism and ideas, as well as our stimulating discussions have significantly contributed towards shaping this thesis.

I also thank Prof. Stefanie Hellweg (ETH Zurich) and Prof. Roland Pomberger (Montanuniversitaet of Leoben) for co-supervising this thesis.

The work presented here forms part of the project 'Benchmarking the Austrian waste management' and I am grateful for the financial support from the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, the Austrian federal states (Vienna, Lower-Austria, Upper-Austria, Styria, Burgenland, Carinthia and Salzburg), Altstoff-Recycling-Austria, and the Association of Austrian Disposal Companies. I also thank my colleagues at the University of Natural Resources and Life Sciences in Vienna, Montanuniversitaet of Leoben and the University of Innsbruck. I appreciate the good collaboration and support that took place within the project.

Special thanks goes to the entire team at the Institute of Water Quality, Resource and Waste Management for their many contributions and for making this a special and unforgettable time.

I thank my family and friends (all whom I gratefully call my loved ones) for enriching my life beyond the limits of the university. I would like to extend huge thanks to my parents for their support over the years and to express my gratitude to my beloved for encouraging me.

ABSTRACT

Decision makers are confronted with the question: Is the current waste management (WM) system the most effective or are there other processes for better reaching set goals? Methods are therefore required that allow for the determination of whether goals are achieved, by evaluating economic, social and environmental aspects. In order to compare the goals and outcomes of any given WM system, it is necessary to adopt an approach that takes a complete set of information into account. This thesis investigates assessment methods that focus on the application of material flow analysis (MFA) for the evaluation of WM systems. Its main goal is to develop a comprehensive novel MFA approach by which to optimize WM systems and support goal-oriented decisions in general.

The starting point of this thesis is a survey of assessment methods in order to show their potential and to provide guidance for the application and (future) research into assessment methods. Furthermore, it assesses the potentials of MFA on the level of goods and substances individually, and discusses their differences in view of applicability, effectiveness and data availability. The results reveal the high potential of MFA in supporting goal-oriented WM if the levels of both goods and substances are taken into account. With respect to given goals, these findings lead to the development of a novel approach based on a defined and comprehensive WM system. Material flows beginning with waste input into the system, continuing with collection, transportation and treatment, and ending with recycling, landfilling and emissions are assessed on the levels of both goods and substances. This generalized MFA system and a survey including the value judgment of WM stakeholders is connected to seven criteria which are identified as fulfilling given goals: (i) waste input into the system, (ii) export of waste, (iii) gaseous emissions from waste-treatment plants, (iv) long-term gaseous and liquid emissions from landfills, (v) recycled waste, (vi) waste for energy recovery and (vii) total landfilled waste.

A case study demonstrates the applicability of the novel approach and indicates the advantages of including the levels of both goods and substances in optimizing WM systems. Using STAN software, a countrywide material flow system is established and quantified for Austria, comprising all relevant inputs, stocks, outputs of wastes, products, residues and emissions. Material balances on the level of goods and selected substances (C, Cd, Cr, Cu, Fe, Hg, N, Ni, P, Pb and Zn) are developed to characterize this system. The seven criteria are calculated and used for a scenario analysis. The results of the case study indicate potential of higher collection and recycling rates, but also show a limitation regarding 'clean' product cycles as certain hazardous substances are recycled instead of eliminated by waste-to-energy plants, for instance, or disposed of in safe deposits. Discharges to the environment can be decreased by promoting 'clean' recycling and by prolonging landfill aftercare. The results are reproducible with known uncertainties, and indicate dependencies and contradictions between given goals and criteria. In addition, a scenario analysis shows that it is not possible to improve all defined criteria only with a single measure.

The novel approach that is developed provides benefits for optimization, design, and decision-making in WM through the mass-balance principle and due to redundancy, data consistency and transparency. However, this study also discloses deficits that cannot yet be overcome by this MFA approach, such as the lack of methodical tools by which to take waste exports and long-term effects on recycling-product cycles into account. Furthermore, making comprehensive decisions on how a WM system should develop demands that social and economic issues are taken into account as well.

PUBLISHED PAPERS AND AUTHOR'S CONTRIBUTION

This thesis brings together the results of four years of research and builds upon three journal articles (see appendix):

I: ASSESSMENT METHODS FOR SOLID WASTE MANAGEMENT: A LITERATURE REVIEW
Astrid Allesch and Paul H. Brunner
Waste Management & Research 2014, 32, (6), pp 461-473
DOI: 10.1177/0734242X14535653

II: MATERIAL FLOW ANALYSIS AS A DECISION SUPPORT TOOL FOR WASTE MANAGEMENT: A LITERATURE REVIEW
Astrid Allesch and Paul H. Brunner
Journal of Industrial Ecology 2015, 19, (5), pp 753-764
DOI: 10.1111/jiec.12354

III: MATERIAL FLOW ANALYSIS AS A TOOL TO IMPROVE WASTE MANAGEMENT SYSTEMS: THE CASE OF AUSTRIA
Astrid Allesch and Paul H. Brunner
Environmental Science & Technology 2017, 51 (1), pp 540-551
DOI: 10.1021/acs.est.6b04204

I, II: Responsible for data acquisition, analysis and writing

III: Responsible for analysis and writing, partly responsible for data acquisition

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LIST OF ABBREVIATIONS

APC .... Air Pollution Control Residues
CBA .... Cost-benefit analysis
CEA .... Cost effectiveness analysis
C&D .... Construction and Demolition
C&I .... Commercial and Industrial
ECO-EFF .... Eco-efficiency analysis
EA .... Emergy analysis
EIA .... Environmental impact assessment
ENE .... Energetic performance
ENV .... Environmental consequences
HAZ .... Release of potential hazardous substances
LCA .... Life cycle assessment
LCC .... Life cycle costing
MFA .... Material Flow Analysis
MCDM .... Multi-criteria-decision-making
MSW .... Municipal Solid Waste
N .... Number
ORG.SUB .... Organic substances
RA .... Risk assessment
RES .... Resource potential
SEA .... Strategic environmental assessment
WEEE .... Waste Electrical and Electronic Equipment
WM .... Waste management
WTE .... Waste-to-energy

1. INTRODUCTION

This introductory chapter provides background information, defines the research gap and outlines the goal and scope of this thesis.

1.1. BACKGROUND AND PROBLEM DEFINITION

The primary goals of waste management (WM) are based on the precautionary principle and aim of protecting human health and the environment, the conservation of resources, and aftercare-free waste treatment and landfilling. These goals encompass the protection of future consumers by removing hazardous substances from today's recycling streams (Brunner 2013) and the provision of socially acceptable WM practices (Wilson et al. 2007). In order to reach these goals, decision makers apply integrated strategies that consist of a multitude of connected processes, including the collection, transportation, treatment, recycling and disposal of waste (Al Sabbagh et al. 2012). Decision makers expect practicable WM at an affordable cost and, balancing environmental, economic, technical, regulatory and other factors (Barton et al. 1996).

As the number of available options for waste collection and treatment continuously grow, and as the economic-boundary conditions repeatedly change, decision makers are constantly confronted with the following questions (Rogge and De Jaeger 2012): Is the current WM system the most cost effective method in reaching set goals? Are there other and better combinations of more advanced processes that can provide identical service at lower costs? In answering these questions, decision makers are on one hand under pressure from different stakeholder groups that demand more sustainability, new technologies or cheaper WM (Wilson et al. (2007). On the other hand, they experience a methodological dilemma in choosing an evaluation tool by which to assess and present new WM systems. This situation is particularly challenging due to the many and diverse approaches that promise support for strategic or policy decisions, WM planning, and WM optimization on all levels (companies, municipalities and governments) (Finnveden et al. 2007).

Societies create waste and must attend to it over time, thereby sometimes having to take conflicting decisions. Waste and its management revolves around the demand for resources, environmental concerns, personal identity, human behavior, finance, global market supply and demand, to name but a few factors (Hornsby et al. 2017). Hence, in making a comprehensive evaluation of the many effects that WM systems have, it is necessary to consider all processes that are involved and to take a complete set of information into account (Diaz et al., 2006).

1.2. AIM, SCOPE AND RESEARCH QUESTIONS

This thesis investigates assessment methods that focus on the application of MFA for the analysis and evaluation of WM systems. The goal is thereby to develop a comprehensive novel MFA approach by which to optimize WM systems and support goal-oriented decisions in general. This thesis therefore presents a survey of assessment methods in order to show their potential and to provide guidance for the application and (future) research into assessment methods. Furthermore, it assesses the potentials of MFA on the level of goods and substances individually, and discusses their differences in view of applicability, effectiveness and data availability. Based on these findings, a novel goal-oriented approach is developed with respect to sustainability.

A selected case study demonstrates the applicability of the novel approach and indicates its advantages in applying MFA. The following research questions derive from the goal of this thesis:

1. Which information and criteria can be quantified and derived from MFA?
2. How can the newly developed MFA approach support goal-oriented decision making?
3. How can the newly developed MFA approach be applied in a case study in order to identify future improvements?
4. What are the strengths and weaknesses of the newly developed MFA approach?

The results should support stakeholders and decision makers on one hand, and the research community on the other. The investigations focus on the WM system in order to identify future improvements of existing highly developed WM systems in order to answer the question of whether the current WM system is the most effective method by which to reach set goals.

1.3. THESIS STRUCTURE

The thesis is based on three research articles (see appendix) which are presented in chapters 2-4. Chapter 2 outlines sustainable development and WM goals on different governmental and organizational levels. The use of MFA as a tool for WM decisions substantiates the value and necessity of applying the fundamental principle of MFA: the conservation of matter. Furthermore, assessment methods, which are common tools used to support decisions regarding WM, are investigated in order to provide guidance for the selection of appropriate evaluation methods. Chapter 3 describes the power of MFA in designing WM systems and supporting decisions with regard to given environmental and resource goals. A comprehensive novel MFA approach for goal-oriented decision-making is defined. Chapter 4 presents a comprehensive case study of a nationwide WM system and discusses advantages and drawbacks of a mass-balance approach. Chapter 5 presents concluding remarks and an outlook onto future research questions.

2. STATE OF THE ART

In this chapter, the given goals on different levels (e.g., international and national) are presented to indicate their connection regarding WM. Furthermore, assessment methods are investigated in order to provide guidance for the selection of appropriate evaluation methods (Allesch and Brunner 2014) and the use of MFA as a decision-support tool for WM is discussed (Allesch and Brunner 2015).

2.1. SUSTAINABLE DEVELOPMENT AND WASTE MANAGEMENT GOALS

As a key utility service on which public health depends, solid WM is one of the most important functions of any government (Wilson et al. 2015). Public health and safety are central factors within society and are closely connected to the environment and the economy. In the European Union (EU 28), about 2.5 billion tons of waste were produced in 2014, of which about 4 % were hazardous (Eurostat 2014). In that year, the per capita municipal-waste generation averaged 475 kg throughout the EU, ranging from about 250 to 790 kg across individual EU Member States (EU Commission 2008; Eurostat 2014). The sustainable management of municipal solid waste (MSW) is necessary in all phases of impact, from planning to design, operation and decommissioning. Consequently, the spectrum of waste-treatment technologies and management strategies spans from maintaining environmental quality in the present to meeting sustainability goals in the future (Pires et al. 2011). Sustainable-development or WM goals are named on different legislative and organizational levels.

A resolution adopted by the UN General Assembly defines a set of 17 goals as a plan of action for people, the planet and prosperity (United Nations 2015). They are integrated and indivisible, and balance the three dimensions of sustainable development: economic, social and environmental. In relation to resources and WM, the new agenda attempts to reduce the negative impacts of urban activities and the use of chemicals that are hazardous for human health and the environment, especially through environmentally sound management and the safe use of chemicals, as well as the reduction and recycling of waste, and a more efficient use of water and energy.

On the European level and through the 7th Environment Action Programme (EU Commission 2008), the EU has agreed to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste, by reducing the overall impact of resource usage and by improving the efficiency of such usage. Within the Environment Action Programme, the following actions relating to WM and policy can be identified:

- Reduce per capita waste generation and waste generation in absolute terms
- Limit energy recovery to non-recyclable materials
- Phase out landfilling of recyclable or recoverable waste
- Ensure high-quality recycling, in which the use of recycled material does not lead to overall adverse environmental or human-health impacts

- Develop markets for secondary raw materials to achieve resource-efficiency objectives
- Manage hazardous waste to minimize significant adverse effects on human health and the environment

In order to achieve these goals, market-based instruments and other measures that privilege prevention, recycling and re-use should be applied far more systematically throughout the EU, including extended producer responsibility, while also supporting the development of non-toxic material cycles.

The Directive 2008/98/EC of the European Parliament and of the Council of 5 April 2006 on waste lays down measures by which to protect the environment and human health by preventing or reducing adverse impacts of the generation and management of waste, pursued by reducing the overall impact of resource use and by improving the efficiency of such use (EU Parliament 2008). Furthermore, the waste hierarchy applies as a priority order in waste prevention and in management legislation and policy. In applying the waste hierarchy, certain measures should be taken into account in order to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams, departing from the hierarchy in which this is justified, by life-cycle thinking on the overall impact of the generation and management of such waste.

At the Austrian national level, the Waste Management Act (WMA 2002) provides the legislative framework and the precautionary to which aftercare is connected forms the basis for sustainability. Accordingly, WM should focus on the following:

- To prevent harmful or adverse effects on humans, animals and plants, as well as their basic resources and natural environment, and to generally minimize other negative effects on human well-being.
- To minimize air pollution and gases that affect the climate.
- To conserve resources (raw materials, water, energy, landscapes, land areas, landfill volumes).
- In the case of recycling, to ensure that the materials that are reclaimed do not present a greater risk than comparable primary raw materials or products from primary raw materials.
- To ensure that only such waste remains which can be stored without endangering future generations.

The WM performance of all EU Member States was subjected to a screening which ranked Austria at the top (BiPRO 2012). The high recycling rates for packaging waste as well as the continuously declining greenhouse-gas emissions underline this fact. For the future, the questions that arise are whether given WM goals are achieved and how current WM system be further developed (Allesch and Brunner 2016).

2.2. ASSESSMENT METHODS

One literature review (Allesch and Brunner 2014) assesses studies in view of investigating their goals, methodologies, investigated systems and results regarding economic, environmental and social aspects. At present, many published assessment methods that support decision making in WM are available, and are quite advanced and sophisticated (Coelho et al. 2012). Decision-support models were first applied to WM in the late 1960s (Karmperis et al. 2013) and focus on individual functional elements, such as collection routes or facility locations (Tanskanen 2000). Table 1 provides an overview of various assessment methods that support decisions regarding WM.

The literature review shows that most of the studies used existing assessment methods (see Figure 1). The percentage distribution of the assessment methods that were used shows that approximately 41 % of the reviewed studies used life cycle assessment (LCA) to evaluate WM systems. Approximately one tenth assessed waste-related topics through multi-criteria-decision-making (MCDM). In order to calculate the positive and negative effects of WM scenarios, cost-benefit analysis was used by 6 % and approximately 14 % of the reviewed studies were performed as benchmark studies. Some of these focus on the environmental performance of WM systems, while others focus on their economic performance (Finnveden et al. 2007).

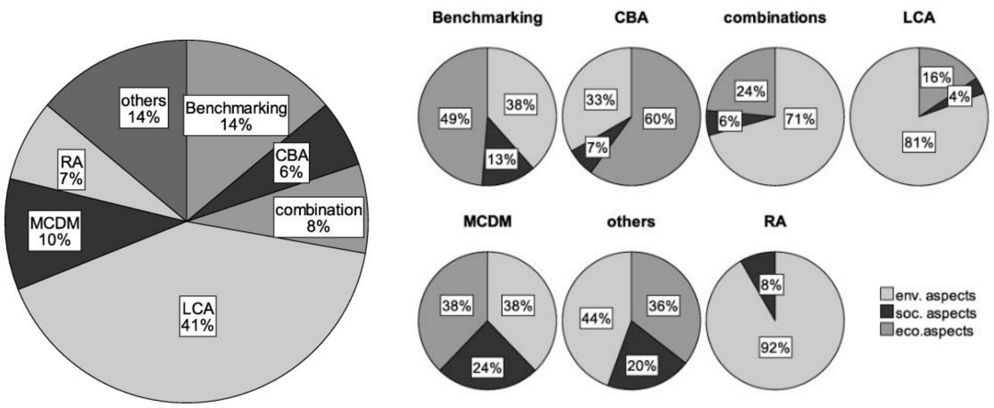


Figure 1: Assessment methods in the reviewed studies (n=151) and considered aspects (Allesch and Brunner 2014).

A comparison of the different aspects (see Figure 1) of the assessment methods in the reviewed studies shows that, in particular, LCA and risk assessment (RA) often evaluated a WM system by considering only environmental impacts. Multi-criteria decision making and the category 'Others' (different methods) appear to be the most complete methods regarding the comprehensive evaluation of social, economic and environmental aspects.

The system boundaries of the reviewed studies differ geographically and thematically. Comparing system boundaries with the object of investigation (see Figure 2) shows that studies that evaluate WM systems, waste-collection systems and waste-prevention options often used geographic boundaries (country, region or city), because these boundaries most likely coincided with administrative boundaries. The functional unit through which to compare different treatment options is primarily one unit of a specific waste stream and the evaluation of a single treatment, often referred to as the inputs and outputs of the investigated plant.

Table 1: Description of different assessment methods (Allesch and Brunner 2014).

ASSESSMENT METHODS	DESCRIPTION
Benchmarking	Benchmarking is a continual comparison of products, services, methods or processes to identify performance gaps, with the goals to learn from the best and to note out possible improvements (Gabler 2005).
Cost-benefit analysis	The essential theoretical foundations of cost-benefit analysis (CBA) are defining benefits as increases in human wellbeing (utility) and costs as reductions in human wellbeing. All benefits are converted to monetary units. The cost component is the other part of the basic CBA equation (Pearce et al. 2006).
Cost-effectiveness-analysis	Cost effectiveness analysis (CEA) evaluates alternatives according to both their cost and their effect concerning producing some outcome (Levin and McEwan 2001). CEA allows the consideration of intangible effects.
Eco-efficiency analysis	Eco-efficiency analysis (Eco-Eff) denotes the ecological optimization off overall systems while not disregarding economic factors. The Eco-Eff analysis by BASF quantifies the sustainability of products and processes, considering the environmental impacts and economic data concerning a business or national economic level (Saling et al. 2002).
Emergy analysis	Emergy is the amount of available energy that is used up in transformations, directly and indirectly for a service or product. The emergy analysis (EA) is an evaluation method that considers both environmental and economic values (Song et al. 2012; Yuan et al. 2011a).
Environmental impact assessment	Environmental impact assessment is a method that has to be performed before consent is given to a project. Significant effects on the environment by virtue, inter alia, of their nature, size or location are made subject to a requirement for development consent and for an assessment concerning their effects (Directive 2011/92/EC).
Exergy analysis	The exergy method evaluates the qualitative change from the available energy to the unusable one in form of work (Szargut 2005; Hiraki and Akiyama 2009).
Life cycle assessment	Life cycle assessment addresses the environmental aspects and potential environmental impacts (e.g., use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (ISO 2006).
Life cycle costing	Life cycle costing is an economic analysis method in combination with life cycle assessment. This method is a tool for accounting the total costs of a product or service over a long life span (EU Guidance 2007; Carlsson Reich 2005).
Multi-criteria-decision-making	Multi-criteria-decision-making (MCDM) is a decision-making tool that facilitates choosing the best alternative among several alternatives. This tool evaluates a problem by comparing and ranking different options and by evaluating their consequences according to the criteria established (Hermann et al. 2007; Hung et al. 2007; Karmperis et al. 2013).
Risk assessment	Risk assessment (RA) is an integral part of the overall organization's performance assessment and measurement system for departments and for individuals. The goal is to provide a comprehensive, fully defined and fully accepted accountability for risks (ISO 2009).
Statistical entropy analysis	The statistical entropy analysis is a method that quantifies the power of a system to concentrate or to dilute substances (Rechberger and Brunner 2002; Brunner and Rechberger 2004).
Strategic environmental assessment	Strategic environmental assessment is a method by which to provide a high level of protection to the environment and to contribute to the integration of environmental considerations into the preparation and adoption of plans and programs. It aims to promote sustainable development by ensuring that an environmental assessment of certain plans and programs, which are likely to have significant effects on the environment, is performed (Directive 2001/42/EC).

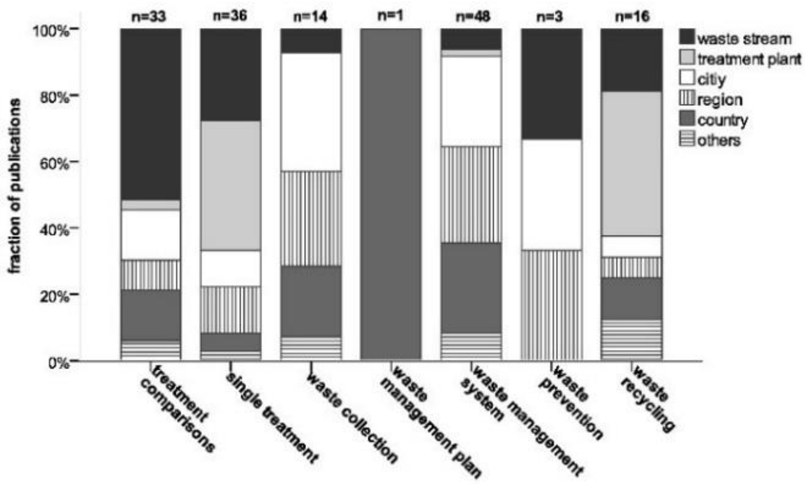


Figure 2: Assessment methods in the reviewed studies: Comparison of the objects of investigation and used scales (Allesch and Brunner 2014).

Figure 3 shows that benchmarking methods were often used in assessing MSW management. However, benchmarking does not appear to be common in investigations of single-waste streams. Compared with other assessment methods, LCA, MCDM and RA were performed more frequently in assessing single-waste streams. E-waste, which is associated with RA, was frequently the topic under investigation. Several RAs were performed in China to evaluate the risks that are related to e-waste treatment plants.

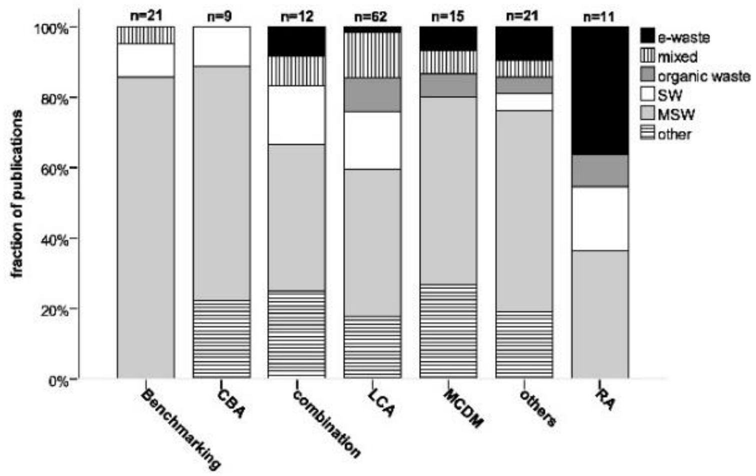


Figure 3: Assessment methods in the reviewed studies: Investigated waste streams as a function of the assessment methods (Allesch and Brunner 2014).

As a framework for WM decisions, assessment methods depict the strengths and weaknesses of different management alternatives and hence, a goal that is shared among all of the reviewed studies is to support stakeholders. Table 2 shows for whom assessments are performed and presents the reviewed assessment methods in relation to the receivers of the studies. Benchmarking and RA are most frequently carried out for governments and only CBAs are carried out to inform citizens.

Table 2: Receiver of the 151 reviewed studies (percentages in bold indicate the most commonly used assessment method in relation to the criteria for each column) (Allesch and Brunner 2014).

METHODS	RECEIVER - FOR WHOM IS THE ASSESSMENT PERFORMED [%]									
	G	G&C	G&O	G&R	C	M	O	O&R	R	NN
Benchmarking	**76**	5	0	0	0	**5**	5	0	0	10
CBA	44	11	22	0	**11**	0	11	0	0	0
Combinations	42	0	8	8	0	0	**17**	0	**25**	0
LCA	56	0	5	6	0	0	5	2	18	8
MCDM	40	7	7	**27**	0	0	7	0	13	0
RA	9	**27**	**27**	18	0	0	0	**9**	0	9
others	52	5	5	5	0	0	14	5	14	0

G Government, C Citizens, O Operators. R Researcher. M Municipalities. NN Not Named

The results of this review (Allesch and Brunner 2014) indicate the heterogeneity within the published studies and show that investigations of WM systems require an individual assessment methodology, depending on the goal of the assessment, the object of investigation, system boundaries and addressees. In order to provide reliable results and data for decision making, Figure 4 summarizes the conclusions of the literature review of assessment methods in WM:

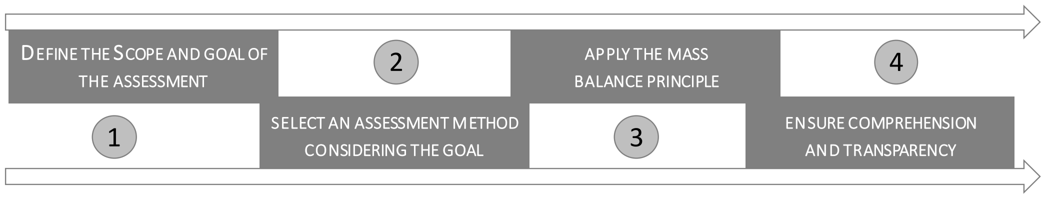


Figure 4: Key elements of a waste management assessment methodology based on Allesch and Brunner (2014).

1. Goals are important and must be clearly stated. Therefore, an assessment must focus on the objectives that legislative frameworks, policy statements or regional guidelines provide for WM. Furthermore, the scope and system boundaries have to be selected carefully, because changing boundaries can have a key influence on the results.

2. The selection of the assessment method must focus on defined goals.

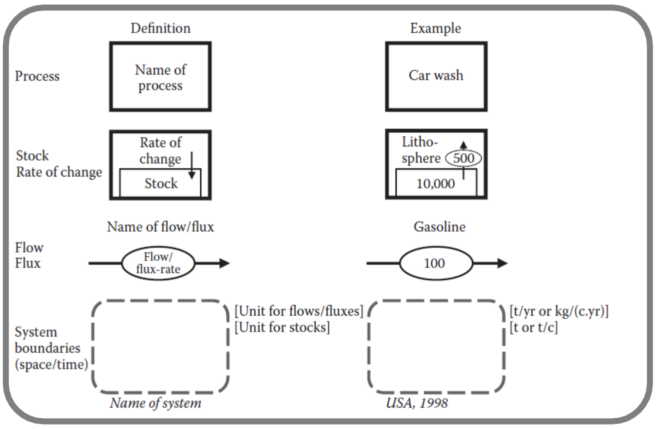
3. The application of the mass-balance principle is crucial for a comprehensive evaluation and results in better support for decision makers.

4. Assessments must be reproducible, comprehensible and transparent regarding methodology and data. Methods that are based on mass balances and promote these characteristics must be favored and applied.

2.3. MATERIAL FLOW ANALYSIS

An extended literature research (Allesch and Brunner 2015) using the keywords 'material flow analysis' and 'waste management' was carried out and 83 studies were used for a review. An MFA delivers a complete and consistent set of information about all flows and stocks of a particular material over time, within a spatially defined system (Brunner and Rechberger 2016). Material flow analysis has been applied in various fields, such as medicine (Santorio 1737), social systems (Fischer-Kowalski 1998) and urban metabolism (Baccini and Brunner 1991), and is currently being increasingly applied in industrial ecology: a quickly developing field of research with mounting policy relevance (Bringezu and Moriguchi 2002).

The growing use of MFA can be attributed to resource-, environment-, economy- and health-related demands. By balancing inputs and outputs, the flows of wastes and environmental loadings become visible and their sources can be identified (Brunner and Rechberger 2016). The goal of MFA is to establish a mass balance for the system of study. The sum of all inputs into the system must equal all outputs plus/minus the changes in stock. The mass-balance principle applies on the level of goods (wastes, air, off-gas, products, etc.), as well as substances (elements or chemical compounds) and must be observed for every process and for the total system. The MFA terms that are used in this study are described in Figure 5 and correspond to those which are presented in the *Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers* (Second Edition). Within the field of MFA, a subdivision in the investigations of goods and substances can be discerned (Brunner and Rechberger 2016).



TERMS	DESCRIPTIONS
Substances	Substances are any (chemical) element or compound that is composed of uniform units (atoms, molecules).
Goods	Goods are any economic entities of matter with a positive or negative economic value and are made up of one or several substances.
Materials	Material serves as an umbrella term for both substances and goods.
Processes	Processes are defined as the transformation, transport or storage of materials.
Flows	Flows are defined as a mass flow rate with the ratio of mass per time.
Transfer coefficients	Transfer coefficients describe the partitioning of materials in a process.
System	System is the actual object of investigation. It connects the flows and stocks of materials and substances by processes, and is limited by system boundaries, which are defined in space and time.

Figure 5: Terminology and main symbols of MFA (Brunner and Rechberger 2016).

Table 3 offers an overview of studies that show the heterogeneity within the field of WM, examined by listing the investigated goods and substances and subdividing them into three levels: 'MFA on goods', 'MFA on substances and goods' and 'MFA on substances'. This review shows that about 25 % focused on the level of goods, 50 % on the substance level and 25 % started with goods and proceeded to substances. Most studies on the goods level focus on municipal solid and electronic waste. Twenty of the reviewed studies provide a MFA for goods and substances for the same system: on the level of goods the analysis is focused primarily on MSW and plastic waste, and on the level of substances it focusses primarily on metals and carbon. On the substance level, MFA focuses on metals (n=28) and non-metals (n=12). It creates an inventory of flows, stocks and treatment processes, and hence offers a basic knowledge and understanding of WM systems. However, an MFA alone cannot assess a system in view of certain goals, such as resource conservation or protection of human health. The reviewed studies investigate the following aspects with regard to the evaluation of MFA results:

- The resource potential is quantified to identify sources and pathways of valuable materials. Recycling potentials, re-use options and the reduction of landfill volumes are often investigated.

- The environmental consequences are investigated by quantifying emissions to the hydrosphere, atmosphere and pedosphere. Often, effects such as eutrophication and climate change are included.

- The release of potentially hazardous substances to the environment or the incorporation of such substances in products is evaluated in order to take into account environmental and human-health risks.

- The energy performance of WM and treatment is assessed in order to reduce energy consumption or to improve energy efficiency by using new or advanced technologies.

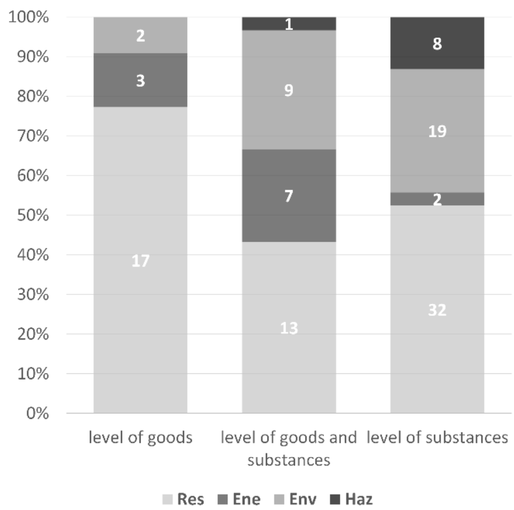


Figure 6: Comparison of the aspects considered in the various MFAs in relation to the investigated materials (n=83). Res = resource potential, Ene = energetic performance, Env = environmental consequences, Haz = release of potential hazardous substances (Allesch and Brunner 2015).

Table 3: Applied MFA in the reviewed studies (n=83) on the level of goods and/or substances (Allesch and Brunner 2015).

MFA	Goods	Substances	#	References
Good level	*Bio-, garden-, food-, wood waste*	-	4	(Bergeron 2014; Betz et al. 2015; Lang et al. 2006a; Lang et al. 2006b)
Good level	*C&D wastes*	-	1	(Nasrullah et al. 2014b)
Good level	*C&I waste*	-	1	(Nasrullah et al. 2014a)
Good level	*MSW, residual waste*	-	5	(Al Sabbagh et al. 2012; Binder and Mosler 2007; Döberl et al. 2002; Masood et al. 2014; Stanic-Maruna and Fellner 2012)
Good level	*plastic waste, tires, PVC*	-	3	(Bogucka et al. 2008; Jacob et al. 2014; Kleijn et al. 2000)
Good level	*General*	-	1	(Eckelman and Chertow 2009)
Good level	*WEEE, computer, TV sets*	-	5	(Gurauskienė and Stasiškienė 2011; Kahhat and Williams 2012; Liu et al. 2006; Steubing et al. 2010; Streicher-Porte et al. 2005)
Good and substance level	*Bio-, garden-, food-, wood waste*	*Mixture*	2	(Andersen et al. 2011, 2012)
Good and substance level	*Bottom ash*	*Metals*	1	(Allegrini et al. 2014)
Good and substance level	*C&D wastes*	*Mixture*	2	(Brunner and Stämpfli 1993; Schachermayer et al. 2000)
Good and substance level	*General*	*Mixture*	1	(Brunner and Baccini 1992)
Good and substance level	*MSW, residual waste*	*Metals*	1	(Morf et al. 2000)
Good and substance level	*MSW, residual waste*	*Mixture*	6	(Arena and Di Gregorio 2013; Brunner and Mönch 1986; Mastellone et al. 2009; Rotter et al. 2004; Stanisavljevic and Brunner 2014; Tonini et al. 2014)
Good and substance level	*MSW, residual waste*	*Organic*	1	(Arena and Di Gregorio 2014a)
Good and substance level	*Plastic waste, tires, PVC*	*Mixture*	2	(Arena and Di Gregorio 2014b; Mastellone et al. 2012)
Good and substance level	*Plastic waste, tires, PVC*	*Organic*	2	(Arena et al. 2011; Di Gregorio and Zaccariello 2012)
Good and substance level	*WEEE, computer, TV sets*	*Metals*	1	(Chancerel et al. 2009)
Substance level	*Main focus on substance level; (though usually based on good flows)*	*Compounds*	3	(Eriksson et al. 2008; Nakamura et al. 2009; Vyzinkarova and Brunner 2013)
Substance level	*Main focus on substance level; (though usually based on good flows)*	*Metals*	28	(Asari et al. 2008; Asari and Sakai 2013; Cain et al. 2007; Chen et al. 2013; Chen and Graedel 2012; Guo et al. 2010; Huang et al. 2014; Kral et al. 2014; Krook et al. 2007; Kuo et al. 2007; Lanzano et al. 2006; Long et al. 2013; Månsson et al. 2009; Morf et al. 2013; Oguchi et al. 2013; Oguchi et al. 2012; Rechberger and Graedel 2002; Saurat and Bringezu 2008; Spatari et al. 2002; Spatari et al. 2003; Spatari et al. 2005; Tanimoto et al. 2010; Vexler et al. 2004; Zhang et al. 2008; Themelis and Gregory 2001; Nakajima et al. 2008; Modaresi and Mueller 2012; Graedel et al. 2011)
Substance level	*Main focus on substance level; (though usually based on good flows)*	*Mixture*	1	(Morf et al. 2007)
Substance level	*Main focus on substance level; (though usually based on good flows)*	*Non metals*	12	(Bi et al. 2013; Chen et al. 2015; Cooper and Carliell-Marquet 2013; Fan et al. 2009; Li et al. 2010; Ma et al. 2012, 2013; Ott and Rechberger 2012; Schmid Neset et al. 2008; Senthilkumar et al. 2014; Senthilkumar et al. 2012; Yuan et al. 2011b)

Note: #=number of studies; WEEE=waste of electrical and electronic equipment; C&D=Construction and demolition; C&I=Commercial and industrial; MSW=Municipal solid waste

Figure 6 shows the number of MFA applications on the level of goods or substances in relation to the aspects that are considered. About 75 % of the reviewed studies apply MFA to assess resource potential, whereby the goal is to analyze the dependency of a regional economy on imported goods and substances, and to explore recovery potentials. Looking at both goods and substances, 13 MFAs aim to identify resource potential by quantifying the mass flow rates of wastes and their main constituents (chemical elements). In 32 of the reviewed studies, the MFA on the substance level is carried out to identify sources, pathways and sinks of single elements (e.g., P, Cu) and particularly, the analysis of whole economies focus on the evaluation of resource potential.

Environmental aspects are the focus of one third of the reviewed studies. Especially, studies on the substance level quantify environmental consequences of emissions to soil, air and water (n=19). Potential hazardous substance emissions are investigated on the substance level (n=8), with the goal of constructing a picture of sources and pathways in order to estimate possible impacts and identify necessary actions for policy makers. On the level of goods, the hazardous aspect was not and cannot be considered. Twelve studies focus on energetic performance, either to evaluate the energy generation of individual plants or to assess the energy efficiency of WM systems.

One third of the reviewed studies investigated two or more aspects (resource potential, energetic performance, environmental consequences or release of potential hazardous substances). Most frequently, resource potentials and environmental consequences are considered. Most studies that apply MFA on the level of goods focus on a single aspect. In contrast, one third of the reviewed studies providing MFAs on the substance level and half of the reviewed studies focusing on goods and substances considered two or more aspects. The results of this review (Allesch and Brunner 2015) corroborate the successful application of MFA methodology. Especially, the combination of MFA on the level of goods and substances can offer a goal-oriented tool for WM decision making (see Table 4).

Material flow analysis that is performed on the level of both goods and substances is an indispensable instrument in assessing whether a given WM system reaches set goals in a comprehensive way. On the levels of goods and substances separately, MFAs have particular strengths and weaknesses, but together (goods and substances), they provide profound and transparent knowledge for decision makers. Because a combined approach on the level of goods and substances takes advantage of the same system definitions and analysis, the effort to perform a combined MFA is less resource consuming than for two individual MFAs. On both levels, MFA provides a systematic analysis of the system based on the mass-balance principle. The results can be used as a well-grounded inventory for life-cycle-impact assessments or other assessment methodologies, as a basis for the application of indicators or to provide a basis for management decisions.

Table 4: Combination of MFA on the level of goods and substances for goal-oriented waste management.

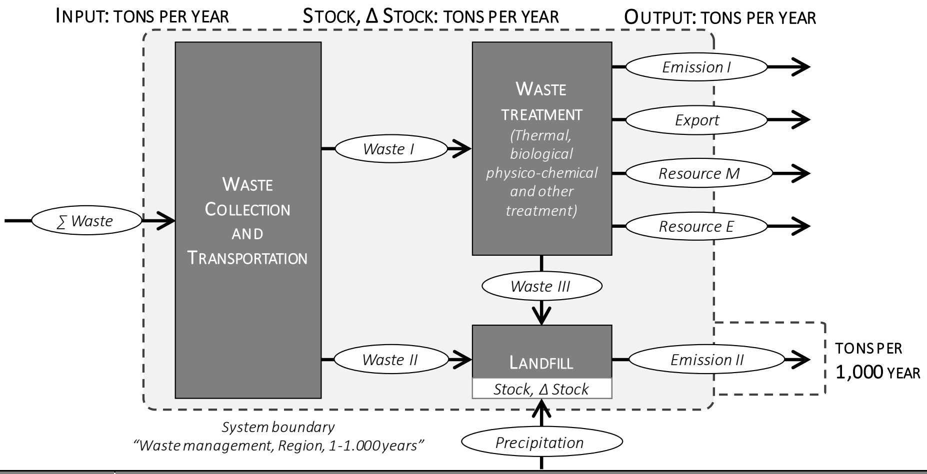
	MFA on the level of goods to…	MFA on the level of substances to…
Goal-oriented waste management	…provide knowledge about the crucial physical flows.	…identify the partition of hazardous substances.
	…implement regulatory mechanisms.	…depict the storage of hazardous substances.
	…understand connections between stakeholders.	…characterize the chemical composition of inflows and the transfer to possible products.
	…understand WM systems.	…evaluate whether WM goals are fulfilled.
	…analyze, control and manage, material flows within a system.	…consider all flows, including those that are sometimes neglected, for instance because they are not regulated.
	…understand how waste is transformed, transported or stored.	…ensure that materials that are reclaimed or recycled do not present a greater risk than comparable primary resources.
	…identify materials leaving (outflows) or accumulating in the system (stocks).	…avoid that potentially harmful substances are hidden or accumulated somewhere in the system.
	…support communication and facilitate transparency between the various groups.	…prevent pollution of the environment or secondary resources.
	MFA on the level of goods and substances to…	

3. DEVELOPING AN ASSESSMENT APPROACH FOR WASTE MANAGEMENT SYSTEMS

In this chapter, a novel goal-oriented approach is presented in order to assess WM systems with respect to given environmental and resource goals (Allesch and Brunner 2017). Hence, the power of MFA in designing systems and supporting decisions is described.

3.1. DEVELOPING A MASS BALANCE BY MATERIAL FLOW ANALYSIS

In order to use MFA for the optimization of WM, it is essential to know which elements (wastes, treatment processes, products, emissions, flows, stocks and processes) are within the system boundaries and are balanced, and which are situated outside the boundaries and are thus neither balanced nor further considered. Therefore, a comprehensive form of visualization is shown in Figure 7, which provides a template by which to design WM systems based on MFA. One of the central points is the focus on the mass-balance principle in order to provide a complete database on the level of goods as well as on the level of substances. The sum of all inputs must equal the outputs ± changes in stock. It must be observed for every process and for the total system, and the mass-balance principle must be applied on the level of goods (wastes, air, off-gas, products, etc.), as well as on the level of substances (elements or chemical compounds).



FLOWS	DESCRIPTION
∑ *Waste*	Total waste input into the system (generated and imported waste).
Export	Export of waste (leaving the investigated geographical system).
Emission I	Gaseous emissions from waste treatment plants.
Emission II	Long-term gaseous and liquid emissions from landfills over a time-period of 1,000y.
Resource M	Reused or (treated) waste suitable for material recycling.
Resource E	Treated waste that is used for energy recovery in non-WM-plants (only substitute fuels).
Waste II & III	Landfilled wastes.
Precipitation	Precipitation on landfills.

Figure 7: Comprehensive MFA system for the evaluation of waste management systems based on Allesch and Brunner (2017).

3.2. MATERIAL FLOW ANALYSIS BASED CRITERIA FOR ASSESSMENT

According to given goals and based on the comprehensive MFA system, Table 5 shows seven criteria by which to assess whether MFA and relating material flows on the level of goods and substances support goal-oriented WM, and which provide a basis for further assessment methods. Every criterion is assessed individually. For a complete evaluation of a WM system, it is also necessary to take into account the dependencies and contradictions between these criteria. The comprehensive WM system and the MFA-based criteria generate a well-founded, reproducible and transparent database for the evaluation of WM systems. The results can be used for the comparison of different scenarios (e.g., years and treatment options), to evaluate WM system, to understand their functioning and to provide a basis for future impact assessments.

Table 5: MFA based criteria for assessment (Allesch and Brunner 2017)

FLOWS	DECISION SUPPORT CRITERIA - *MFA ON THE LEVEL OF*		NOTE
	GOODS	*SUBSTANCES*	
∑ *Waste*	Reduction of waste generation [t $year^{-1}$]	Reduction of hazardous substances in generated waste [mg/kg]	To conserve resources and reduce environmental impacts through WM (outside of WM's sphere of influence).
Export	Reduction of waste exports [t $year^{-1}$]	Reduction of exports of waste with hazardous or beneficial substances [mg/kg]	To conserve resources (beneficial substances) and provide treatment autarky (hazardous substances).
Emission I	Reduction of emissions from waste-treatment plant [t $year^{-1}$]	Reduction of air pollutants and climate-relevant gases: e.g., SO_2, NO_x, CO_2, N_20, CH_4 [t $year^{-1}$]	To protect the environment, improve air quality and ensure the achievement of legal objectives.
Emission II	Reduction of long-term emissions from landfills [t $year^{-1}$]	Reduction of gaseous emissions: e.g., CO_2, CH_4, [t 1-1000 $year^{-1}$] Reduction of leachate load: e.g., TOC, NH_4, Cd, Cr, Fe, Hg, Pb [t 1-1000 $year^{-1}$]	To provide aftercare free waste treatment and ensure that only such waste remains which can be stored without endangering future generations.
Resource M	Increase in secondary raw-material generation [t $year^{-1}$]	Reduction of hazardous substances in secondary raw materials: e.g., Cd, Cr, Cu, Ni, Hg, Pb, Zn [mg/kg]	To conserve resources (raw materials) and, in the case of recycling, to ensure that reclaimed materials do not present a greater risk than comparable primary raw materials.
Resource E	Increase in energy recovery [t $year^{-1}$]		To conserve resources (energy).
Waste II and Waste III	Reduction of landfill volume [t $year^{-1}$]	Reduction of hazardous or beneficial substances to landfills: e.g., Cr, Cd, Cu, Hg, Ni, Pb, Zn [mg/kg]	To conserve resources (landfill volume) and ensure that only that waste remains which can be stored without danger to future generations.

The choice of the investigated system's thematic and geographic boundaries is crucial for an impartial assessment, in interpreting data and results, and in generating transparent information for stakeholders and the public. Depending on the WM system that is in focus, different evaluation criteria can be derived. A survey and value judgment of WM stakeholders can be used to identify different criteria, in which MFA and relating material flows can provide a basis for further assessment methods. Other goals and stakeholders' value choices may lead to different criteria.

4. CASE STUDY: AUSTRIAN WASTE MANAGEMENT

Based on the case study of a nationwide WM system, the advantages and drawbacks of the mass-balance approach are disclosed and discussed (Allesch and Brunner 2017). The case study's results demonstrate the power of MFA in designing WM systems and in supporting decisions with regard to given environmental and resource goals.

4.1. SCOPE

For the case study, the geographic system boundary corresponds to the national boundary of Austria. The thematic system boundary is the WM system, including all processes (collection, treatment, recycling, incineration, landfilling, etc.), material flows, recycling products, residues and emissions. The inputs into the WM system are domestic as well as imported wastes and precipitation falling on landfills. The outputs, which are measured and calculated by means of transfer coefficients, are secondary products for material or energy recovery, and exported waste and emissions to the environment. The temporal system boundary is one year for all WM processes and subsequent flows before landfilling. A static approach is applied in order to evaluate the Austrian WM system. The year 2012 was chosen because, at the start of the project, the best and most complete data set was available for this period. Landfills are defined as long-term stocks within the WM system and are the only stocks in this model. For the investigation of long-term effects within this case study, the temporal boundary for the biogeochemical reactor 'landfill', and its input (precipitation) and outputs (emissions) is 1,000 years (Döberl et al. 2002).

The following substances were selected for mass balancing: C, Cd, Cr, Cu, Fe, Hg, N, Ni, P, Pb and Zn. These substances are of interest because on one hand they are useful as resources and on the other may act as hazardous substances and are of potential harm to the environment. Data uncertainties are calculated and estimated according to Laner et al. (2015), and the software tool STAN 2.5 is used to perform MFA (Cencic and Rechberger 2008). In considering data uncertainties, the calculation algorithm of STAN 2.5 uses mathematical tools such as data reconciliation, error propagation and gross-error detection. The calculation algorithm of STAN 2.5 allows for the use of redundant information in order to reconcile uncertain 'conflicting' data with data reconciliation and to subsequently compute unknown variables, including their uncertainties, with error propagation (Cencic 2016).

4.2. INVENTORY ANALYSIS

The detailed data inventory, including input quantities, substance concentrations and transfer coefficients is provided in Allesch and Brunner (2017) and in the associated study (Brunner et al. 2015).

In the year 2012, Austria generated about 48.7 million tons of waste (5,800 kg/inhabitant), of which about 30 million tons consist of uncontaminated excavation material (50 % landfilled and 50 % backfilled). This waste and certain other waste fractions are not included in the case study. Seventeen million tons of waste are considered in detail, comprising about 500 different waste fractions. For the MFA, these 500 waste fractions were merged into selected waste groups with similar substance concentrations. For the data collection, a comprehensive search was carried out, including official statistics, stakeholder interviews and literature reviews. In total, over 100 processes of collection, recycling, treatment and disposal, and about 300 flows of wastes, residues, secondary products and emissions were taken into account and quantified.

Austrian and imported waste, as well as precipitation on landfills serve as inputs into the MFA system. The outputs, which were calculated by means of transfer coefficients, are emissions to air, soil and water, secondary products, and exported waste. Through literature researches and the use of own data from previous work, the transfer coefficients were defined for each waste treatment plant. Landfills' long-term gaseous emissions were calculated for residues from mechanical biological treatment (MBT) based on Tabasaran and Rettenberger (1987). Long-term leachate concentrations of TOC and NH_4-N after t years are modelled based on the mobilizable substance potential of the landfilled waste (Laner 2011). For metals and phosphorus, a constant substance concentration over time in the leachate is assumed. Data uncertainty was also considered. According to an approach for characterization uncertainty (Laner et al. 2015), data quality is evaluated with respect to reliability, completeness, and temporal and geographical correlation. For the evaluation of expert estimates, only one data-quality dimension is used.

4.3. RESULTS

4.3.1. MATERIAL FLOW ANALYSIS

The total input into the investigated system is about 17 million tons of waste. Figure 8 shows an overview of the MFA on the level of goods and offers details about inputs, outputs and stocks in million tons per year.

About 65 % of the waste is transferred into secondary products for material or energy recovery, which include materials for reuse or which are ready for recycling without treatment (1.1 million tons) and treated waste, which can be directly used as a substitution for raw materials (9.8 million tons).

The treatment of construction and demolition (C&D) waste for recycling provides the major share with about 6 million tons, followed by metals with about 2 million tons. Secondary products for energy recovery are plastic and wood waste which is processed to refuse-derived-fuels, thereby fulfilling the end-of-waste criteria (0.6 million tons). About 15 % of the total waste input is incinerated in waste-to-energy (WTE) plants, and 7 % is either mechanically-biologically treated (MBT) or biotechnologically treated in composting or biogas plants. About 18 % of the input is released into the environment, mainly as off-gas into the air through biotechnical and thermal treatment. About 12 % is landfilled and 4 % is exported to other countries. The largest shares of the deposited materials are bottom ashes from incineration processes, residues after mechanical- and biological-waste treatment, and C&D-waste. Figure 9 shows substance balances for C, Cd, Cr, Cu, Fe, Hg, N, Ni, P, Pb and Zn. About one third of the carbon and half of the nitrogen are released into the air by biotechnical and thermal treatment. Carbon is discharged mainly in the form of CO_2, and to a lesser extent to CH_4 and nitrogen, mainly as N_2, and in small quantities as N_2O and NO_x.

The carbon content of all landfilled materials, despite prior treatment, remains over 50g/kg: the legal limit for landfilling in Austria. Residues from thermal processes, which are landfilled, contain relevant concentrations of Cd, P, Cr, Pb and Zn. About one third of the phosphorus is contained in ashes and dusts, which are used either for the production of concrete or recycled within the cement industry. Separate collected metal fractions such as Fe, Cu, Pb, Ni and Zn are mainly recycled. About 50 % of the Cd is deposited as residue from thermal treatment. Recycled cadmium is mainly contained in metals and plastics. Mercury is mainly landfilled and around 20 % of mercury can be found in secondary resources, such as paper and plastics. The detailed MFA on the level of goods and substances is provided in Allesch and Brunner (2017).

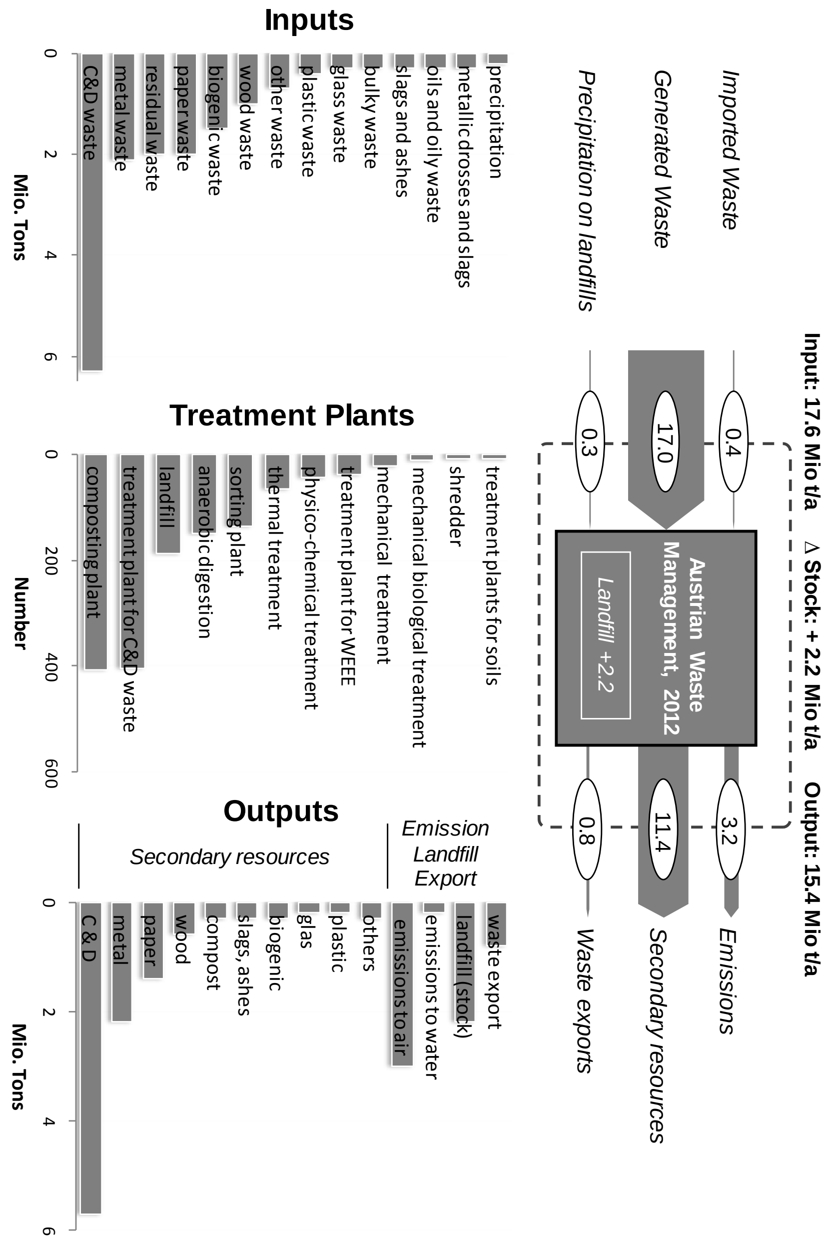


Figure 8: MFA system representing the Austrian WM in 2012 (Allesch and Brunner 2017).

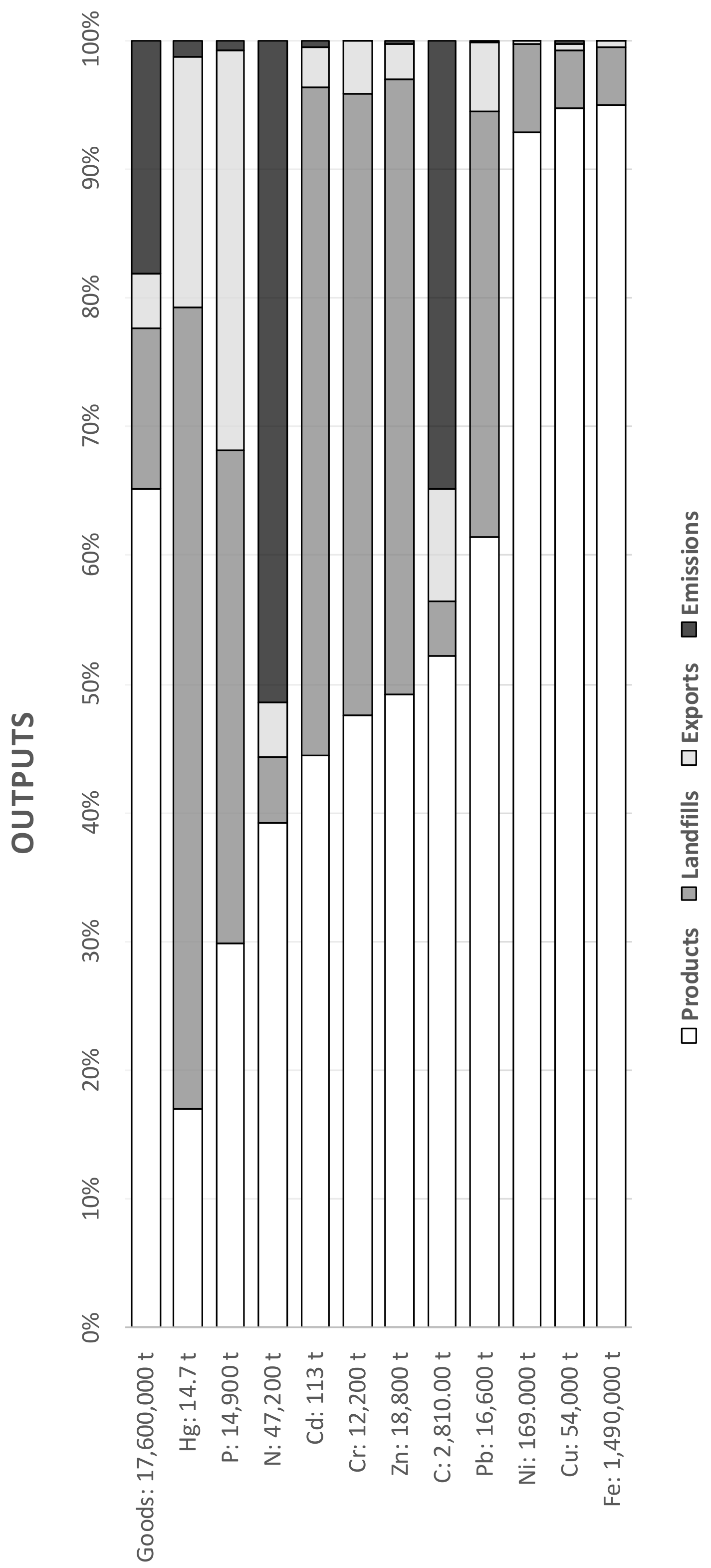


Figure 9: MFA: Inputs, outputs, stocks and releases to the environment for selected substances (Allesch and Brunner 2017).

Table 6: MFA based criteria: case study Austria (Allesch and Brunner 2017).

Flow		Goods [kt]	Unit	C	Cd	N	P	Fe	Cr	Cu	Hg	Ni	Pb	Zn
				Current State – Substances										
Input (1y)	**∑ Waste**	17,300	[t year⁻¹]	2,810,000	113	47,200	14,900	1,490,000	12,200	54,000	15	169,000	16,600	18,800
	Precipitation	268		not calculated (n.c.)										
Stock (1y)	**Waste II and Waste III**	2,190	[mg/kg]	54,700	27	1,110	2,600	30,600	2,680	1,100	4	5,270	2,510	4,100
Output (1y)	**Emissions I**	2,900	[t year⁻¹]	977,000	1	24,200	113	219	4	153	0.2	19	22	47
	Export	751	[mg/kg]	326,000	5	2,680	6,160	9,910	670	369	4	639	1,190	687
	Resources M	10,900		111,000	4	1,470	397	130,000	530	4,690	0.2	14,400	935	846
	Resources E	563		466.000	5	4,360	229	3,090	20	168	0.5	14	49	69
	Emissions II	270	[t year⁻¹]	927	8.7E-04	1.3E+00	1.0E-02	3.1E-01	9.5E-04	(n.c.)	8.1E-05	(n.c.)	1.7E-04	2.7E-03
	Landfill Gas	2		926	not calculated (n.c.)									
	Leachate Load	1.9E-03		3.3E-01	8.7E-04	1.3E+00	1.0E-02	3.1E-01	9.5E-04	(n.c.)	8.1E-05	(n.c.)	1.7E-04	2.7E-03
	Evaporation, surface runoff	268		not calculated (n.c.)										
changes in viewing long-term effects (1.000.years)	**Precipitation**	268,000	[t 1000 year⁻¹]	not calculated (n.c.)										
	Stock	2,180		115,000	58	2,350	5,590	66,300	5,870	2,410	8	11,500	5,490	8,970
	Emissions II	268,000		5,640	0.1	91	90	700	2	(n.c.)	1	(n.c.)	1	15
	Landfill Gas	13		5,310	not calculated (n.c.)									
	Leachate Load	1		331	0.1	91	90	700	2	(n.c.)	1	(n.c.)	1	15
	Evaporation, surface runoff	268,000		not calculated (n.c.)										

4.3.2. *MATERIAL FLOW ANALYSIS BASED CRITERIA*

Based on the results of the MFA on the level of goods and substances, the developed assessment approach (see chapter 3) can be applied and the MFA-based criteria can be calculated. The approach that is presented is based on (i) the mass-balance principle, to ensure that all inputs are equal to the outputs and stock changes, (ii) the seven goal-oriented criteria according to the Austrian WM act and (iii) a stakeholder survey. Nine complete questionnaires and six additional statements could be included (Brunner et al. 2015) to identify criteria by which MFA and relating material flows can provide a basis for further assessment methods and support goal-oriented WM. The results (see Table 6) can be used for the comparison of different scenarios (e.g., years and treatment options), to evaluate WM systems, to understand their functioning and to provide a basis for future impact assessments.

4.3.3. *SCENARIO ANALYSIS*

Scenario analysis provides a powerful tool in looking into a possible future in an organized way. Based on the MFA results, three scenarios were defined to better understand and evaluate the Austrian WM system. The aim of this scenario analysis is to investigate changes within the system and to gain insight into the functioning of the WM system and its associated impacts. Each scenario examines different key aspects in order to investigate the effects of different measures on future WM (see Table 7).

Table 7: Description of scenarios (Allesch and Brunner 2017).

SCENARIOS	Key aspect	Changes	Motivation
ECONOMY (E1)	Reducing costs	No separate household collection of metals, textiles, biogenic waste and plastics	Reduce cost for citizens, Reduce costs for collection and transportation
		Plastic waste is incinerated	The collection and treatment of plastics is costly
		WEEE are incinerated	The collection and treatment of WEEE is costly
		No mechanical or mechanical and biological treatment	MBT and following treatment paths are costly
RESOURCES (R2)	Optimize resource efficiency, increase conservation of resources	Increase of collection ratios for separated recyclables in households, trade and industries	Transfer from mixed to separate waste streams
		Doubling material recycling of plastic and wood wastes	Increase in material recycling
		Doubling material recycling of WTE bottom ashes	
		Two-stage process for biogenic waste: Firstly biogasification and secondly composting fermentation residue	Increase in material and energy recovery
SUSTAINABILITY (S3)	Provide clean product cycles, reduce long-term emission	Residual and bulky waste from households are incinerated	In order to reduce the dissipation of hazardous substances
		Combustible recyclables (wood, plastics, paper and biogenic waste) are incinerated	
		Enhanced landfill aftercare for long time periods	Reduces long-term emissions from landfills

Based on the defined scenarios, the MFA was performed again on the level of goods and substances for each scenario. The detailed results of the scenario analysis, including the MFA, is provided in Allesch and Brunner (2017). Shifts in flows for the primary waste as well as the consequent change in the secondary waste streams are evident. Figure 10 shows the changes of secondary-waste quantity and different treatment paths for the status quo (SQ) and for each scenario. Scenarios E1 and S3 show higher incineration rates compared to the SQ, and biotechnical treatment is reduced accordingly. Scenario E1 is most similar to the SQ. The landfill volumes are approximately equal for all scenarios, with a slight increase in scenario S3. Scenario R2 shows the highest sorting and processing of separate collected waste with a focus on recycling. In scenario R2, material recycling is increased by about 14%.

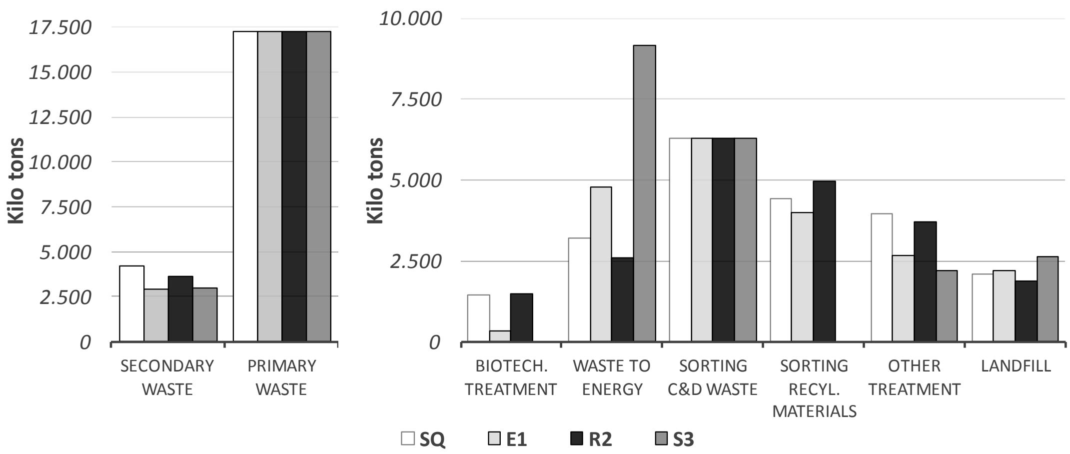


Figure 10: Scenario analysis: Variation of secondary waste treatment based on Allesch and Brunner (2017).

In terms of material recycling, the most significant change is the shift of wood and plastic wastes from energy recovery to material recycling (see Figure 11). This also increases the amount of carbon that is contained in secondary resources (products of waste treatment). Increased recycling within scenario R2 decreases the concentration of different substances, but the absolute amount of recycled substances increases. Especially, the increased flow of Hg and Cd into recycling products needs to be carefully assessed in view of the goal of 'protection of human health and environment'. For further impact assessment of hazardous substances within product cycles, it is necessary to evaluate single recycling products and especially their area of application. Scenario S3 recycles the least waste due to the increased WTE, although bottom ashes are partly used as secondary products.

The MFA-based seven criteria are calculated for each scenario. Table 8 (level of goods) and Figure 12 (level of substances) provide an overview of the percentage changes for each scenario compared to the SQ. On average, the changes are about +30 %. Nevertheless, on the level of goods, changes become visible between -100 % and +134 % and on the level of substances, changes become visible between -100 % and +1.160 %.

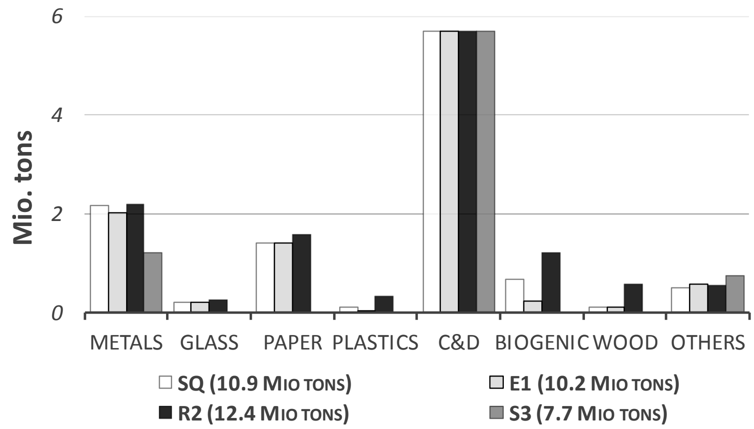


Figure 11: Scenario analysis: Products from waste treatment as secondary resources (Allesch and Brunner 2017).

Although waste prevention is the most favored option according to the EU waste hierarchy, it was not included in the scenario analysis. Waste prevention comprises using less products and/or less material per product, thereby keeping products in the use phase for a longer time and using less hazardous materials. In general, waste prevention lies outside of the sphere of influence of WM. Nevertheless, feedback from WM stakeholders to other sectors of the economy (e.g., designers, producers, and manufacturers of goods and services) is necessary.

Table 8: Scenario analysis: Percentage change relative to the SQ - level of goods (Allesch and Brunner 2017).

Flow		Percent Change Relative to the Status Quo		
		E1 [%]	R2 [%]	S3 [%]
Input(1y)	**∑ Waste**	0	0	0
	Precipitation	-1	-13	17
Stock (1y)	**Waste II and Waste III**	0	-14	20
Output 1y)	**Emissions I**	27	-30	134
	Export	-2	10	-72
	Resources M	-6	14	-30
	Resources E	-21	-75	-100
	Emissions II 1y	-1	-13	16
	Landfill gas	-52	-24	-100
	Leachate load	-36	-17	-32
	Evaporation, surface runoff	-1	-13	17
Changes in viewing long-term effects (1.000.years)	**Precipitation**	-1	-13	17
	Stock	0	-14	21
	Emissions II	-1	-13	17
	Landfill gas	-69	-22	-100
	Leachate load	-7	-13	-61
	Evaporation, surface runoff	-1	-13	17

According to the Austrian WM act, treatment autarky should be sought. Hence, on the level of goods, scenario S3 is the most favored option with a reduction in waste exports of about 70 %. An increased waste-to-energy ratio reduces the export of C and N in waste products, and concentrates many metals in bottom ash and APC residue, the latter of which are mainly exported to Germany and disposed of in underground storages. On the level of goods, releases to the air are reduced by 30 % within scenario R2, and increased by about 130 % within scenario S3.

Increased recycling reduces discharges, especially of C and N, to the air by about 25 %. Additionally, within scenario R2, metal emissions in very small quantities to the gas stream can be reduced by between 3 % and 19 % due to reduced thermal treatment. Long-term gaseous emissions and leachate loads from landfills can be reduced within all scenarios, with scenario S3 showing the highest reduction. Landfilling of pre-treated biogenic waste is significantly reduced within scenarios E1 and S3. Hence, gaseous emissions are also substantially decreased. Long-term leachate emissions from landfill are about equally reduced within scenarios R2 and S3. On the level of substances, leachate loads are reduced within S3 by extended landfill aftercare treatment. In scenario R2, material recycling is increased by about 14%. However, increased WTE reduces waste volumes that are sent to landfills within scenario S3 and due to the decreased recycling, the waste mass that is sent to landfill is not reduced compared to the SQ.

4.4. SUMMARY

The system 'Austrian waste management' was analyzed and evaluated in its entirety. Its structure was mapped in a coherent, transparent and verifiable way by displaying the SQ by means of the mass-balance principle on the level of goods and selected substances. This MFA facilitates the understanding of how a particular WM system functions, and simplifies the comparison of different treatment options and their effects on emissions, secondary resources, exports and landfilled wastes. The developed approach requires the selection of criteria for the evaluation of the WM system. These criteria are based on stakeholder's value choices and on predefined WM goals, which, in the case of Austria, are stated in the Federal Waste Management Act.

The selected criteria represent the specific WM system that is in focus and are not universal: they may be different for different stakeholders and WM goals. Based on the MFA results for the year 2012, a scenario analysis was carried out in order to understand and evaluate the Austrian WM system. On the level of goods, scenario R2 (focusing on recycling) provides the best results for material recycling and the reduction of emissions from waste-treatment plants.

Scenario S3 (focusing on clean cycles) significantly reduces exports and long-term emissions from landfills. On the level of substances, complex relations become apparent. The best scenario varies according to the substance that is taken into account. In summary, the scenario analysis of Austrian WM reveals a potential for higher collection and recycling rates, but also shows a limitation regarding 'clean' product cycles. Some hazardous substances are recycled rather than eliminated by WTE, or are disposed of in safe deposits. Furthermore, short- and long-term discharges to the environment can be decreased by promoting recycling and by prolonging landfill aftercare. The assessment of the three scenarios compared to the SQ shows that it is not possible to improve every defined criterion with only a single measure.

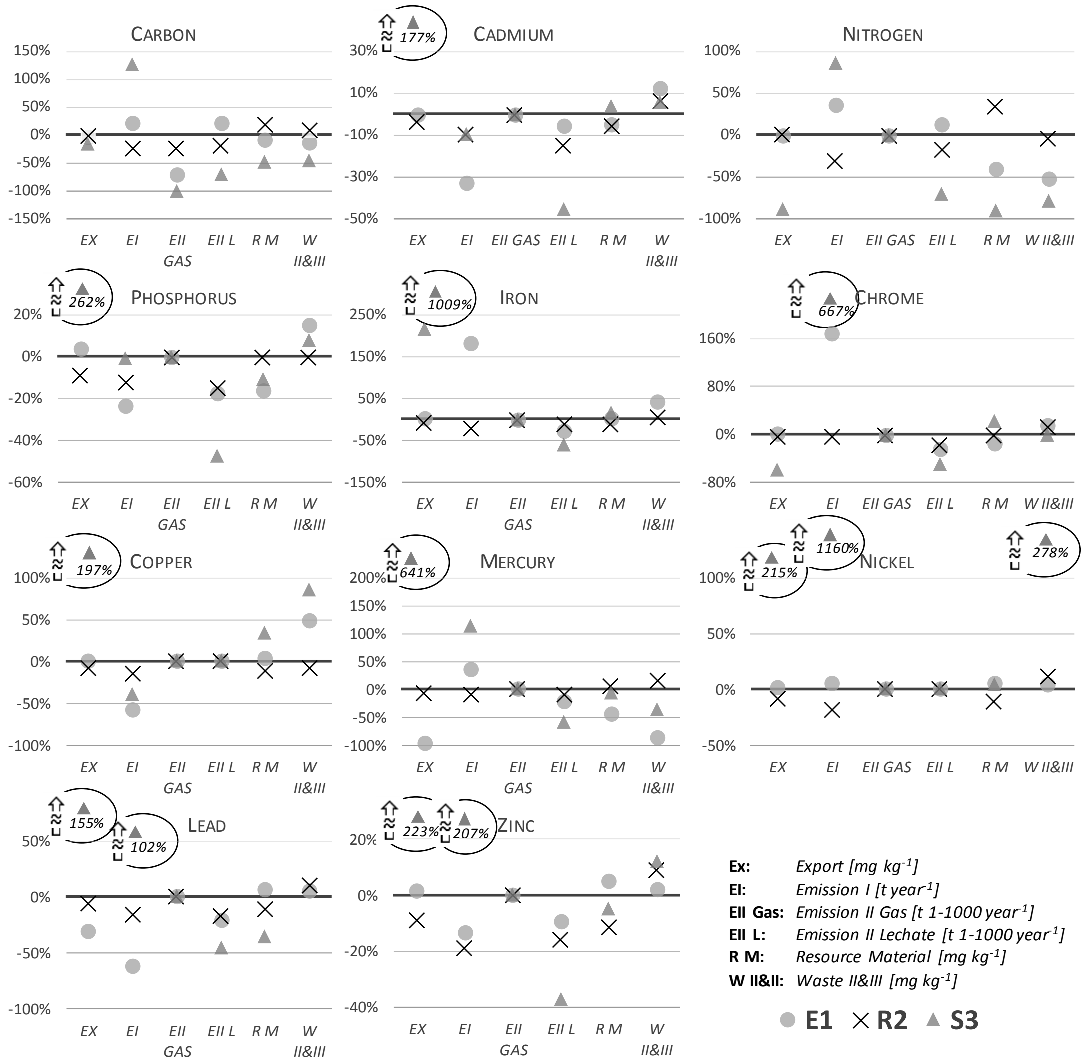


Figure 12: Scenario analysis: Percentage change relative to SQ - level of substances based on Allesch and Brunner (2017)

5. DISCUSSION AND CONCLUSION

This chapter summarizes the results and findings of the three research articles and offers an outlook for future research focusing on the emphasis of the thesis:

- Assessment methods for decision making (Allesch and Brunner 2014)
- The application of MFA for analysis and evaluation (Allesch and Brunner 2015)
- A comprehensive novel MFA approach for goal-oriented decision making (Allesch and Brunner 2017)

5.1. ASSESSMENT METHODS

Comparing and analyzing assessment methods in a literature review (n= 151) shows that any investigation of WM systems requires an individual assessment methodology, which depends on the goal of the assessment, the object of investigation, the system boundaries, and the addressees. Goals are important and must be clearly stated. This concerns two types of goals:

- Firstly, the objectives for WM, as provided by the legislative framework, policy statement or regional guideline, must be considered. It is important to concentrate on these objectives because they can be manifold and even contradictory, and because they have a determining influence on the methodology that must be chosen for the evaluation.
- Secondly, the purpose, scope and goals for the assessment must be clearly defined, considering the addressees and objectives of WM. It is relevant to select an assessment method, or, most frequently, a set of assessment methods that is capable of tackling all of the criteria that are necessary in characterizing the goals that are established in the first step.

It becomes evident that sophisticated assessment methods are required. Only such methods are able to evaluate the economic, ecological and social effects of a WM system. The choice of the starting- and end-points of an assessment can have a decisive impact on the results. The scope and the system boundaries have to be selected carefully because changing the boundaries can strongly influence the results. Assessments must be reproducible, comprehensible and transparent regarding methodology and data. Methods that are founded on mass balances must be favored and applied because they promote these characteristics. Good, impartial and reliable data sources with known uncertainty are crucial. Objectivity, transparency and confirmability are necessary for the assessment step as well as for data acquisition.

5.2. MATERIAL FLOW ANALYSIS

The investigation of the application of MFA through a literature review (n=83) indicates that the application of the mass-balance principle is significant for an impartial, comprehensible evaluation. In evaluating WM systems, data availability and data quality are often limiting steps. Wastes contain numerous products that are made from complex mixtures of many elements and are composed of countless substances, yielding highly heterogeneous combinations. In fact, wastes may and do contain everything because their content cannot be completely controlled. Thus, analyzing waste inputs over longer periods of time for real situations is a non-trivial, time-consuming and costly endeavor. A more effective means is output-oriented analysis. If inputs and outputs of waste-treatment systems are monitored and balanced, the law of conservation of matter allows for the comparison of information concerning substance flows from the input side with the output side. Hence, data can be crosschecked, deviations can be detected and additional investigations can be performed, if necessary.

On the level of goods, MFA is highly useful in understanding WM systems. It represents a tool for analyzing, controlling and managing material flows within a system. For WM, it is essential to know the quantity of waste that is to be treated (inflows), how this waste is transformed, transported or stored (processes), what kind of materials leave (outflows) or are accumulated in the system (stocks). On the level of goods, MFA is also a valuable means by which to implement regulatory mechanisms. Yet, the level of goods does not include sufficient qualitative information.

In addition to mere bulk-material flows, it is highly recommended to select key substances and to balance them throughout the system. This allows answering questions regarding the accumulation and depletion of beneficial as well as hazardous substances in goods. The level of substances is indispensable in evaluating whether WM goals are fulfilled. A mass balance also prevents potentially harmful substances from becoming hidden or accumulated somewhere in the system, thereby preventing pollution of the environment or secondary resources.

5.3. MATERIAL FLOW ANALYSIS AS A BASE FOR DECISION-MAKING

The results and findings of the literature reviews lead to the development of a comprehensive approach by which to assess WM systems. Based on a real-world WM system, seven criteria were identified whereby MFA and relating material flows on the level of goods and substances provide a basis for further assessment and support goal-oriented WM: (i) waste input into the system, (ii) export of waste (iii) gaseous emissions from waste-treatment plants, (iv) long-term gaseous and liquid emissions from landfills, (v) waste being recycled, (vi) waste for energy recovery and (vii) total landfilled waste.

The developed approach defines the system boundaries explicitly. The comprehensive WM system ensures that all elements are considered and that no flows or stocks are lost or forgotten. It thus provides a suitable tool by which to indicate dependencies and contradictions between given goals and criteria due to the fact that the mass-balance principle takes into account all in- and outflows. The approach serves as a factual basis for future decision making and is an important and necessary basis for subsequent assessments, such as benchmarking or LCA.

A comprehensive case study of a nationwide WM system demonstrates the applicability of the developed approach. It shows that MFA that is performed on the level of both goods and substances is an indispensable tool in assessing whether a WM system reaches given goals in a comprehensive way. The MFAs of goods and substances separately have their strengths and weaknesses, but together (goods and substances), they provide profound and transparent knowledge for decision makers. The results of this study reveal the following benefits of a mass-balance approach if the levels of both goods and substances are taken into account.

- Inputs, outputs and stocks are balanced and data consistency is ensured.
- Deficiencies become evident if balances do not close and if data inconsistency is observed.
- Results are reproducible with known uncertainties.

- Material flow analysis forms a transparent and open way by which to inform researchers as well as external stakeholders.
- The application of different criteria enables revealing contradictions.
- A complete, unambiguous and consistent data set can be used as a basis for subsequent assessment methods

This approach is helpful in understanding WM systems and facilitates well-founded and goal-oriented decisions. Hence, it is an essential basis in developing effective and goal-oriented WM strategies by which to plan and operate WM systems.

5.4. FUTURE RESEARCH AND OUTLOOK

This thesis demonstrates the power of MFA in designing WM systems and in supporting decisions with regard to given environmental and resource goals. A novel approach is developed by which to optimize WM systems and a case study proves that this approach is a powerful tool in assessing whether a chosen system reaches designated WM goals.

However, this study also discloses deficits that cannot yet be overcome by this approach, such as the lack of proper methodical tools by which to take into account possible risks that are related to waste exports, as well as the long-term effects of recycling products. The increasing variety and complexity of chemicals, and the ever-longer and more intricate chemical supply chains and waste streams expose serious gaps, lapses and inconsistencies in governmental and international policies, and corporate practices (UNEP 2012). Therefore, further research and possibly regulatory activities are needed in order to close data gaps, especially regarding hazardous substances in different waste streams.

Knowledge about waste export is essential and an appropriate assessment demands that re-use, collection, storage, treatment and disposal within destination countries are taken into account. Hence, considering waste export and associated risks requires an extension of the spatial system boundary compared to the approach introduced here, which includes the global economy.

There is also a need for research into the shift of pollutants from wastes to recycling-product cycles. A ‘clean cycle’ philosophy requires a change in recycling strategy: rather than focusing simply on increasing recycling quantities, recycling qualities should also be taken into account (Brunner 2010). The interactions between pollutants in products and the transfers of pollutants to safe sinks are not yet sufficiently investigated. For future assessments, the extension of the thematic system boundary (including the area of application of recycling products) and the temporal system boundary (including future effects) that are associated with the developed approach is recommended.

In order to close the gaps mentioned above, the extension of geographic, temporal and thematic system boundaries is required. Nevertheless, doing so will also significantly increase the complexity of the developed MFA approach. For final decisions on how WM systems should develop, social and economic issues also need to be taken into account.

6. BIBLIOGRAPHY

Al Sabbagh, M. K., Velis, C. A., Wilson, D. C., and Cheeseman, C. R. (2012): Resource management performance in Bahrain: a systematic analysis of municipal waste management, secondary material flows and organizational aspects. Waste Management & Research 30: 8 813-824.

Allegrini, E., Maresca, A., Olsson, M. E., Holtze, M. S., Boldrin, A., and Astrup, T. F. (2014): Quantification of the resource recovery potential of municipal solid waste incineration bottom ashes. Waste Management 34: 9 1627-1636.

Allesch, A. and Brunner, P. H. (2014): Assessment methods for solid waste management: A literature review. Waste Management & Research 32: 6 461-473.

Allesch, A. and Brunner, P. H. (2015): Material flow analysis as a decision support tool for waste management: A literature review. Journal of Industrial Ecology 19: 5 753-764.

Allesch, A. and Brunner, P. H. (2016): Benchmarking für die österreichische Abfallwirtschaft– Werden die Ziele der Abfallwirtschaft erreicht? Österreichische Wasser-und Abfallwirtschaft 68: 9-10 405-414.

Allesch, A. and Brunner, P. H. (2017): Material Flow Analysis as a Tool to improve Waste Management Systems: The Case of Austria. Environmental Science & Technology 51: 1 540-551.

Andersen, J. K., Boldrin, A., Christensen, T. H., and Scheutz, C. (2011): Mass balances and life cycle inventory of home composting of organic waste. Waste Management 31: 9–10 1934-1942.

Andersen, J. K., Boldrin, A., Christensen, T. H., and Scheutz, C. (2012): Home composting as an alternative treatment option for organic household waste in Denmark: An environmental assessment using life cycle assessment-modelling. Waste Management 32: 1 31-40.

Arena, U. and Di Gregorio, F. (2013): Element partitioning in combustion- and gasification-based waste-to-energy units. Waste Management 33: 5 1142-1150.

Arena, U. and Di Gregorio, F. (2014a): A waste management planning based on substance flow analysis. Resources, Conservation and Recycling 85: 54-66.

Arena, U. and Di Gregorio, F. (2014b): Energy generation by air gasification of two industrial plastic wastes in a pilot scale fluidized bed reactor. Energy 68: 735-743.

Arena, U., Di Gregorio, F., Amorese, C., and Mastellone, M. L. (2011): A techno-economic comparison of fluidized bed gasification of two mixed plastic wastes. Waste Management 31: 7 1494-1504.

Asari, M. and Sakai, S.-i. (2013): Li-ion battery recycling and cobalt flow analysis in Japan. Resources, Conservation and Recycling 81: 52-59.

Asari, M., Fukui, K., and Sakai, S.-i. (2008): Life-cycle flow of mercury and recycling scenario of fluorescent lamps in Japan. Science of The Total Environment 393: 1 1-10.

Baccini, P. and Brunner, P. H. (1991): Metabolism of the Anthroposphere: Springer-Verlag.

Barton, J. R., Dalley, D., and Patel, V. S. (1996): Life cycle assessment for waste management. Waste Management 16: 1–3 35-50.

Bergeron, F. C. (2014): Assessment of the coherence of the Swiss waste wood management. Resources, Conservation and Recycling 91: 62-70.

Betz, A., Buchli, J., Göbel, C., and Müller, C. (2015): Food waste in the Swiss food service industry – Magnitude and potential for reduction. Waste Management 35: 218-226.

Bi, J., Chen, Q., Zhang, L., and Yuan, Z. (2013): Quantifying Phosphorus Flow Pathways Through Socioeconomic Systems at the County Level in China. Journal of Industrial Ecology 17: 3 452-460.

Binder, C. R. and Mosler, H.-J. (2007): Waste-resource flows of short-lived goods in households of Santiago de Cuba. Resources, Conservation and Recycling 51: 2 265-283.

BiPRO (2012): Screening of Waste Management Performance of EU Member States. Report submitted under the EC project "Support to Member States in improving waste management based on assessment of Member States' performance". Report prepared for the European Commission, DG ENV.

Bogucka, R., Kosinska, I., and Brunner, P. H. (2008): Setting priorities in plastic waste management-lessons learned from material flow analysis in Austria and Poland. Polimery 53: 1 55-59.

Bringezu, S. and Moriguchi, Y. (2002): 8. Material flow analysis. In *A handbook of industrial ecology*, edited by R. U. Ayres and L. W. Ayres. Cheltenham, UK: Edward Elgar Publishing Limited.

Brunner, P. (2010): Clean cycles and safe final sinks. Waste Management & Research 28: 7 575.

Brunner, P. H. and Mönch, H. (1986): The flux of metals through municipal solid waste incinerators. Waste Management & Research 4: 1 105-119.

Brunner, P. H. and Baccini, P. (1992): Regional material management and environmental protection. Waste Management & Research 10: 2 203-212.

Brunner, P. H. and Stämpfli, D. M. (1993): Material balance of a construction waste sorting plant. Waste Management & Research 11: 1 27-48.

Brunner, P. H. and Rechberger, H. (2004): Practical handbook of material flow analysis. Boca Raton: CRC Press LLC.

Brunner, P. H. and Rechberger, H. (2016): Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers Second Edition. Boca Raton: CRC Press.

Brunner, P. H., Allesch, A., Getzner, M., Huber-Humer, M., Pomberger, R., Müller, W., Jandric, A., Kanitschar, G., Knapp, J., Kreindl, G., Grüblinger, G., Mostbauer, P., Obersteiner, G., Pertl, A., Plank, L., Salhofer, S., Schwarz, T., and Färber, B. (2015): Benchmarking für die österreichische Abfallwirtschaft - Benchmarking for the Austrian waste management. Wien. Technische Universität Wien, Institut für Wassergüte, Ressourcenmanagement und Abfallwirtschaft.

Cain, A., Disch, S., Twaroski, C., Reindl, J., and Case, C. R. (2007): Substance Flow Analysis of Mercury Intentionally Used in Products in the United States. Journal of Industrial Ecology 11: 3 61-75.

Carlsson Reich, M. (2005): Economic assessment of municipal waste management systems—case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). Journal of Cleaner Production 13: 3 253-263.

Cencic, O. (2016): Nonlinear data reconciliation in material flow analysis with software STAN. Sustainable Environment Research 26: 6 291-298.

Cencic, O. and Rechberger, H. (2008): Material flow analysis with software STAN. JOURNAL OF ENVIRONMENTAL ENGINEERING AND MANAGEMENT 18: 1 3.

Chancerel, P., Meskers, C. E. M., Hagelüken, C., and Rotter, V. S. (2009): Assessment of Precious Metal Flows During Preprocessing of Waste Electrical and Electronic Equipment. Journal of Industrial Ecology 13: 5 791-810.

Chen, G., Zhang, N., Ma, W., Rotter, V. S., and Wang, Y. (2015): Investigation of chloride deposit formation in a 24MWe waste to energy plant. Fuel 140: 317-327.

Chen, P.-C., Su, H.-J., and Ma, H.-W. (2013): Trace anthropogenic arsenic in Taiwan—substance flow analysis as a tool for environmental risk management. Journal of Cleaner Production 53: 13-21.

Chen, W.-Q. and Graedel, T. E. (2012): Dynamic analysis of aluminum stocks and flows in the United States: 1900–2009. Ecological Economics 81: 92-102.

Coelho, H. M. G., Lange, L. C., and Coelho, L. M. G. (2012): Proposal of an environmental performance index to assess solid waste treatment technologies. Waste Management 32: 7 1473-1481.

Cooper, J. and Carliell-Marquet, C. (2013): A substance flow analysis of phosphorus in the UK food production and consumption system. Resources, Conservation and Recycling 74: 82-100.

Di Gregorio, F. and Zaccariello, L. (2012): Fluidized bed gasification of a packaging derived fuel: energetic, environmental and economic performances comparison for waste-to-energy plants. Energy 42: 1 331-341.

Directive 2001/42/EC (2001): Assessment of the effects of certain plans and programmes on the environment, edited by T. E. P. a. t. Council. Brussels.

Directive 2011/92/EC (2011): Assessment of the effects of certain public and private projects on the environment, edited by T. E. P. a. t. Council. Brussels.

Döberl, G., Huber, R., Brunner, P. H., Eder, M., Pierrard, R., Schönbäck, W., Frühwirth, W., and Hutterer, H. (2002): Long-term assessment of waste management options - a new, integrated and goal-oriented approach. Waste Management & Research 20: 4 311-327.

Eckelman, M. J. and Chertow, M. R. (2009): Using Material Flow Analysis to Illuminate Long-Term Waste Management Solutions in Oahu, Hawaii. Journal of Industrial Ecology 13: 5 758-774.

Eriksson, E., Andersen, H. R., and Ledin, A. (2008): Substance flow analysis of parabens in Denmark complemented with a survey of presence and frequency in various commodities. Journal of Hazardous Materials 156: 1–3 240-259.

EU Commission (2008): General Union Environment Action Programme to 2020 ‘ Living well, within the limits of our planet’ . 1386/2013/EU of the European Parliament and of the Council of 20 November 2013.

EU Guidance (2007): Life cycle costing (LCC) as a contribution to sustainable construction. Guidance on the use of the LCC Methodology and its application in public procurement.

EU Parliament (2008): Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain Directives. Official Journal of the European Union.

Eurostat (2014): Generation of waste by waste category, hazardousness and NACE Rev. 2 activity [env˙wasgen]. Accessed 27.02 2014.

Fan, Y., Hu, S., Chen, D., Li, Y., and Shen, J. (2009): The evolution of phosphorus metabolism model in China. Journal of Cleaner Production 17: 9 811-820.

Finnveden, G., Björklund, A., Moberg, Å., Ekvall, T., and Moberg, Å. (2007): Environmental and economic assessment methods for waste management decision-support: possibilities and limitations. Waste Management & Research 25: 3 263-269.

Fischer-Kowalski, M. (1998): Society’s Metabolism. Journal of Industrial Ecology 2: 1 61-78.

Gabler (2005): Gabler Wirtschaftslexikon. Wiesbaden.

Graedel, T. E., Allwood, J., Birat, J. P., Buchert, M., Hagelüken, C., Reck, B. K., Sibley, S. F., and Sonnemann, G. (2011): What do we know about metal recycling rates? Journal of Industrial Ecology 15: 3 355-366.

Guo, X., Zhong, J., Song, Y., and Tian, Q. (2010): Substance flow analysis of zinc in China. Resources, Conservation and Recycling 54: 3 171-177.

Gurauskienė, I. and Stasiškienė, Ž. (2011): Application of material flow analysis to estimate the efficiency of e-waste management systems: the case of Lithuania. Waste Management & Research 29: 7 763-777.

Hermann, B. G., Kroeze, C., and Jawjit, W. (2007): Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. Journal of Cleaner Production 15: 18 1787-1796.

Hiraki, T. and Akiyama, T. (2009): Exergetic life cycle assessment of new waste aluminium treatment system with co-production of pressurized hydrogen and aluminium hydroxide. International Journal of Hydrogen Energy 34: 1 153-161.

Hornsby, C., Ripa, M., Vassillo, C., and Ulgiati, S. (2017): A roadmap towards integrated assessment and participatory strategies in support of decision-making processes. The case of urban waste management. Journal of Cleaner Production 142, Part 1: 157-172.

Huang, C.-L., Vause, J., Ma, H.-W., Li, Y., and Yu, C.-P. (2014): Substance flow analysis for nickel in mainland China in 2009. Journal of Cleaner Production 84: 450-458.

Hung, M.-L., Ma, H.-w., and Yang, W.-F. (2007): A novel sustainable decision making model for municipal solid waste management. Waste Management 27: 2 209-219.

ISO (2006): Environmental Management - Life cycle assessment – Require-ments and guidelines. International Standard ISO 14044. In International Organisation for Standardisation. Geneva.

ISO (2009): Risk management - Principles and guidelines, ISO 31000:2009. Geneva.

Jacob, P., Kashyap, P., Suparat, T., and Visvanathan, C. (2014): Dealing with emerging waste streams: Used tyre assessment in Thailand using material flow analysis. Waste Management & Research 32: 9 918-926.

Kahhat, R. and Williams, E. (2012): Materials flow analysis of e-waste: Domestic flows and exports of used computers from the United States. Resources, Conservation and Recycling 67: 67-74.

Karmperis, A. C., Aravossis, K., Tatsiopoulos, I. P., and Sotirchos, A. (2013): Decision support models for solid waste management: Review and game-theoretic approaches. Waste Management 33: 5 1290-1301.

Kleijn, R., Huele, R., and van der Voet, E. (2000): Dynamic substance flow analysis: the delaying mechanism of stocks, with the case of PVC in Sweden. Ecological Economics 32: 2 241-254.

Kral, U., Lin, C.-Y., Kellner, K., Ma, H.-w., and Brunner, P. H. (2014): The Copper Balance of Cities. Journal of Industrial Ecology 18: 3 432-444.

Krook, J., Mårtensson, A., and Eklund, M. (2007): Evaluating waste management strategies—A case of metal-contaminated waste wood. Resources, Conservation and Recycling 52: 1 103-118.

Kuo, N.-W., Ma, H.-W., Yang, Y.-M., Hsiao, T.-Y., and Huang, C.-M. (2007): An investigation on the potential of metal recovery from the municipal waste incinerator in Taiwan. Waste Management 27: 11 1673-1679.

Laner, D. (2011): Understanding and evaluating long-term environmental risks from landfills. Vienna. Vienna University of Technology.

Laner, D., Feketitsch, J., Rechberger, H., and Fellner, J. (2015): A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and its Application to Plastics Flows in Austria. Journal of Industrial Ecology 20: 5 1050-1063.

Lang, D. J., Binder, C. R., Scholz, R. W., Schleiss, K., and Stä ubli, B. (2006a): Impact factors and regulatory mechanisms for material flow management: Integrating stakeholder and scientific perspectives: The case of bio-waste delivery. Resources, Conservation and Recycling 47: 2 101-132.

Lang, D. J., Binder, C. R., Stauffacher, M., Ziegler, C., Schleiss, K., and Scholz, R. W. (2006b): Material and money flows as a means for industry analysis of recycling schemes: A case study of regional bio-waste management. Resources, Conservation and Recycling 49: 2 159-190.

Lanzano, T., Bertram, M., De Palo, M., Wagner, C., Zyla, K., and Graedel, T. E. (2006): The contemporary European silver cycle. Resources, Conservation and Recycling 46: 1 27-43.

Levin, H. M. and McEwan, P. J. (2001): Cost-effectiveness analysis: Methods and applications. Vol. 4: Sage.

Li, S., Yuan, Z., Bi, J., and Wu, H. (2010): Anthropogenic phosphorus flow analysis of Hefei City, China. Science of The Total Environment 408: 23 5715-5722.

Liu, X., Tanaka, M., and Matsui, Y. (2006): Generation amount prediction and material flow analysis of electronic waste: a case study in Beijing, China. Waste Management & Research 24: 5 434-445.

Long, Y.-Y., Feng, Y.-J., Cai, S.-S., Ding, W.-X., and Shen, D.-S. (2013): Flow analysis of heavy metals in a pilot-scale incinerator for residues from waste electrical and electronic equipment dismantling. Journal of Hazardous Materials 261: 427-434.

Ma, D., Hu, S., Chen, D., and Li, Y. (2012): Substance flow analysis as a tool for the elucidation of anthropogenic phosphorus metabolism in China. Journal of Cleaner Production 29– 30: 188-198.

Ma, D., Hu, S., Chen, D., and Li, Y. (2013): The Temporal Evolution of Anthropogenic Phosphorus Consumption in China and Its Environmental Implications. Journal of Industrial Ecology 17: 4 566-577.

Må nsson, N., Bergbä ck, B., and Sö rme, L. (2009): Phasing Out Cadmium, Lead, and Mercury. Journal of Industrial Ecology 13: 1 94-111.

Masood, M., Barlow, C. Y., and Wilson, D. C. (2014): An assessment of the current municipal solid waste management system in Lahore, Pakistan. Waste Management & Research 32: 9 834-847.

Mastellone, M. L., Brunner, P. H., and Arena, U. (2009): Scenarios of Waste Management for a Waste Emergency Area. Journal of Industrial Ecology 13: 5 735-757.

Mastellone, M. L., Zaccariello, L., Santoro, D., and Arena, U. (2012): The O2-enriched air gasification of coal, plastics and wood in a fluidized bed reactor. Waste Management 32: 4 733-742.

Modaresi, R. and Mueller, D. B. (2012): The role of automobiles for the future of aluminum recycling. Environmental Science & Technology 46: 16 8587-8594.

Morf, L. S., Brunner, P. H., and Spaun, S. (2000): Effect of operating conditions and input variations on the partitioning of metals in a municipal solid waste incinerator. Waste Management and Research 18: 1 4-15.

Morf, L. S., Tremp, J., Gloor, R., Schuppisser, F., Stengele, M., and Taverna, R. (2007): Metals, non-metals and PCB in electrical and electronic waste – Actual levels in Switzerland. Waste Management 27: 10 1306-1316.

Morf, L. S., Gloor, R., Haag, O., Haupt, M., Skutan, S., Lorenzo, F. D., and Bö ni, D. (2013): Precious metals and rare earth elements in municipal solid waste – Sources and fate in a Swiss incineration plant. Waste Management 33: 3 634-644.

Nakajima, K., Matsubae-Yokoyama, K., Nakamura, S., Itoh, S., and Nagasaka, T. (2008): Substance flow analysis of zinc associated with iron and steel cycle in Japan, and environmental assessment of EAF Dust Recycling Process. ISIJ international 48: 10 1478-1483.

Nakamura, S., Nakajima, K., Yoshizawa, Y., Matsubae-Yokoyama, K., and Nagasaka, T. (2009): Analyzing Polyvinyl Chloride in Japan With the Waste Input− Output Material Flow Analysis Model. Journal of Industrial Ecology 13: 5 706-717.

Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., and Kä rki, J. (2014a): Mass, energy and material balances of SRF production process. Part 1: SRF produced from commercial and industrial waste. Waste Management 34: 8 1398-1407.

Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., and Kä rki, J. (2014b): Mass, energy and material balances of SRF production process. Part 2: SRF produced from construction and demolition waste. Waste Management 34: 11 2163-2170.

Oguchi, M., Sakanakura, H., and Terazono, A. (2013): Toxic metals in WEEE: Characterization and substance flow analysis in waste treatment processes. Science of The Total Environment 463–464: 1124-1132.

Oguchi, M., Sakanakura, H., Terazono, A., and Takigami, H. (2012): Fate of metals contained in waste electrical and electronic equipment in a municipal waste treatment process. Waste Management 32: 1 96-103.

Ott, C. and Rechberger, H. (2012): The European phosphorus balance. Resources, Conservation and Recycling 60: 159-172.

Pearce, D., Atkinson, G., and Mourato, S. (2006): Cost-benefit analysis and the environment: recent developments. 315 vols. Paris, France: OECD Publishing.

Pires, A., Martinho, G., and Chang, N.-B. (2011): Solid waste management in European countries: A review of systems analysis techniques. Journal of Environmental Management 92: 4 1033-1050.

Rechberger, H. and Brunner, P. H. (2002): A New, Entropy Based Method To Support Waste and Resource Management Decisions. Environmental Science & Technology 36: 4 809-816.

Rechberger, H. and Graedel, T. E. (2002): The contemporary European copper cycle: statistical entropy analysis. Ecological Economics 42: 1– 2 59-72.

Rogge, N. and De Jaeger, S. (2012): Evaluating the efficiency of municipalities in collecting and processing municipal solid waste: A shared input DEA-model. Waste Management 32: 10 1968-1978.

Rotter, V. S., Kost, T., Winkler, J., and Bilitewski, B. (2004): Material flow analysis of RDF-production processes. Waste Management 24: 10 1005-1021.

Saling, P., Kicherer, A., Dittrich-Krä mer, B., Wittlinger, R., Zombik, W., Schmidt, I., Schrott, W., and Schmidt, S. (2002): Eco-efficiency analysis by BASF: The method. The International Journal of Life Cycle Assessment 7: 4 203-218.

Santorio, S. (1737): Medicina statica: Being the aphorisms of Sanctorius. 5th edition. London: T. Longman and J. Newton.

Saurat, M. and Bringezu, S. (2008): Platinum Group Metal Flows of Europe, Part 1. Journal of Industrial Ecology 12: 5-6 754-767.

Schachermayer, E., Lahner, T., and Brunner, P. H. (2000): Assessment of two different separation techniques for building wastes. Waste Management & Research 18: 1 16-24.

Schmid Neset, T.-S., Bader, H.-P., Scheidegger, R., and Lohm, U. (2008): The flow of phosphorus in food production and consumption — Linkö ping, Sweden, 1870– 2000. Science of The Total Environment 396: 2– 3 111-120.

Senthilkumar, K., Nesme, T., Mollier, A., and Pellerin, S. (2012): Conceptual design and quantification of phosphorus flows and balances at the country scale: The case of France. Global Biogeochemical Cycles 26: 2.

Senthilkumar, K., Mollier, A., Delmas, M., Pellerin, S., and Nesme, T. (2014): Phosphorus recovery and recycling from waste: An appraisal based on a French case study. Resources, Conservation and Recycling 87: 97-108.

Song, Q., Wang, Z., Li, J., and Duan, H. (2012): Sustainability evaluation of an e-waste treatment enterprise based on emergy analysis in China. Ecological Engineering 42: 0 223-231.

Spatari, S., Bertram, M., Fuse, K., Graedel, T. E., and Rechberger, H. (2002): The contemporary European copper cycle: 1 year stocks and flows. Ecological Economics 42: 1– 2 27-42.

Spatari, S., Bertram, M., Fuse, K., Graedel, T. E., and Shelov, E. (2003): The contemporary European zinc cycle: 1-year stocks and flows. Resources, Conservation and Recycling 39: 2 137-160.

Spatari, S., Bertram, M., Gordon, R. B., Henderson, K., and Graedel, T. E. (2005): Twentieth century copper stocks and flows in North America: A dynamic analysis. Ecological Economics 54: 1 37-51.

Stanic-Maruna, I. and Fellner, J. (2012): Solid waste management in Croatia in response to the European Landfill Directive. Waste Management & Research 30: 8 825-838.

Stanisavljevic, N. and Brunner, P. H. (2014): Combination of material flow analysis and substance flow analysis: A powerful approach for decision support in waste management. Waste Management & Research 32: 8 733-744.

Steubing, B., Böni, H., Schluep, M., Silva, U., and Ludwig, C. (2010): Assessing computer waste generation in Chile using material flow analysis. Waste Management 30: 3 473-482.

Streicher-Porte, M., Widmer, R., Jain, A., Bader, H.-P., Scheidegger, R., and Kytzia, S. (2005): Key drivers of the e-waste recycling system: Assessing and modelling e-waste processing in the informal sector in Delhi. Environmental Impact Assessment Review 25: 5 472-491.

Szargut, J. (2005): Exergy method: technical and ecological applications. Vol. 18. Southampton, UK: WIT Press.

Tabasaran, O. and Rettenberger, G. (1987): Grundlage zur Planung von Entgasungsanlagen - Basis for planning of degassing systems, Müllhandbuch. Berlin: Erich Schmidt Verlag.

Tanimoto, A. H., Gabarrell Durany, X., Villalba, G., and Pires, A. C. (2010): Material flow accounting of the copper cycle in Brazil. Resources, Conservation and Recycling 55: 1 20-28.

Tanskanen, J.-H. (2000): Strategic planning of municipal solid waste management. Resources, Conservation and Recycling 30: 2 111-133.

Themelis, N. J. and Gregory, A. F. (2001): Sources and Material Balance of Mercury in the New York-New Jersey Harbor. In Report to the New York Academy of Sciences.

Tonini, D., Dorini, G., and Astrup, T. F. (2014): Bioenergy, material, and nutrients recovery from household waste: Advanced material, substance, energy, and cost flow analysis of a waste refinery process. Applied Energy 121: 64-78.

UNEP (2012): Global Chemicals Outlook: Towards Sound Management of Chemicals. United Nations Environment Programme (UNEP).

United Nations, G. A. (2015): Resolution adopted by the General Assembly on 25 September 2015. Washington: United Nations.

Vexler, D., Bertram, M., Kapur, A., Spatari, S., and Graedel, T. E. (2004): The contemporary Latin American and Caribbean copper cycle: 1 year stocks and flows. Resources, Conservation and Recycling 41: 1 23-46.

Vyzinkarova, D. and Brunner, P. H. (2013): Substance Flow Analysis of Wastes Containing Polybrominated Diphenyl Ethers. Journal of Industrial Ecology 17: 6 900-911.

Wilson, D. C., Smith, N. A., Blakey, N. C., and Shaxson, L. (2007): Using research-based knowledge to underpin waste and resources policy. Waste Management & Research 25: 3 247-256.

Wilson, D. C., Rodic, L., Cowing, M. J., Velis, C. A., Whiteman, A. D., Scheinberg, A., Vilches, R., Masterson, D., Stretz, J., and Oelz, B. (2015): 'Wasteaware' benchmark indicators for integrated sustainable waste management in cities. Waste Management 35: 329-342.

WMA (2002): Waste Management Act (Bundesgesetz über eine nachhaltige Abfallwirtschaft). In BGBl. I Nr. 102/2002.

Yuan, F., Shen, L.-y., and Li, Q.-m. (2011a): Emergy analysis of the recycling options for construction and demolition waste. Waste Management 31: 12 2503-2511.

Yuan, Z., Liu, X., Wu, H., Zhang, L., and Bi, J. (2011b): Anthropogenic phosphorus flow analysis of Lujiang County, Anhui Province, Central China. Ecological Modelling 222: 8 1534-1543.

Zhang, H., He, P.-J., and Shao, L.-M. (2008): Implication of heavy metals distribution for a municipal solid waste management system - a case study in Shanghai. Science of The Total Environment 402: 2–3 257-267.

7. APPENDIX

ARTICLE I:

ASSESSMENT METHODS FOR SOLID WASTE MANAGEMENT: A LITERATURE REVIEW

Astrid Allesch and Paul H. Brunner
Waste Management & Research 2014, 32, (6), pp 461-473
DOI: 10.1177/0734242X14535653

ARTICLE II:

MATERIAL FLOW ANALYSIS AS A DECISION SUPPORT TOOL FOR WASTE MANAGEMENT: A LITERATURE REVIEW

Astrid Allesch and Paul H. Brunner
Journal of Industrial Ecology 2015, 19, (5), pp 753-764
DOI: 10.1111/jiec.12354

ARTICLE III:

MATERIAL FLOW ANALYSIS AS A TOOL TO IMPROVE WASTE MANAGEMENT SYSTEMS: THE CASE OF AUSTRIA

Astrid Allesch and Paul H. Brunner
Environmental Science & Technology 2017, 51 (1), pp 540–551
DOI: 10.1021/acs.est.6b04204

ARTICLE I:

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Waste Management & Research 2014, 32, (6), pp 461-473
DOI: 10.1177/0734242X14535653

Review Article

WM&R

Waste Management & Research
2014, Vol. 32(6) 461–473

DOI: 10.1177/0734242X14535653
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Assessment methods for solid waste management: A literature review

Astrid Allesch and Paul H Brunner

Abstract

Assessment methods are common tools to support decisions regarding waste management. The objective of this review article is to provide guidance for the selection of appropriate evaluation methods. For this purpose, frequently used assessment methods are reviewed, categorised, and summarised. In total, 151 studies have been considered in view of their goals, methodologies, systems investigated, and results regarding economic, environmental, and social issues. A goal shared by all studies is the support of stakeholders. Most studies are based on life cycle assessments, multi-criteria-decision-making, cost-benefit analysis, risk assessments, and benchmarking. Approximately 40% of the reviewed articles are life cycle assessment-based; and more than 50% apply scenario analysis to identify the best waste management options. Most studies focus on municipal solid waste and consider specific environmental loadings. Economic aspects are considered by approximately 50% of the studies, and only a small number evaluate social aspects. The choice of system elements and boundaries varies significantly among the studies; thus, assessment results are sometimes contradictory. Based on the results of this review, we recommend the following considerations when assessing waste management systems: (i) a mass balance approach based on a rigid input–output analysis of the entire system, (ii) a goal-oriented evaluation of the results of the mass balance, which takes into account the intended waste management objectives; and (iii) a transparent and reproducible presentation of the methodology, data, and results.

Keywords

Assessment methods, benchmarking, cost benefit analysis, life cycle assessment, mass balance, material flow analysis, multi criteria decision making, risk assessment, waste management

Introduction

The primary goals of sustainable waste management are to protect human health and the environment and to conserve resources. Additional goals include prevention of the export of waste-related problems into the future (e.g. 'clean' cycles and landfills requiring little after care (Brunner, 2013)) and socially acceptable waste management practices (Wilson et al., 2007). A key precondition is affordable waste management costs. To reach these goals, decision makers apply integrated strategies that consist of a multitude of connected processes, such as collection, transportation, treatment, recycling, and disposal (Al Sabbagh et al., 2012). As a result, decision makers expect practicable waste management at an acceptable cost, balancing environmental, economic, technical, regulatory, and other social factors (Barton et al., 1996).

Because the number of available options for waste collection and treatment is always growing and because the economic boundary conditions are changing often, decision makers are constantly confronted with the following questions: Is the current waste management system the most cost effective method for reaching the goals of waste management? Are there other and better combinations of more advanced processes that can provide an identical service at lower costs (Rogge and De Jaeger, 2012)? When answering these questions, decision makers on one hand are under pressure of different stakeholder groups that ask for more sustainability, new technologies, or for cheaper waste management (Wilson et al., (2007). On the other hand, the decision makers experience the methodological dilemma in the choice of the evaluation tool to assess present and new waste management systems.

This situation is a particular challenge because of the many and diverse approaches that promise support for strategic or policy decisions, for waste management planning, and for waste management optimisation on all levels (companies, municipalities, and governments) (Finnveden et al., 2007).

Decision support models were first applied to waste management in the late 1960s (Karmperis et al., 2013). These early

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approaches, which primarily focused on individual functional elements, such as collection routes or facility locations (Tanskanen, 2000), were followed during the 1980s by studies assessing entire waste management systems. Computer-aided decision support began in the 1980s (Banar et al., 2009). Regarding the economic impacts of waste services, the first study dates back to 1965 (Hirsch, 1965), with a rapid development and increasing number of publications peaking between 2000 and 2010 (Simões and Marques, 2012).

At present, many published assessment methods for waste management systems are quite advanced and sophisticated because waste management is considered a strategic sector of public service (Coelho et al., 2012). The high goal to provide sustainability as a balance between society, economy, and ecology requires an integrated approach. Hence, for an evaluation of the many effects of waste management systems, it is necessary to consider all of the processes involved (Diaz and Warith, 2006). An assessment method as discussed in this review should be understood as a cornerstone within such a decision framework. The method should be goal oriented and provide an overview of the advantages and disadvantages of different options, while being objective, transparent, and comprehensible.

Aim and scope of this article

The objective of this article is to support decision makers when choosing assessment methods for waste management. Commonly used assessment methods are reviewed and categorised, and conclusions are drawn that consider the selection of methods for decision support. For this purpose, 151 studies have been examined considering their goals, methodologies, systems investigated, and results regarding economic, environmental, and social issues. Similar reviews have been previously performed. These reviews usually included studies concerning municipal solid waste (MSW) or single assessment methods (Beigl et al., 2008, Cleary, 2009, Morrissey and Browne, 2004). Other overviews concerning assessment methods have compared different assessment methods and discussed their weaknesses and strengths; have looked at the historical development of assessment methods; or have presented a new combined approach (Finnveden and Moberg, 2005; Finnveden et al., 2007; Karmperis et al., 2013; Pires et al., 2011).

This study focuses on stakeholders and decision makers on the one hand, and the research community on the other hand. The purpose is to present a survey of assessment methods, to show their potentials and to provide guidance for the application of, and for future research into, methods for the assessment of waste management systems. In contrast to other reviews, this study focuses less on the assessment methodology itself, but on the actual content of the assessment. The objects of investigations, specific addressees, and goals of the studies are characterised to indicate why and for whom assessments are performed. In addition, we examine the data quality of the studies using the mass balance principle. Finally, key elements within waste management assessment methodologies are addressed to provide suggestions for future developments within the research community.

Materials and methods

The current study is based on a thorough literature search that was composed of articles in journals through September 2013 in the Science Direct database and in specific SAGE Publications journals. The keywords used for the literature search included ‘waste’, ‘assess’, and ‘different assessment methods’ according to the state of the art. Some further studies were identified through the reference list of these articles and Google was used to find special reports or conference proceedings. After a pre-review of the collected articles, 151 studies were selected for this review (Supplementary Table, available online). This database allows a systematic examination of the goals and scope of investigations: How did the investigations assess the impacts of waste management systems on technical, economic, environmental, and social levels? Which system boundaries, waste treatments, waste streams, and compositions were considered? Was there a weighting step included in the assessment, and how and by whom was the weighting performed? Which novelties concerning the assessment method were introduced? The results of the review are categorised and discussed to answer the following questions.

- What were the objectives of the studies?
- Which assessment methods were used?
  - Which software/tools were applied?
  - Were there any novelties with respect to the assessment tool?
- Which scales were observed?
- Which waste streams were considered?
- Which aspects were considered?
  - General goals of waste management.
  - Economic aspects (business economy or national economy).
  - Environmental aspects.
  - Social aspects.
- Were weighting steps performed?
- Did the study contain information concerning the impact of the study?

Rounding and rough categorising were used to simplify the results. Categories with a contribution <5% were grouped under the term ‘others’. Differences to 100% in the figures were caused by rounding errors.

Results and discussion

Overview of different assessment methods, software, and novelties

Table 1 provides an overview of the different assessment methods used in the 151 reviewed studies.

Table 1. Description of the reviewed assessment methods.

Assessment method	Description
Benchmarking	Benchmarking is a continual comparison of products, services, methods, or processes to identify performance gaps, with the goals to learn from the best and to note out possible improvements (Gabler, 2014).
Cost benefit analysis (CBA)	The essential theoretical foundations of CBA are defining benefits as increases in human wellbeing (utility) and costs as reductions in human wellbeing. All benefits are converted to monetary units. The cost component is the other part of the basic CBA equation (Pearce et al., 2006).
Cost effectiveness analysis (CEA)	CEA evaluates alternatives according to both their cost and their effect concerning producing some outcome (Levin and McEwan, 2000). CEA allows the consideration of intangible effects.
Eco-efficiency analysis (Eco-Eff)	Eco-efficiency analysis (Eco-Eff) denotes the ecological optimisation of overall systems while not disregarding economic factors. The Eco-Eff analysis by BASF quantifies the sustainability of products and processes, considering the environmental impacts and economic data concerning a business or national economic level (Saling et al., 2002).
Emergy analysis (EA)	Emergy is the amount of available energy that is used up in transformations, directly and indirectly for a service or product. The EA is an evaluation method that considers both environmental and economic values (Song et al., 2012; Yuan et al., 2011).
Environmental impact assessment (EIA)	EIA is a method that has to be performed before consent is given to a project. Significant effects on the environment by virtue, inter alia, of their nature, size, or location are made subject to a requirement for development consent and for an assessment concerning their effects (Directive 2011/92/EC).
Exergy analysis	The exergy method evaluates the qualitative change from the available energy to the unusable one in the form of work (Hiraki and Akiyama 2009; Szargut, 2005).
Life cycle assessment (LCA)	LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (ISO 2006).
Life cycle costing (LCC)	LCC is an economic analysis method in combination with LCA. This method is a tool for accounting the total costs of a product or service over a long life span (Carlsson Reich, 2005; Langdon, 2007).
Multi-criteria-decision-making (MCDM)	MCDM is a decision-making tool that facilitates choosing the best alternative among several alternatives. This tool evaluates a problem by comparing and ranking different options and by evaluating their consequences according to the criteria established (Hermann et al., 2007; Hung et al., 2007; Karmperis et al., 2013).
Risk assessment (RA)	RA is an integral part of the overall organisation's performance assessment and measurement system for departments and for individuals. The goal is to provide a comprehensive, fully defined, and fully accepted accountability for risks (ISO 2009).
Statistical entropy analysis	The statistical entropy analysis is a method that quantifies the power of a system to concentrate or to dilute substances (Brunner and Rechberger, 2004; Rechberger and Brunner, 2002).
Strategic environmental assessment (SEA)	SEA is a method to provide a high level of protection to the environment and to contribute to the integration of environmental considerations into the preparation and adoption of plans and programmes, with an aim to promote sustainable development by ensuring that an environmental assessment of certain plans and programmes, which are likely to have significant effects on the environment, is performed (Directive 2001/42/EC).

Most of the reviewed studies used existing assessment methods and models. However, new approaches have also been developed to evaluate waste management systems, and often, existing assessment methods have been modified or supplemented. Figure 1 shows the percentage distribution of the assessment methods used in the reviewed articles. Approximately 41% of the 151 reviewed studies have used life cycle assessment (LCA) as a method to evaluate waste management systems. Particularly since the 1990s, the interest in LCA has rapidly grown (Finnveden et al., 2009), and in the recent years, it has become popular to analyse MSW management systems with LCAs (Cleary, 2009). Since 1990, attempts have been made to develop and to standardise the LCA methodology (Burgess and Brennan, 2001), and since the publication of the guidelines for LCA (ISO 2006), an international standard has been defined. Commonly used software tools for LCAs include EASEWASTE and SimaPro software programs. Approximately one-third of the reviewed studies using LCAs performed their evaluation with one of these software programs. One of the reviewed studies linked economic information to a LCA in a so-called life cycle cost (LCC) assessment. To evaluate the positive and negative effects of waste management scenarios, cost-benefit analysis (CBA) was used by 6% of the reviewed articles. For assessing the socio-economic implications of waste to energy (WtE), a social CBA was developed on one study (Jamasb and Nepal, 2010). Approximately 14% of the reviewed studies were performed as benchmark studies. Benchmarking is commonly used to compare countries, regions, or cities to identify the best

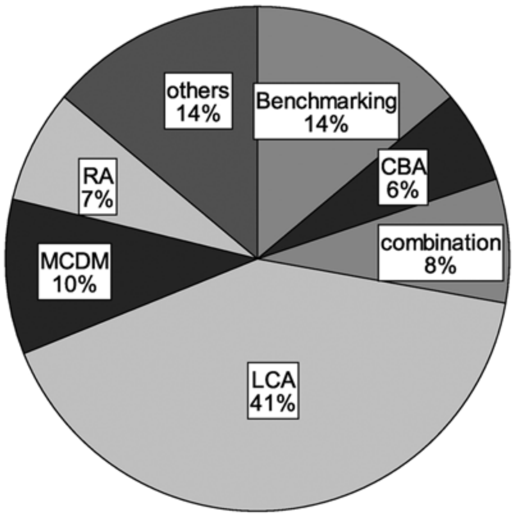

Figure 1. Assessment methods in the reviewed studies (n = 151).
CBA: cost-benefit analysis; LCA: life cycle assessment; MCDM: multi-criteria-decision-making; RA: risk assessment.

practice, with the aim of learning from each other. Approximately one-tenth of the reviewed articles assessed waste-related topics with multi-criteria-decision-making (MCDM). Commonly used MCDM software tools include analytic hierarchy process, ELECTRE, and PROMETHEE (Achillas et al., 2013). In the reviewed studies that were performed with MCDM, one-quarter was performed using ELECTRE. Approximately 7% of the researchers adopted risk assessment (RA) for the assessment, primarily for the evaluation of local environmental impacts through waste treatment plants.

The analysis of the assessment methods LCA, MCDM, and CBA by Karmperis et al. (2013) shows that all frameworks have shortcomings. The main weaknesses of a LCA are the assumptions required by the researchers. The required number of assumption within a LCA is large and leads to diverging results (Heijungs and Guinée, 2007). Moreover, a review concerning a LCA of sewage sludge by Yoshida et al. (2013) shows that the different assumptions made (e.g. energy and chemical consumption) vary greatly between the LCA studies. The results of MCDM are difficult to interpret because the choice of the criteria and the weighting are highly subjective. Additionally, using a CBA method, the valuing of intangible goods is not possible and the selection of the discount rate is a critical issue (Karmperis et al., 2013). Cost effectiveness analysis (CEA) can circumvent some of these disadvantages. Future methods and models should combine different methods to maximise their strengths and/or to minimise their weaknesses. Combinations of different assessment methods have been used to provide a more comprehensive picture (Finnveden and Moberg, 2005). In the reviewed studies for example, the Cumulative Energy Demand and the Centrum voor Milieukunde Leiden CML method (LCA impact assessment) have been combined for the evaluation of energetic and environmental impacts (Giugliano et al., 2011). Furthermore, combinations of LCA, RA, emergy analysis (EA), or the joint application of geographic information system (GIS) to MCDM have been performed (Benetto et al., 2007; Gómez-Delgado and Tarantola, 2006; Song et al., 2012). Overall, 12 studies have used a combined approach to investigate waste management-related topics. Some of the reviewed studies report novelties according to the assessment methods. On-going methods and supplementary software tools have been modified to enhance the quality of the methods and of the results. Different assessment methods have been modified, such as the MCDM methodology TOPSIS for the selection of appropriate disposal methods (Ekmekçioğlu et al., 2010) or the MCDM software ELECTRE III to help decision makers more objectively negotiate alternatives that rank close to each other (El Hanandeh and El-Zein, 2010). In few assessments, new indices have been developed or used for the first time in the context of waste management. Examples are the *Cleaner Treatment Index*, which aggregates several indicators based on operational parameters to assess the environmental performance of waste treatment technologies (Coelho et al., 2012); the *Net Recovery Index* to assess the capacity of a MSW management system for converting waste into resources; the *Transport Intensity Index* with the aim of minimising transport requirements for managing specific waste flows (Font Vivanco et al., 2012); or the *Resource Conservation Efficiency* to benchmark the ecological sustainability of waste management practices across multiple locations with minimal data (Kaufman et al., 2010).

Aims of the reviewed studies

The general goals of all the reviewed studies were to support stakeholders by (i) noting the current state of waste management systems and/or (ii) naming best waste management options for a specific local situation. Hence, one comprehensive aim of the reviewed studies is the simplification of the complex waste management processes and their environmental, economic, and social impacts to provide a basis for adequate decision making. Although there are many reasons for assessing waste management systems, in this article the reviewed studies are classified into four categories according to their aims.

- ‘Scenario-based’: an evaluation of different scenarios to find the best scenario for a single project/company or for a whole waste management system.
- ‘Comparison-based’: a comparison of countries/cities/regions or companies to determine the best in a defined category.
- ‘Performance-based’: an evaluation of the performance of a single project (e.g. treatment plant) or strategy (waste management system) with the goal to increase efficiency.
- ‘goal-based’: an evaluation of the current status of a project or strategy concerning provided goals or regulations.

The reviewed studies show that it is common to compare the current situation with different scenarios. Approximately 60% of

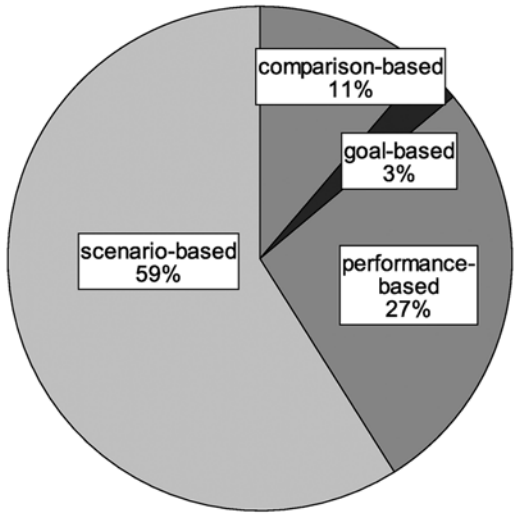

Figure 2. Aims of the reviewed studies (n = 151).

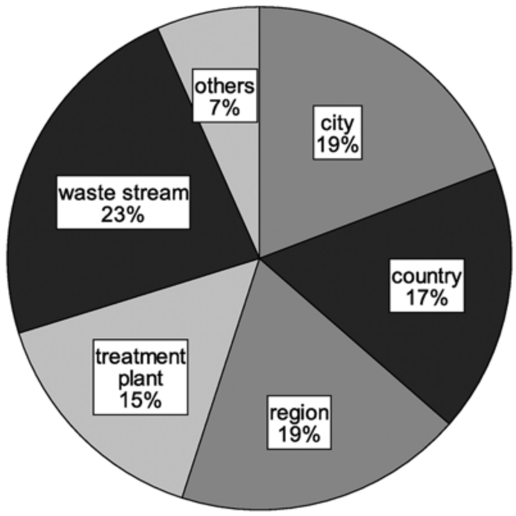

Figure 3. Observed scale in the reviewed studies (n = 151).

the studies were 'scenario-based'. Often, three or four scenarios were compared; however, the range of the considered scenarios in the reviewed studies was from one to 19. One-third of the studies used the 'performance-based' approach, and approximately 10% were 'comparison-based'. Only four studies compared the efficiency of current waste management systems with provided goals or laws (see Figure 2).

As already mentioned, the reviewed studies were performed with the overall goal to support decision makers in developing new laws, to provide the decision makers with a base for decisions concerning current waste management and for future projects, or to note new assessment methods. The target group of the reviewed studies were primarily official institutions. Only a few studies were performed to provide direct support for citizens or to introduce new methods or software tools.

Scale of the reviewed studies

The scale refers to the boundaries and functional unit observed in the reviewed assessments. The scales used in the studies were (i) one unit of a specific waste stream (e.g. 1 tonne organic household waste), (ii) the entire waste input and output of a treatment plant, or (iii) the waste management system of a city, country, or region. In a few cases, household waste or waste generated through the demolition of buildings was investigated.

This review shows that more than half of the studies geographically defined their system boundaries by assessing the waste management of a city, region, or country, and that approximately 25% of the 151 studies investigated one unit of a waste stream. The waste input and output streams of a treatment plant were evaluated in 15% of the reviewed studies (see Figure 3).

Only approximately one-fifth of the reviewed studies used the mass balance principle (Brunner and Rechberger, 2004) to identify the inputs and outputs of the investigated system. More commonly, only the outputs of the systems were considered.

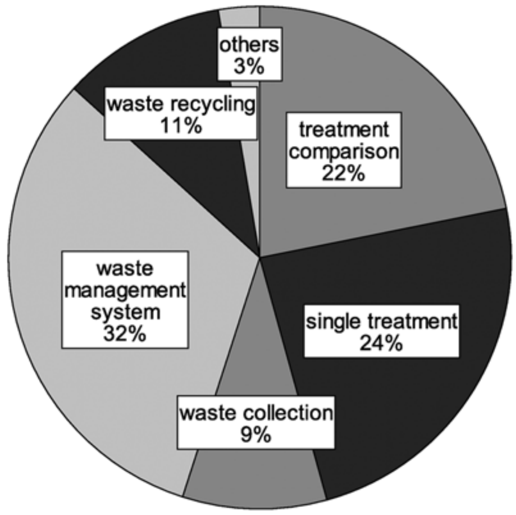

Figure 4. Object of investigation of the reviewed studies (n = 151).

Objects of investigation

Categorising the reviewed articles by their objects of investigation shows that many studies assessed entire waste management systems. The life cycle of a product ends with waste management, which includes the waste management system from waste generation, waste collection, recycling, and treatment to final disposal. Therefore, the efficient planning of waste management systems requires an accounting of complete sets of effects caused by the entire life cycle of waste (Emery et al., 2007). One-quarter of the reviewed works assessed either one treatment plant or compared different treatment options to determine the best available alternative (Figure 4.). In particular, the performances of incinerators or landfills were often the objects of such investigations.

Comparing system boundaries with the object of investigation shows that studies evaluating waste management systems, waste

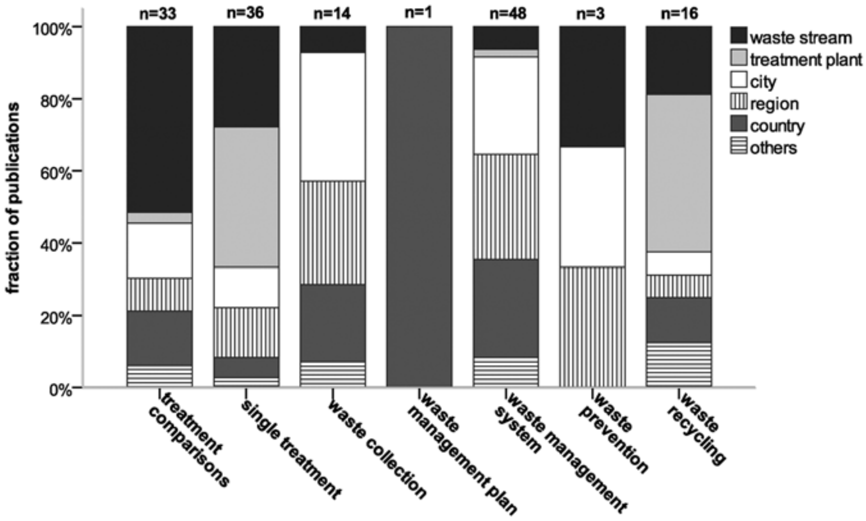

Figure 5. Comparison of the objects of investigation and scales used (n = 151).

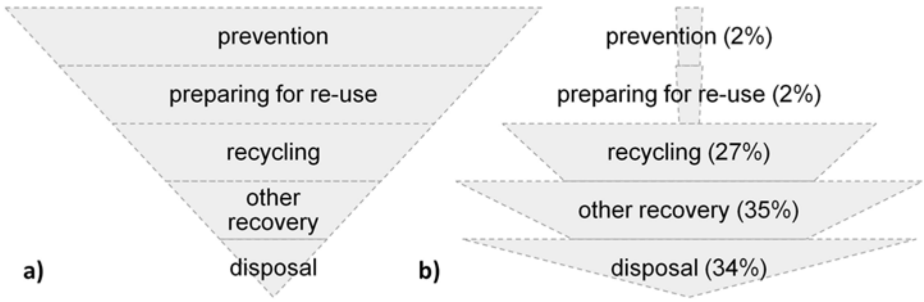

Figure 6. (a) Waste hierarchy of solid waste management (Directive 2008/98/EC). (b) Objects of investigation of the reviewed studies according to the EU waste hierarchy.

collection systems, and waste prevention options often used geographic boundaries (country, region, or city). The reason is that these boundaries most likely coincided with administrative boundaries. The functional unit to compare different treatment options was primarily one unit of a specific waste stream, and the evaluation of single treatment often referred to the inputs and outputs of the investigated plant (Figure 5).

According to the European Union waste hierarchy (Directive 2008/98/EC), waste prevention is ranked as the highest goal in waste management (see Figure 6(a)). The allocation of the reviewed studies to the five steps of the EU waste hierarchy (without considering the categories of waste management system and waste collection) shows that waste prevention is not ranked among the top issues by the waste management assessment community (see Figure 6(b)).

In only 4% of the reviewed studies, the main object of the investigations was waste prevention or re-use; however, approximately 25% assessed waste recycling systems. Most frequently, other recovery methods, such as incineration, with energy recovery or disposal methods, such as landfills, have been the objects of investigations.

The investigated waste stream can be categorised as solid waste, MSW, different waste fractions (mixed), or a single waste fraction (organic, plastic waste, paper waste, aluminium waste, construction and demolition waste (C&D) waste, glass waste, or other single waste streams). Over 50% of the reviewed articles assessed waste management systems considering MSW, and 12% investigated the combined solid waste of a region or the solid waste applied to a specific waste treatment plant (see Figure 7).

Because of the growing production and consumption of electronic products, the question of how to manage e-waste has become important (Song et al., 2012). Approximately 6% of the articles attempted to determine the best e-treatment option. The increasing attention to climate change and the diversion of organic waste away from landfills lead to the fact that 6% of the studies specifically observed organic waste.

Figure 8 shows that benchmarking methods were often used for assessing MSW management. However, benchmarking does not seem common for investigations of single waste streams. Compared with the other assessment methods, LCA, MCDM, and RA were more often performed for assessing single waste streams. Associated with risk management, e-waste was often the topic of investigations. Many RAs were performed in China to evaluate the risks concerning e-waste treatment plants.

Considered aspects

For a comprehensive assessment of waste management systems or processes, it appears necessary to examine all three aspects associated with the term sustainability: social, economic, and environmental aspects. However, depending on the goal of a study, sometimes only one or two aspects were considered.

Economic aspects are an important factor because money, in combination with available technology, is generally the limiting factor for a sophisticated, properly functioning waste management system. Economic aspects are mentioned on a business (micro-economic) level or on a public (macro-economic) level. In the reviewed articles, on the business level, the investment and operational costs were usually evaluated. Macro-economically, the costs for waste management are labelled as a percentage of the gross domestic product, or the total costs of a waste management system of a region or country are calculated and evaluated. However, many studies did not consider the economic aspects. This lack may be a common reason why different waste management strategies, scenarios, and plans are not implemented.

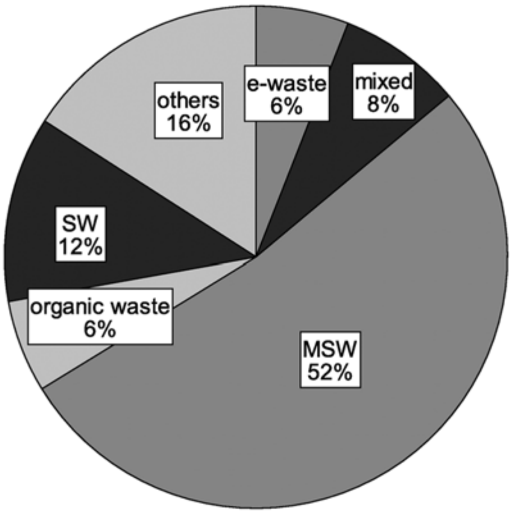

Figure 7. Observed waste streams in the reviewed studies (n = 151).
MSW: municipal solid waste; SW: solid waste.

The purpose of considering environmental aspects in waste management (from waste generation over collection, recycling, and treatment to the final disposal) is to evaluate the impacts on air, soil, and water, as well as on resource consumption (Su et al., 2010). To protect humans, flora, and fauna, it is necessary to know the environmental aspects of a service or a process. Studies using LCA methodology for an assessment often evaluate environmental impacts by examining the following categories: global warming potential; stratospheric ozone depletion; acidification; terrestrial eutrophication; aquatic eutrophication; photochemical ozone formation; human toxicity; and ecotoxicity.

Social sustainability can be classified under three different perspectives (den Boer et al., 2005): social acceptability (the waste management system must be acceptable); social equity (the equitable distribution of waste management system benefits and detriments between citizens); and social function (the social benefit of waste management systems). Public health and safety are important factors within society, with a close link to the economy and to the environment. Social aspects also refer to the employment market, governance, ethics, security, education systems, and to culture (European Commission, 2009).

In this article, to categorise the reviewed studies depending on the economic, environmental, and social impacts, a modified classification of the 'Impact Assessment Guidelines' that was provided by the EC was used (see Table 2). Notably, many evaluated impacts can not only refer to one of the three pillars of sustainability, but also interactions between social, economic, and environmental sustainability are frequent. For example, human health can be associated with the social sustainability, depending on the DALY (disability-adjusted life years), the economic

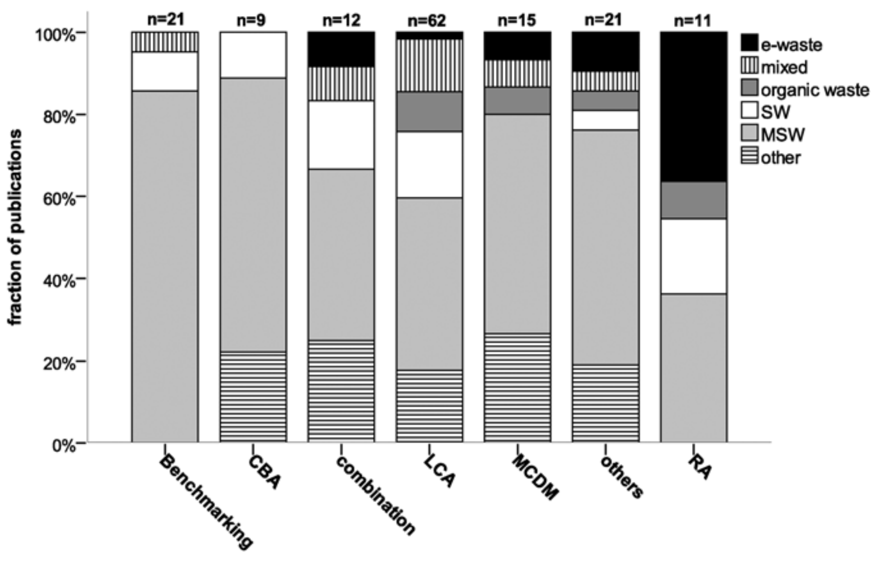

Figure 8. Investigated waste streams as a function of the assessment methods (n = 151).
MSW: municipal solid waste; SW: solid waste.

Table 2. Economic, environmental, and social impacts of waste management, based on European Commission (2009).

Economic impacts	Environment impacts	Social impacts
– Function of the internal market	– Climate	– Employment and labour markets
– Investment costs	– Energy	– Social inclusion and protection of particular groups
– Operating costs	– Air quality	– Non-discrimination
– Administrative burdens	– Biodiversity, flora, fauna, and landscapes	– Individuals, private and family life, personal data
– Public authorities	– Water quality and resources	– Governance, participation, good administration, access to justice, media, and ethics
– Property rights innovation and research	– Soil quality or resources	– Public health and safety
– Economic effects on consumers and households	– Land use	– Security
– Economic effects on industry and business	– Renewable or non-renewable resources	– Access to and effects on social protection, health, and educational systems
	– Environmental consequences of firms and consumers	– Culture
	– Likelihood or scale of environmental risks	
	– Animal welfare	

sustainability with the future costs of different toxic impacts, and on the environmental sustainability as the cause for future diseases. Particularly as a function of time, environmental aspects can influence the economy and society.

The categorisation of the reviewed articles shows that common environmental impacts were investigated. Approximately 90% of the reviewed studies considered environmental impacts; 45% of the reviewed studies considered economic impacts; and only 19% of the reviewed studies considered social issues. Few studies considered environmental, and/or economic, and/or social aspects. However, only 28 of the 151 reviewed studies analysed the impacts on all three pillars of sustainability. Studies assessing the economic aspects more often considered macroeconomic than micro-economic effects.

A comparison of the different aspects in the reviewed studies with respect to the assessment methods (Figure 9) shows that, in particular, LCA and RA often evaluated a waste management system by only considering the environmental impacts. According to LCA guidelines (ISO 2006), economic and social aspects are typically not considered within a LCA. MCDM and the category ‘others’ (different methods, e.g. CEA, EA, exergy analysis, strategic environmental assessment (SEA)) appear to be the most complete methods regarding the comprehensive evaluation of social, economic, and environmental aspects.

Weighting

Weighting is defined as converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices; data before weighting should remain available (ISO 2006). The weighting steps are based on value-choices of the stakeholders, and are not scientifically based (ISO 2006). This lack of a scientific basis is the reason why weighting is prone to criticism (Finnveden et al., 2007). For comparison or for converting different indicators, approximately 50% of the reviewed studies performed a weighting step.

Conclusions and recommendations for the application of assessment methods and for future research

In total, 151 studies have been reviewed to compare goals, methods, object of investigations, considered aspects, and system boundaries. The results of this review show the heterogeneity within the published studies. The results also show that any investigation of waste management systems requires an individual assessment methodology, depending on the goal of the assessment, the object of investigation, system boundaries, and on addressees. For a complete knowledge of a waste management system, an assessment is fundamental (Zurbrügg et al., 2014) for providing reliable results and data for decision making.

Based on the results of this review, the following recommendations are suggested for the future evaluation of waste management systems.

1. Goals are important and must be clearly stated. This concerns two types of goals: (i) First, the *objectives for waste management*, as provided by the legislative framework, policy statement, or regional guideline, must be considered. It is important to focus on these objectives because these objectives can be manifold and even contradictory and because these objectives have a determining influence on the methodology that must be chosen for the evaluation. (ii) Second, the purpose, scope, and the *goals for the assessment* must be clearly defined, considering the addressees and the objectives of waste management stated in (i). It is important to select an assessment method, or, most often, a set of assessment methods, that is capable of addressing all the criteria necessary for characterising the goals established in the first step. To meet these expectations, numerous studies have been published. Table 3 summarises why, and for whom, assessments are performed, and presents the reviewed assessment methods in relation

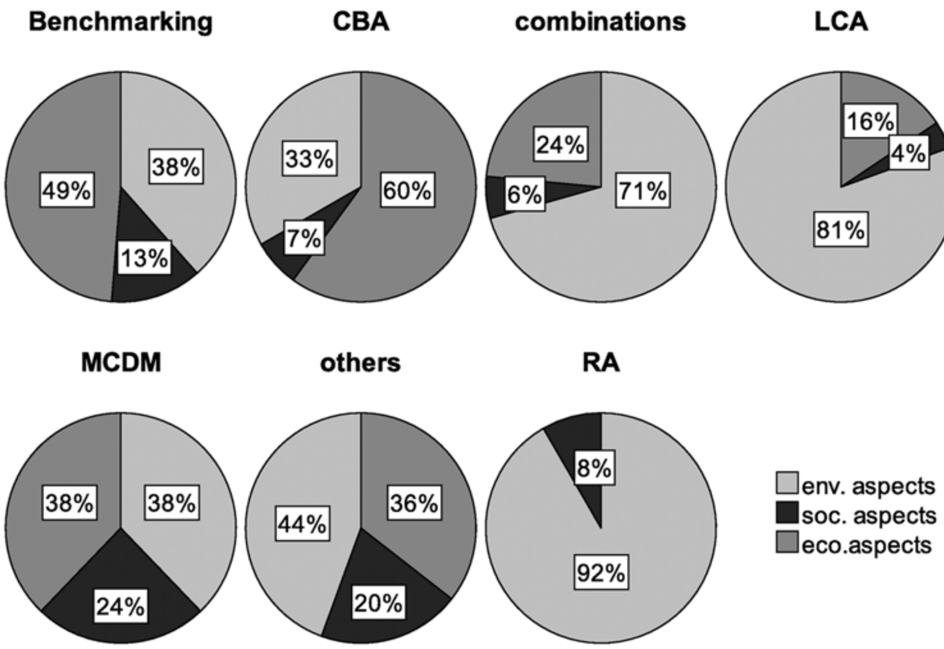

Figure 9. Considered aspects in the reviewed studies with respect to the different assessment methods (n = 151).
CBA: cost-benefit analysis; LCA: life cycle assessment; MCDM: multi-criteria-decision-making; RA: risk assessment.

to the receivers of the studies, objects of the investigation, and aspects considered.

If only a part of the goals are to be considered, for example environmental protection such as in a LCA, this consideration must be clearly stated to allow for the comparison of different studies. Regarding goals of waste management, it is recommended to choose comprehensive social, environmental, and economic goals that meet the requirements of sustainability. In specific terms, this recommendation suggests affordable and acceptable waste management of proven reliability that protects humans and the environment, conserves resources, and minimises after-care. According to the purpose of the assessment, it may be necessary to address additional issues, such as the value of previous investments and of existing waste treatment components. It is evident that such a comprehensive evaluation is a demanding task requiring reliable methodologies, sound data, and experienced evaluators.

2. Often, waste management systems are assessed by evaluating the impacts caused by selected single outputs, for example emissions. A comprehensive evaluation must consider all direct and indirect impacts. Waste management should be perceived as a ‘throughput economy’, with inputs from the market and with outputs to the market and to the environment (Figure 10).

Taking this view, the complexity of the economic system is apparent. It becomes evident that sophisticated assessment methods are required. Only such methods are able to evaluate the economic, ecological, and social effects of a waste management system. The choice of the starting point and end point of an assessment can have a decisive impact on the results. The scope and system boundaries have to be selected carefully, because changing the boundaries can have a key influence on the results. Particularly in the case of recycling, it is important to consider not only emissions but also all the risks. The fate of hazardous substances that are not released to the environment, but that are retained in the recycling goods, must be followed as well. If not, then an ‘after-care-free’ waste management cannot be established because these hazardous substances will have to be managed after x cycles (Velis and Brunner, 2013). Hence, when recycling processes are assessed, waste composition, process characteristics, emissions, and recycling product qualities must be known. In summary, inputs must be linked with outputs.

3. The application of the mass balance principle is crucial for an impartial, comprehensible evaluation. As stated before, assessment methods can be divided into two groups: methods that are based on the mass balance principle and other methods that do not require this strict precondition. The establishment mass balances of the total waste management system is recommended as a base for any subsequent evaluation step. Such mass balances on the level of goods and substances represent required and highly useful tools for evaluation because these tools allow the cross-checking plausibility of available information (Brunner and Rechberger, 2004). When evaluating waste management systems, data availability and data quality are often limiting steps. Wastes contain many products that are made from complex mixtures of elements and that are composed of countless substances, yielding highly heterogeneous combinations. In fact, wastes may contain everything because their content cannot be completely controlled. Thus, to analyse waste inputs over longer periods for real situations

Table 3. Overview of the 151 reviewed studies and their classifications (percentages in bold indicate the most commonly used assessment method in relation to the criteria for each column).

Methods	Receiver									
	Government	Government/ citizens	Government/ operators	Government/ researchers	Citizens	Municipalities	Operators	Operators/ researchers	Researchers	Not named
Benchmarking	**76%**	5%	0%	0%	0%	**5%**	5%	0%	0%	10%
CBA	44%	11%	22%	0%	**11%**	0%	11%	0%	0%	0%
combinations	42%	0%	8%	8%	0%	0%	**17%**	0%	**25%**	0%
LCA	56%	0%	5%	6%	0%	0%	5%	2%	18%	8%
MCDM	40%	7%	7%	**27%**	0%	0%	7%	0%	13%	0%
RA	9%	**27%**	**27%**	18%	0%	0%	0%	**9%**	0%	9%
others	52%	5%	5%	5%	0%	0%	14%	5%	14%	0%
Methods	Object of investigation									
	Different treatments	Treatment	Waste collection	Waste management plan	Waste management system	Waste prevention	Waste recycling			
Benchmarking	5%	10%	29%	0%	**48%**	5%	5%			
CBA	0%	44%	**33%**	0%	11%	0%	11%			
Combinations	17%	33%	0%	0%	33%	0%	17%			
LCA	**39%**	23%	6%	0%	24%	2%	6%			
MCDM	20%	7%	7%	0%	47%	**7%**	13%			
RA	0%	**64%**	0%	0%	0%	0%	**36%**			
Others	14%	19%	0%	**5%**	52%	0%	10%			
Methods	Aspects									
	Eco. aspects (macro)	Eco. aspects (micro)	Env. aspects	Soc. aspects						
Benchmarking	**86%**	5%	71%	24%						
CBA	67%	**33%**	56%	11%						
Combinations	17%	17%	**100%**	8%						
LCA	15%	5%	**100%**	5%						
MCDM	60%	**33%**	93%	**60%**						
RA	0%	0%	**100%**	9%						
Others	57%	19%	95%	43%						

CBA: cost-benefit analysis; LCA: life cycle assessment; MCDM: multi-criteria-decision-making; RA: risk assessment.

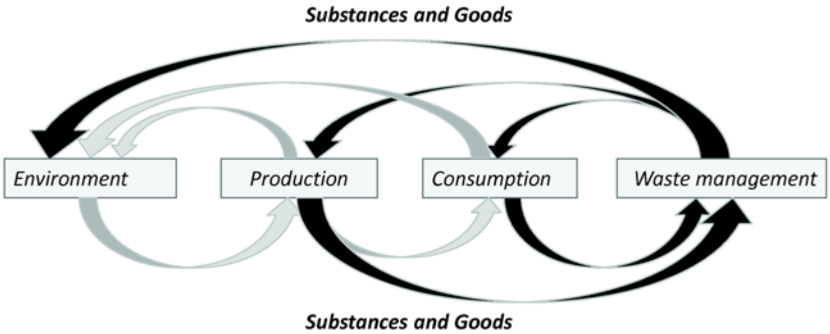

Figure 10. Waste management as a 'throughput economy'.

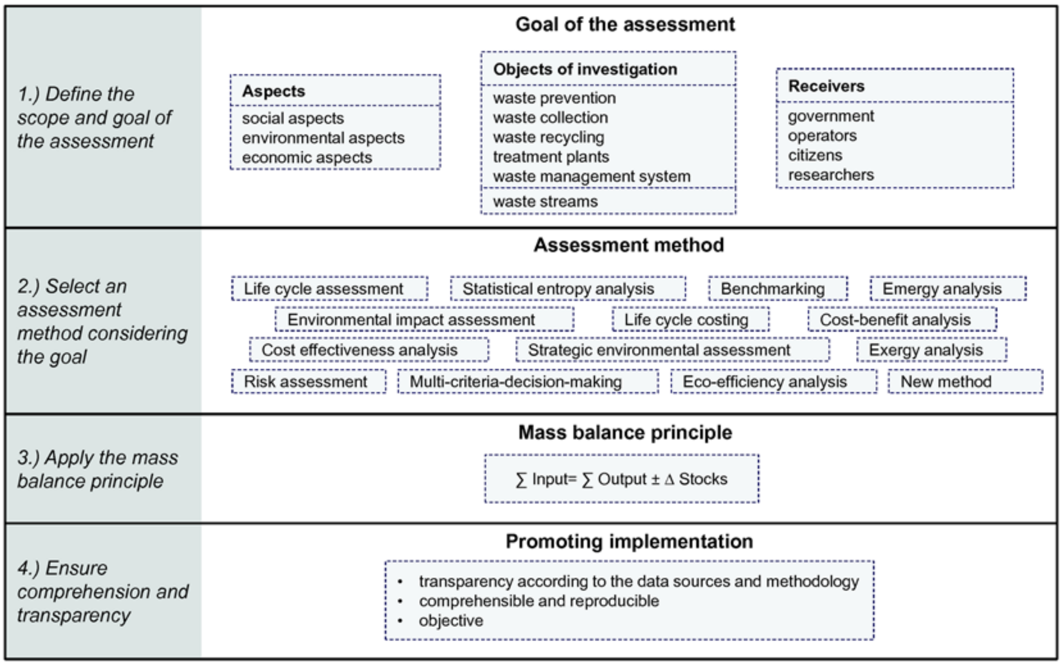

Figure 11. Key elements of a waste management assessment methodology.

is a non-trivial, time-consuming, and costly endeavour. A more effective means is output-oriented analysis. If inputs and outputs of waste treatment systems are monitored and balanced, then the law of conservation of matter allows the comparison of information concerning material flows from the input side with the output side. Hence, data can be cross-checked, deviations can be detected, and additional investigations can be performed, if necessary. The products of waste treatment are generally more homogenous and easier to analyse, and the accuracy of waste composition data calculated from the products of waste treatment is usually higher (Brunner and Ernst, 1986). This advantage becomes even more pronounced when, in addition to the level of goods, the level of substances is considered. Mass balances on the level of goods ensure that the total input (wastes) and total output (products, residues, emissions) match. Substance balances go one step further; these balances ensure that inputs and outputs correspond on the level of individual elements or chemical compounds (e.g. carbon or CO_2). Thus, if an array of valuable and hazardous substances is balanced together with the flow of inputs and outputs of goods, then the resulting information serves as a reliable and comprehensive base for subsequent evaluation steps. Hence, a mass balance approach based on a rigid input–output analysis of the entire waste management system should be taken. Well suited for this purpose is material flow analysis, a systematic assessment that considers all processes, flows, and stocks in a defined system, delivering a complete and consistent set of information concerning a waste management system (Brunner and Rechberger, 2004).

4. Assessments must be reproducible, comprehensible, and transparent regarding methodology and data. Methods based on mass balances must be favoured and applied that promote these characteristics. Good, impartial, and reliable data sources with known uncertainty are crucial. Objectivity, transparency, and confirmability are not only necessary during the assessment step; these qualities are also of key importance when the results are presented, for example policy decisions.

> Politicians, stakeholders, and decision makers generally require results that these individuals can grasp with little effort. If informative and convincing text, figures, and tables are produced in a transparent and reproducible manner, then the results of the assessment are likely to have a larger impact.

Figure 11 summarises the conclusions of this review. As a framework for waste management decisions, assessment methods depict the strengths and weaknesses of different management alternatives. An approach based on mass balances and on a goal-oriented evaluation of impacts is a powerful means to ensure comprehension, objectivity, rigidity, and transparency. Applying this approach for assessing waste management systems will result in better and more comprehensive support for decision makers.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

Achillas C, Moussiopoulos N, Karagiannidis A, Banias G and Perkoulidis G (2013) The use of multi-criteria decision analysis to tackle waste management problems: A literature review. *Waste Management & Research* 31: 115–129.

Al Sabbagh MK, Velis CA, Wilson DC and Cheeseman CR (2012) Resource management performance in Bahrain: A systematic analysis of municipal waste management, secondary material flows and organizational aspects. *Waste Management & Research* 30: 813–824.

Banar M, Cokaygil Z and Ozkan A (2009) Life cycle assessment of solid waste management options for Eskisehir, Turkey. *Waste Management* 29: 54–62.

Barton JR, Dalley D and Patel VS (1996) Life cycle assessment for waste management. *Waste Management* 16: 35–50.

Beigl P, Lebersorger S and Salhofer S (2008) Modelling municipal solid waste generation: A review. *Waste Management* 28: 200–214.

Benetto E, Tiruta-Barna L and Perrodin Y (2007) Combining lifecycle and risk assessments of mineral waste reuse scenarios for decision making support. *Environmental Impact Assessment Review* 27: 266–285.

Brunner PH (2013) Cycles, spirals and linear flows. *Waste Management & Research* 31: 1–2.

Brunner PH and Ernst WR (1986) Alternative methods for the analysis of municipal solid waste. *Waste Management & Research* 4: 147–160.

Brunner PH and Rechberger H (2004) *Practical Handbook of Material Flow Analysis*. Boca Raton: CRC Press LLC.

Burgess AA and Brennan DJ (2001) Application of life cycle assessment to chemical processes. *Chemical Engineering Science* 56: 2589–2604.

Carlsson Reich M (2005) Economic assessment of municipal waste management systems—case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). *Journal of Cleaner Production* 13: 253–263.

Cleary J (2009) Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature. *Environment International* 35: 1256–1266.

Coelho HMG, Lange LC and Coelho LMG (2012) Proposal of an environmental performance index to assess solid waste treatment technologies. *Waste Management* 32: 1473–1481.

den Boer E, den Boer J, Berger J and Jager J (2005) Deliverable Report on D5.1 and D5.2: Social Sustainability Criteria and Indicators for Waste Management (Work Package 5) *The Use of Life Cycle AssessmentTool for the Development of Integrated Waste Management Strategies for Cities and Regions with Rapid Growing Economies*.

Diaz R and Warith M (2006) Life-cycle assessment of municipal solid wastes: development of the wasted model. *Waste Management* 26: 886–901.

Directive 2001/42/EC (2001) Assessment of the effects of certain plans and programmes on the environment. Brussels: The European Parliament and the Council.

Directive 2008/98/EC (2008) Waste and repealing certain directives. Brussels: The European Parliament and the Council.

Directive 2011/92/EC (2011) Assessment of the effects of certain public and private projects on the environment. Brussels: The European Parliament and the Council.

Ekmekçioğlu M, Kaya T and Kahraman C (2010) Fuzzy multicriteria disposal method and site selection for municipal solid waste. *Waste Management* 30: 1729–1736.

El Hanandeh A and El-Zein A (2010) The development and application of multi-criteria decision-making tool with consideration of uncertainty: The selection of a management strategy for the bio-degradable fraction in the municipal solid waste. *Bioresource Technology* 101: 555–561.

Emery A, Davies A, Griffiths A and Williams K (2007) Environmental and economic modelling: A case study of municipal solid waste management scenarios in Wales. *Resources, Conservation and Recycling* 49: 244–263.

European Commission (2009) Impact assessment guidelines. SEC (2009) 92 Brussels: European Commission.

Finnveden G and Moberg Å (2005) Environmental systems analysis tools – an overview. *Journal of Cleaner Production* 13: 1165–1173.

Finnveden G, Björklund A, Moberg Å, Ekvall T and Moberg Å (2007) Environmental and economic assessment methods for waste management decision-support: Possibilities and limitations. *Waste Management & Research* 25: 263–269.

Finnveden G, Hauschild MZ, Ekvall T, et al. (2009) Recent developments in life cycle assessment. *Journal of Environmental Management* 91: 1–21.

Font Vivanco D, Puig Ventosa I and Gabarrell Durany X (2012) Building waste management core indicators through spatial material flow analysis: Net recovery and transport intensity indexes. *Waste Management* 32: 2496–2510.

Gabler (2014) Definition of 'benchmarking': http://wirtschaftslexikon.gabler.de/Archiv/2297/benchmarking-v7.html (accessed 12 May 2014).

Giugliano M, Cernuschi S, Grosso M and Rigamonti L (2011) Material and energy recovery in integrated waste management systems. An evaluation based on life cycle assessment. *Waste Management* 31: 2092–2101.

Gómez-Delgado M and Tarantola S (2006) Global sensitivity analysis, gis and multi-criteria evaluation for a sustainable planning of a hazardous waste disposal site in Spain. *International Journal of Geographical Information Science* 20: 449–466.

Heijungs R and Guinée JB (2007) Allocation and 'what-if' scenarios in life cycle assessment of waste management systems. *Waste Management* 27: 997–1005.

Hermann BG, Kroeze C and Jawjit W (2007) Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. *Journal of Cleaner Production* 15: 1787–1796.

Hiraki T and Akiyama T (2009) Exergetic life cycle assessment of new waste aluminium treatment system with co-production of pressurized hydrogen and aluminium hydroxide. *International Journal of Hydrogen Energy* 34: 153–161.

Hirsch WZ (1965) Cost functions of an urban government service: Refuse collection. *The Review of Economics and Statistics* 47: 87–92.

Hung M-L, Ma H-W and Yang W-F (2007) A novel sustainable decision making model for municipal solid waste management. *Waste Management* 27: 209–219.

ISO (2006) Environmental Management – Life Cycle Assessment – Require-Ments and Guidelines. International Standard ISO 14044, Geneva.

ISO (2009) Risk Management – Principles and Guidelines, ISO 31000:2009. International Organisation for Standardisation, Geneva.

Jamasb T and Nepal R (2010) Issues and options in waste management: A social cost–benefit analysis of waste-to-energy in the UK. *Resources, Conservation and Recycling* 54: 1341–1352.

Karmperis AC, Aravossis K, Tatsiopoulos IP and Sotirchos A (2013) Decision support models for solid waste management: Review and game-theoretic approaches. *Waste Management*. 33: 1290–1301.

Kaufman SM, Krishnan N and Themelis NJ (2010) A screening life cycle metric to benchmark the environmental sustainability of waste management systems. *Environmental Science & Technology* 44: 5949–5955.

Langdon D (2007) Life cycle costing (LCC) as a contribution to sustainable construction – Guidance on the use of the LCC Methodology and its application in public procurement. Available from EU Publications (2007): http://ec.europa.eu/DocsRoom/documents/5060/attachments/1/translations/en/renditions/native (accessed 12 May 2014).

Levin HM and McEwan PJ (2000). *Cost-Effectiveness Analysis: Methods and Applications*. SAGE Publications.

Morrissey AJ and Browne J (2004) Waste management models and their application to sustainable waste management. *Waste Management* 24: 297–308.

Pearce D, Atkinson G and Mourato S (2006). *Cost-Benefit Analysis and the Environment: Recent Developments*. Paris, France: OECD Publishing.

Pires A, Martinho G and Chang N-B (2011) Solid waste management in European countries: A review of systems analysis techniques. *Journal of Environmental Management* 92: 1033–1050.

Rechberger H and Brunner PH (2002) A new, entropy based method to support waste and resource management decisions. *Environmental Science & Technology* 36: 809–816.

Rogge N and De Jaeger S (2012) Evaluating the efficiency of municipalities in collecting and processing municipal solid waste: A shared input dea-model. *Waste Management* 32: 1968–1978.

Saling P, Kicherer A, Dittrich-Krämer B, et al. (2002) Eco-efficiency analysis by Basf: The method. *The International Journal of Life Cycle Assessment* 7: 203–218.

Simões P and Marques RC (2012) On the economic performance of the waste sector. A literature review. *Journal of Environmental Management* 106: 40–47.

Song Q, Wang Z, Li J and Duan H (2012) Sustainability evaluation of an E-waste treatment enterprise based on emergy analysis in China. *Ecological Engineering* 42: 223–231.

Su J-P, Hung M-L, Chao C-W and Ma H-W (2010) Applying multi-criteria decision-making to improve the waste reduction policy in Taiwan. *Waste Management & Research* 28: 20–28.

Szargut J (2005) *Exergy Method: Technical and Ecological Applications*. Southampton, UK: WIT Press.

Tanskanen J-H (2000) Strategic planning of municipal solid waste management. *Resources, Conservation and Recycling* 30: 111–133.

Velis CA and Brunner PH (2013) Recycling and resource efficiency: It is time for a change from quantity to quality. *Waste Management & Research* 31: 539–540.

Wilson DC, Smith NA, Blakey NC and Shaxson L (2007) Using research-based knowledge to underpin waste and resources policy. *Waste Management & Research* 25: 247–256.

Yoshida H, Christensen TH and Scheutz C (2013) Life cycle assessment of sewage sludge management: A review. *Waste Management & Research* 31: 1083–1101.

Yuan F, Shen L-Y and Li Q-M (2011) Emergy analysis of the recycling options for construction and demolition waste. *Waste Management* 31: 2503–2511.

Zurbrügg C, Caniato M and Vaccari M (2014) How assessment methods can support solid waste management in developing countries—a critical review. *Sustainability* 6: 545–570.

Supplementary data: assessment methods for solid waste management: a literature review

Allesch Astrid[1,2], Brunner Paul H.[1]

The following table includes the supplementary data to the article '*assessment methods for solid waste management: a literature review'* and shows the reviewed 151 studies (**X** Yes, **-** No)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
1	Bench-marking	comparison of waste management systems to assist councils to achieve best value in their refuse collection services	waste collection	MSW	country (Scotland)	-	government	COM-PARE	-	X	-	X	-	-	(Accounts Commission 2000)
2	Bench-marking	comparison of the performance of waste and resource management in Bahrain with other cities and construction of a material flow diagram	waste management system	MSW	country (Bahrain)	X	government	STAN2	-	X	-	X	X	-	(Al Sabbagh et al., 2012)
3	Bench-marking	comparison of the performances of SWMS of the EU Member States	waste management system	MSW	EU Member States	-	government	-	-	X	-	X	-	X	(BiPRO 2012)
4	Bench-marking	comparison of the performance of 19 MSWI	incineration	MSW	MSWI (Taiwan)	-	operators	-	-	-	X	X	-	X	(Chen et al., 2010b)
5	Bench-marking	assessment of environmental performance of waste treatment technologies based on the cleaner treatment index	WtE treatment plants	SW	waste to energy plants	-	-	-	Cleaner Treatment Index in SWM	-	-	X	-	X	(Coelho et al., 2012)
6	Bench-marking	evaluation of the impact of some local policies aimed on MSW reduction on the cost efficiency of MSW collection and disposal	waste prevention	MSW	region (Flanders)	-	government	-	-	X	-	-	-	X	(De Jaeger et al., 2011)

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no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
7	Bench-marking	evaluation of the performance of the local government in Australia	waste man-agement system	MSW	country (Australia)	-	government	-	-	X	-	X	X	-	(Dollery et al., 2007)
8	Bench-marking	comparison of the SWM ser-vices of Ireland with other countries	waste man-agement system	MSW	country (Ireland)	-	government	-	-	X	-	X	-	-	(Forfas 2010)
9	Bench-marking	to provide guidelines and benchmarks to improve the SWM in cities	waste man-agement system	MSW	country (India)	-	government and private sector	-	-	X	-	X	X	-	(Government of India 2009)
10	Bench-marking	comparison of the EU member states on prices and costs of WM system	waste man-agement system	MSW	EU Mem-ber states	-	EU Member States	-	-	X	-	-	-	-	(Hogg et al., 2002)
11	Bench-marking	comparison of the MSW collec-tion efficiency of local govern-ments based on multiple factors	waste collec-tion	MSW	regions (Taiwan)	-	government	-	aggregate indicator (AI)	X	-	-	-	X	(Huang et al., 2011)
12	Bench-marking	comparison of the MSW logistic efficiency of prefectures in Japan	waste collec-tion	MSW	regions (Japan)	-	government	-	-	X	-	-	-	X	(Ichinose et al., 2013)
13	Bench-marking	evaluation of the effectiveness of MSW management systems with respect to lifecycle energy utilization and resources con-servation	waste man-agement system	MSW	cities (San Francisco, Honolulu)	-	-	-	Resource Conservation Efficiency (RCE)	-	-	X	-	X	(Kaufman et al., 2010)
14	Bench-marking	comparison of municipalities to evaluate if MSW Recycling is economically efficient	landfilling, recycling	municipal plastic, paper, card-board and glass waste	country (Israel)	-	government	-	computer-based simu-lation for assessing the costs	X	-	-	-	-	(Lavee 2007)
15	Bench-marking	tions for Individual Waste the factors influencing the recycling potential of	recycling	MSW	country (Israel)	-	government	-	-	X	-	-	-	-	(Lavee et al., 2010)
16	Bench-marking	to measure the performance of the Portuguese SWM services	waste man-agement system	SW	country (Portugal)	-	government	-	-	X	-	X	X	X	(Marques et al., 2009)
17	Bench-marking	comparison of the cost efficien-cy of different municipalities	waste collec-tion	MSW	region (Flanders)	-	government	-	modified DEA	X	-	X	-	X	(Rogge et al., 2012)
18	Bench-marking	development of the shared input DEA-model in evaluating the cost efficiencies	waste collec-tion	MSW	region (Flanders)	-	government	-	modified DEA	X	-	X	-	X	(Rogge et al., 2013)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
19	Bench-marking	comparison of the efficiency of urban solid waste collection of different municipalities	waste collec-tion	MSW	cities (in Spain)	-	government	-	-	X	-	-	-	X	(Sanchez 2006)
20	Bench-marking	to describe the urban solid waste services to encourage Portuguese operators to better performances and to include environmental factors in the analysis	waste man-agement system	MSW	country (Portugal)	-	government	-	-	X	-	X	-	X	(Simões et al., 2010)
21	Bench-marking	comparison of the solid waste management systems in cities around the world	waste man-agement system	SW	20 cities	X	government	-	-	X	-	X	X	-	(Wilson et al., 2012)
1	CBA	evaluation of economic feasibil-ity of waste in terms of cost savings	re-use, recy-cling	C&D waste	building (Malaysia)	-	construction industry	-	-	-	X	-	-	-	(Begum et al., 2006)
2	CBA	to analyse the economic per-formance of source categorized collection	waste collec-tion	MSW	city (Shanghai)	-	government	-	-	X	-	-	-	-	(Feng et al., 2009)
3	CBA	comparison of different models to analyse the cost benefit of the switch to automated collec-tion of waste with single stream recycling	waste collec-tion	MSW	HH (Madi-son)	-	households	-	-	X	-	-	-	X	(Jamelske et al., 2006)
4	CBA	evaluation of landfill systems with gas recovery	landfilling	MSW	region (Andaman Islands)	-	government	-	-	X	-	X	-	-	(Kumar et al., 2004)
5	CBA	evaluation of the ecological-economic efficiency of a MSW management scheme	landfilling	MSW	landfill site (Sweden)	-	government/ operators	-	-	-	X	X	-	-	(Moutavtchi et al., 2008)
6	CBA	evaluation of ecological–economic efficiency to support decision makers by develop-ment of a general model	landfilling	MSW	landfill site (Sweden)	-	government/ operators	-	-	-	X	X	-	-	(Moutavtchi et al., 2010)
7	CBA	cost benefit analysis of the MSW collection	waste collec-tion	MSW	city (Yan-gon)	-	government	-	-	X	-	-	-	-	(Tin et al., 1995)
8	CBA	comparison of the effectiveness of MSW management systems	waste man-agement system	MSW	country (Taiwan)	-	government/ citizens	-	-	X	-	X	X	-	(Weng et al., 2011)
9	CBA	comparison of different treat-ment scenarios to investigate all essential activities that are in relevant to the cost–benefit of C&D waste management throughout the waste chain	waste man-agement system	C&D waste (con-crete)	city (Shen-zhen)	-	government	-	-	X	-	X	-	-	(Yuan et al., 2011b)

no	assessment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	software/ tool	novelties (with respect to the assessment tool)	macro	micro	env. aspect	soc. aspect	weighting	reference
1	CBA (social)	assessment of energy and environmental aspects of WtE as an alternative waste management option that is compatible with recycling	composting, incineration, landfilling, recycling	MSW	country (UK)	-	government	-	-	X	-	X	X	-	(Jamasb et al., 2010)
1	combination (CF, MFA)	application of a set of material flow indicators to track progress over time of MSW collection and management treatments	waste management system	MSW	region (Northern Spain)	X	government	-	-	X	-	X	-	-	(Cifrian et al., 2012)
2	combination (ECO-EFF, LCA)	comparison of different recycling routes of waste glass to produce recycled foam glass (RFG)	recycling	glass waste	1 ton RFG	X	operators	-	-	-	-	X	-	X	(Blengini et al., 2012)
3	combination (EF, MCDM)	comparison and ranking of waste treatment alternatives to identify the most beneficial	waste management system	MSW	1 kg MSW (Campania)	X	government	-	-	-	-	X	-	X	(Herva et al., 2013)
4	combination (emergy analysis, LCA)	evaluation of the key environmental impacts related to e-waste treatment, determine the main pollution processes, and provide some appropriate suggestions for improving the treatment process	recycling	e-waste	region (Macau)	-	government/ operators	-	combined use of emergy and LCA	-	X	X	-	X	(Song et al., 2013)
5	combination (exergy analysis, LCA)	comparison of the conventional aluminium waste treatment with a new treatment system with co-production of pressurized hydrogen and aluminium hydroxide	aluminium treatment	aluminium waste	waste aluminium (containing 15 mass% metallic aluminium)	X	researchers	-	-	-	-	X	-	-	(Hiraki et al., 2009)
6	combination (indicators, MFA)	regional based material flow analysis in e-waste management systems to measure the potential points for improvement	waste management system	e-waste	country (Lithuania)	X	government	STAN	-	X	-	X	-	-	(Gurauskienė et al., 2011)
7	combination (LCA, CF)	comparison of treatment options to evaluate which option is more sustainable with respect to the carbon footprint	incineration, landfilling	MSW	1 ton MSW (UK)	-	government	CCaLC, GABI	-	-	-	X	-	-	(Jeswani et al., 2013)
8	combination (LCA, LCC)	assessment of MSW systems by linking economic information to a LCA	waste management system	MSW	cities (Uppsala, Stockholm, Älvdalen)	X	researchers	ORWARE	-	X	-	X	-	X	(Carlsson Reich 2005)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
9	combina-tion (LCA, MFA)	comparison of waste disposal alternatives which are able to minimize the amount of land-filled waste while maximizing material and energy recovery	incineration, landfilling with and without bio-gas combus-tion, sorting plant	MSW	city (Rome)	X	government	-	-	-	-	X	-	-	(Cherubini et al., 2009)
10	combina-tion (LCA,RA)	comparison of waste re-use scenarios for mineral waste and to identify key issues for further researches	waste in road construction	MSWI residues, C&D waste	-	-	researchers	-	Integrated Environmen-tal Assess-ment (com-bine LCA and RA)	-	-	X	-	X	(Benetto et al., 2007)
11	combina-tion (LCA, input-output analysis)	evaluation of potential impacts of urban agglomeration mate-rial metabolism upon resources and environment	waste recy-cling	scrap tire	region (Su-Xi-Chang)	X	government/ researchers	-	mixed-unit input–output life cycle assessment	-	-	X	-	-	(Qu et al., 2013)
12	combina-tion (MCDM, RA)	comparison of alternatives for a waste incineration project	incineration	MSW	200,000 ton per year	-	operators	-	risk-based multi-criteria assessment (RBMCA)	-	X	X	X	X	(Karmperis et al., 2012)
13	combina-tion (MFA, Indica-tors)	comparison of six waste man-agement scenarios based on firm objectives and recent legislation	waste man-agement system	MSW	region (campania)	X	government	STAN	-	-	-	X	-	-	(Mastellone et al., 2009)
1	ECO-EFF	evaluation of the MSW system to improve the eco-efficiency	waste man-agement system	MSW	city (Kawa-saki)	-	government	-	-	X	-	X	-	-	(Geng et al., 2010)
2	ECO-EFF	evaluation of the existing MSW management system and to investigate different strategies	waste man-agement system	MSW	city (Tian-jin)	-	government	-	-	X	-	X	-	-	(Zhao et al., 2011a)
1	EF	to develop the EF of wastes, including hazardous and non-hazardous wastes and to test the proposed method on wastes generated in a textile process	waste man-agement system	industry waste (textile process)	company (textile process)	-	operators	-	EF of toxic and hazard-ous wastes	-	-	X	-	-	(Herva et al., 2010)
1	EIA	to characterise municipal waste landfills and to quantify the impact of deposit points on environmental elements	landfilling	MSW	landfill site (Valparai-so)	-	government/ operators	-	-	-	-	X	-	X	(Calvo et al., 2007)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
2	EIA	evaluation of environmental impacts of APC residues from MSWI to fail to be further used as building material	recycling	APC Residues	cylindrical monoliths (4 cm diameter and 4 cm height)	-	government	-	-	-	-	X	-	-	(Quina et al., 2011)
1	emergy analysis	comparison of emergy benefits and costs for three different waste treatment alternatives	composting, sorting	MSW	treatment plants (Sao Paolo)	-	government	-	Net emergy benefit	-	-	X	X	-	(Agostinho et al., 2013)
2	emergy analysis	evaluation of the Macao's waste treatment in the years 1995, 1999, 2003, 2004	waste man-agement system	MSW	region (Macao)	-	researchers	-	-	X	-	X	X	-	(Lei et al., 2008)
3	emergy analysis	evaluation of the sustainability of an e-waste treatment enter-prise	e-waste treatment	e-waste	e-waste treatment enterprise (Suzhou)	-	operators	-	-	-	X	X	-	-	(Song et al., 2012)
4	emergy analysis	evaluation of the efficiency of recycling C&D waste to achieve the integration between eco-nomic, social and environmen-tal effects	landfilling, recycling	C&D waste (con-crete)	region (China))	-	operators	-	-	X	-	X	X	-	(Yuan et al., 2011a)
1	exergy analysis	comparison of two waste-disposal options and evaluation of energy conversion process-es and systems, based on an extended representation of their exergy flow diagram	waste man-agement system	MSW	-	-	researchers	-	Including non-energetic quantities to the exergy analysis	-	X	X	X	-	(Sciubba 2003)
1	HMA Model (Helsinki Metropoli-tan Area)	comparison of effects of differ-ent separation strategies on the costs and emissions of MSW management	waste man-agement system	MSW	city (Hel-sinki)	-	government	HMA Model	HMA Model	X	-	X	-	X	(Tanskanen 2000)
1	Industrial Source Complex	assessment of the environmen-tal impacts of a MSWI based on the PCDD/F concentrations	incineration	MSW	region (3x3 km) around incinerator	-	govern-ment/citizen	-	-	-	-	X	-	-	(Wang et al., 2008)
1	integrate model	evaluation of waste manage-ment system to re-introduce long-term unemployed people	re-use, recy-cling	C&D waste	cities (Trond-heim, Östersund)	-	researchers/ operators	-	Integrate model to evaluate environmen-tal, economic and social aspects	-	X	X	X	X	(Klang et al., 2003)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
1	LCA	comparison of the environmental impacts of existing MSW strategies to improve the current system	composting, landfilling	MSW	1 ton MSW (Teheran)	-	government	-	-	-	X	X	-	X	(Abduli et al., 2011)
2	LCA	comparison of environmental impacts of different scenarios for treatment of organic household waste	home composting, incineration, landfilling	OHW	1 ton OHW (Denmark)	X	government	EASE WASTE	-	-	-	X	-	X	(Andersen et al., 2012)
3	LCA	comparison of environmental impacts of SWM scenarios	waste management system	MSW	1kg MSW (Campania)	X	government/researchers	-	-	-	-	X	-	-	(Arena et al., 2003)
4	LCA	to select an optimum waste management system for Eskisehir by evaluating from an environmental point of view	waste management system	SW	region (Eskisehir)	-	government	SIMAPRO 7	-	-	-	X	-	X	(Banar et al., 2009)
5	LCA	comparison of environmental impacts of current separation systems with different scenarios	waste collection	MSW	region (Sweden)	-	government	EASE WASTE	-	-	-	X	-	X	(Bernstad et al., 2011)
6	LCA	to assess environmental impacts of two different disposal scenarios for MSWI bottom ash	landfilling, recycling	Bottom ash	4400 tons bottom ash (Denmark)	-	government	ROAD-RES	-	-	-	X	-	-	(Birgisdóttir et al., 2007)
7	LCA	evaluation of the environmental impacts of the waste incineration tax proposal, to investigate possibilities of more optimal design of such a tax	incineration	SW	country (Sweden)	-	government	SIMAPRO 5	-	-	-	X	-	X	(Björklund et al., 2007)
8	LCA	comparison of environmental impacts of different biological treatment methods	composting windrow, composting tunnel, anaerobic digestion, combined anaerobic–aerobic reactor	organic MSW	1 ton organic waste (2/3 vegetable food waste, 1/3 garden waste)	X	researchers	EASE WASTE	-	-	-	X	-	X	(Boldrin et al., 2011)
9	LCA	to quantify the environmental burdens associated by managing organic household waste materials and to determine the optimum way of recovering energy	anaerobic digestion, gasification, incineration, combustion in a cement kiln	biodegradable fractions of MSW food,	1 ton of each waste material (England)	-	researchers	WRATE	-	-	-	X	-	-	(Burnley et al., 2012)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
				garden, paper, wood municipal waste and refuse-derived fuel											
10	LCA	comparison of environmental impacts associated to materials previously considered as waste after their status have been revised by considering the EU directive 2008	waste recy-cling	fly ash, blast furnace slag	cement industry 1kg of CEM I (com-pared to 1.11kg of GBFS, and to 1.67kg of fly ash)	X	government	-	-	-	X	X	-	X	(Chen et al., 2010a)
11	LCA	comparison of two flue gas cleaning processes in MSWIs	incineration	MSW	treatment of 60.000 Nm^3/h of raw flue gas	-	operators	-	-	-	-	X	-	X	(Chevalier et al., 2003)
12	LCA	comparison of SWM alterna-tives to assess the global warming potential according to the actual C load to atmosphere	waste man-agement system	SW	-	X	researchers	-	-	-	-	X	-	-	(Christensen et al., 2009)
13	LCA	assessment and quantification of the environmental im-portance of the development of air pollution control (APC) of waste incineration environmen-tal aspects	incineration	MSW	1 ton MSW	-	researchers	EASE WASTE	-	-	-	X	-	X	(Damgaard et al., 2010)
14	LCA	comparison of urban waste management scenarios to support decision makers in planning urban waste man-agement systems	waste man-agement system	MSW	countries (Spain, Slovakia, Poland, Greece, Lithuania)	-	government	LCA-IWM (Inte-grate Waste Man-age-ment)	LCA-IWM	X	-	X	X	X	(den Boer et al., 2007)
15	LCA	to examine the environmental and economic impacts of a number of waste disposal systems	waste man-agement system	MSW	region (South Wales)	-	government	WISAR D	-	X	-	X	-	-	(Emery et al., 2007)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
16	LCA	comparison of advantages and disadvantages of different treatment methods of solid waste and to identify critical factors in the systems	anaerobic digestion, composting incineration with heat recovery, landfilling with gas extraction, recycling,	food waste, news-print, corrugat-ed card-board, mixed card-board, PE, PP, PS, PVC, PET	per hh (Sweden)	-	government	-		-	-	X	-	X	(Finnveden et al., 2005)
17	LCA (EIO)	comparison of the cost, energy, and global warming implications of the use of several emerging food waste to energy technolo-gies at the University of Toledo	anaerobic digestion, thermophilic acidogenic hydro-genesis, landfilling,	organic waste (food waste)	waste of the Univer-sity of Toledo	-	government	-	-	-	X	X	-	-	(Franchetti 2013)
18	LCA	comparison of treatment and disposal options for APC resi-dues	landfilling, backfilling in salt mines, neutralization of waste acids, filler material in asphalt, Ferrox stabi-lization, vitrification, thermal co-treatment with automo-bile shredder, residue	air pollu-tion control residues	1 ton of APC resi-dues	-	government/ operators	EASE WASTE	-	-	-	X	-	X	(Fruergaard et al., 2010)
19	LCA	evaluation of the environment consequences of waste pre-vention on SWM systems and wider society	waste pre-vention	food waste, unsolicit-ed mail and beverage packag-ing	100.000 ton of MSW	-	government	EASE WASTE	-	-	-	X	-	X	(Gentil et al., 2011)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
20	LCA	comparison of collection alter-natives to identify optimised activities for subsequent treat-ments	waste collec-tion	MSW	cities (750.000 and 150.000 ton/year of MSW)	-	government	-	Combination of CED, and CML-Method)	-	-	X	-	X	(Giugliano et al., 2011)
21	LCA	comparison of energetic valori-sation options with the existing solid waste treatment	landfilling with energy recovery, incineration, anaerobic digestion, gasification	SW	region (Yoyakarta, Sleman, Bantul)	-	government	-	-	-	-	X	-	-	(Gunamanth a et al., 2012)
22	LCA	comparison of environmental impacts of different waste treatment scenarios	landfilling, incineration, BMT-compost, BMT-incineration, BMT-landfill	MSW	1 ton MSW (Pudong)	-	government	-	-	-	-	X	-	X	(Hong et al., 2006)
23	LCA	comparison of environmental impacts of MSW	composting, incineration, land applica-tion, land-filling	MSW	1 ton dry MSW (China)	-	government	-	-	-	-	X	-	X	(Hong et al., 2010)
24	LCA	comparison of the overall po-tential environmental impacts of three selective collection ser-vices in urban areas	waste collec-tion	organic, paper, packag-ing and glass MSW	1500 tons /month	-	researchers	-	-	-	-	X	-	X	(Iriarte et al., 2009)
25	LCA	comparison of environmental impacts of various waste con-version systems	gasification, pyrolysis	MSW, wood, organic waste, RDF, tyres	Output: 1 ton product gas (Sin-gapore)	-	government	GaBi	-	X	-	X	-	X	(Khoo 2009)
26	LCA	comparison and evaluation of environmental impacts of differ-ent food waste disposal sys-tems	composting, dry and wet feeding, landfilling	food waste (MSW)	1 ton food waste (South Korea)	X	-	-	-	-	-	X	-	-	(Kim et al., 2010)
27	LCA	to design a more complete model of PET waste manage-ment system, including both open and closed-loop strate-	waste recy-cling	plastic waste (PET)	1 kg PET bottles	-	researchers	-	mathematical model (modi-fied CML-Method)	-	-	X	-	X	(Komly et al., 2012)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
		gies, and the possibility of multiple recycling trips													
28	LCA	comparison and evaluation of environmental and economic effects of treatment alternative	landfilling, recycling, shredding	e-waste (electric home applianc-es)	country (Japan)	X	govern-ment/researc hers	-	modified LCA by waste input output analysis (WIO)	X	-	X	-	-	(Kondo et al., 2004)
29	LCA	comparison of GHG impacts of landfilling and alternative waste treatment methods	anaerobic digestion, composting, landfilling	organic waste (textiles, wood, food, yard trimming, misc. organics)	1 ton wet organic matter	-		-	-	-	-	X	-	-	(Kong et al., 2012)
30	LCA	comparison and environmental assessment of different MSW treatment strategies	anaerobic digestion, landfilling, recycling,	MSW	city (Thes-saloniki)	-	researchers	-	-	-	-	X	-	X	(Koroneos et al., 2012)
31	LCA	evaluation of the environmental impacts of four categories of waste recycling in China's paper industry	recycling	waste paper, crop straw, bagasse, textile scrap paper	paper industry (China)	X	operators/ researchers	-	physical input–output life-cycle assessment (PIO-LCA)	-	-	X	-	-	(Liang et al., 2012)
32	LCA	comparison of alternative treatment methods for food waste and evaluation of the In-Sink-Erator food waste proces-sor system	home com-posting, centralised composting, In-Sink-Erator food waste processor	organic waste (food waste)	food waste per hh and y (Sydney)	-	researchers	-	-	-	-	X	-	-	(Lundie et al., 2005)
33	LCA	comparison of environmental impacts of six landfilling tech-nologies	landfilling	MSW	1 ton MSW	X	government/ operators	EASE WASTE	-	-	-	X	-	X	(Manfredi et al., 2009)
34	LCA	comparison of environmental impacts of a low organic waste landfill with a conventional landfill	landfilling	other (low organic waste, MSW)	1 ton low organic waste or hh-waste)	-	government	EASE WASTE	-	-	-	X	-	X	(Manfredi et al., 2010)
35	LCA	comparison of environmental impacts of different waste treatment options	composting, incineration, landfilling,	organic, paper, plastic,	1 ton of each frac-tion	-	-	EASE WASTE	-	-	-	X	-	X	(Manfredi et al., 2011)

no	assessment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	software/ tool	novelties (with respect to the assessment tool)	macro	micro	env. aspect	soc. aspect	weighting	reference
			recycling	aluminium and glass waste											
36	LCA	comparison of environmental impacts of treatment methods of municipal organic waste	biogasification, composting, landfilling	MSW	1 ton MSW (Sao Paolo)	-	government	-	-	-	-	X	-	-	(Mendes et al., 2003)
37	LCA	evaluation of the performance of a full scale life cycle sustainability assessment of waste management systems	waste management system	MSW	1 ton MSW (Nonthaburi)	-	government	-	-	X	-	X	X	X	(Menikpura et al., 2012)
38	LCA	comparison of environmental impacts of waste paper recycling and incineration	incineration, recycling	waste paper	1 ton waste paper	-	government	EASE WASTE	-	-	-	X	-	X	(Merrild et al., 2008)
39	LCA	comparison of environmental impacts of integrated waste management solutions	waste management system	MSW	region (Southern Lithuania)	-	government	WAMPS	-	-	-	X	-	-	(Miliūte et al., 2010)
40	LCA	comparison of different treatment options to test the validity of the waste hierarchy	incineration, landfilling, recycling	paper waste (newsprint), plastic waste (PET)	country (Sweden)	-	government	-	-	X	-	X	-	X	(Moberg et al., 2005)
41	LCA	comparison of environmental impacts from two different types of waste incineration systems	incineration	MSW	1 ton MSW	-	operators	-	-	-	-	X	-	X	(Ning et al.,)
42	LCA	to develop an environmental assessment of a landfill	landfilling	SW	landfill site (Finland)	-	researchers	EASE WASTE	-	-	-	X	-	X	(Niskanen et al., 2009)
43	LCA	comparison of different alternatives for solid waste management	waste management system	MSW	region (Península de Setúbal)	-	government	UMBERTO 5.5	-	-	-	X	-	X	(Pires et al., 2011)
44	LCA	to model environmental aspects of waste incineration	incineration	MSW	MSWI (Aarhus)	X	-	EASE WASTE	-	-	-	X	-	X	(Riber et al., 2008)
45	LCA	comparison of energetic and environmental impacts of two MSW management system	waste management system	MSW	region (North Italy)	X	researchers	SimaPro 7	-	-	-	X	-	X	(Rigamonti et al., 2009)
46	LCA	to quantify and compare environmental impact of different MSW collection systems that use waste containers	waste collection	MSW	region (Spain)	-	government	SimaPro 7	-	-	-	X	-	X	(Rives et al., 2010)
47	LCA	to quantify environmental im-	composting	organic	1 ton com-	-	researchers	SIMAP	-	-	-	X	-	-	(Saer et al.,)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
		pacts and benefits of a food waste composting system		waste (food waste)	post, (Pennsyl-vania)			RO 7							
48	LCA	comparison of different waste paper management scenarios to evaluate the goals of the EU waste hierarchy	incineration, landfilling, recycling	waste paper	country (Denmark)	X	government	-	-	-	-	X	-	X	(Schmidt et al., 2007)
49	LCA	to assess the environmental quality of different waste treat-ment scenarios when planning a new project in an existing town	waste man-agement system	MSW	new set-tlement - 1500 hh (Trond-heim)	-	government	EASE WASTE	-	-	-	X	-	X	(Slagstad et al., 2012)
50	LCA	evaluation of the reconstruction of the MSW management system comprehensively from both environmental and eco-nomic points of view	waste man-agement system	MSW	1 kg MSW (Iwate)	-	government/ researchers	JEMAI-LCA Pro, 3EID	-	X	-	X	-	X	(Tabata et al., 2011)
51	LCA	evaluation of the environmental sustainability of a specific waste refinery concept in which organ-ic waste materials are liquefied using enzymes and recoverable materials are separated out in a ''solid fraction'	anaerobic digestion, co-combustion, incineration, recycling	MSW	1 ton MSW	-	-	-	-	-	-	X	-	X	(Tonini et al., 2012)
52	LCA	to help the local municipality administration in Irkutsk (Rus-sia) identify the most appropri-ate direction for current waste management and its optimiza-tion	waste man-agement system	MSW	region (Irkutsk)	-	government/ researchers	IWM Soft-ware	-	X	-	X	X	-	(Tulokhonov a et al., 2013)
53	LCA	comparison of three alternative waste management strategies for energy recovery from waste	WtE treat-ment plants	MSW	country (England)	-	government	WRAT E	-	-	-	X	-	-	(Tunesi 2011)
54	LCA	comparison of two incinerators to provide a quantitative as-sessment of the importance of local conditions and model choice for the environmental profile of waste incineration	incineration	SW	1 ton wet waste	-	operators	EASE WASTE , SIMAP RO	-	-	-	X	-	X	(Turconi et al., 2011)
55	LCA	comparison of the environmen-tal impacts of selected technol-ogies for beverage carton recycling and to support deci-	waste recy-cling	beverage carton packages	100 kg sorted beverage carton	-	government/ operators	-	-	X	-	X	-	-	(Varžinskas et al., 2012)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
		sion-makers			waste										
56	LCA	comparison of the environmental impacts for bioethanol production from waste papers and to compare them with the alternative waste management options	bioethanol production, incineration, recycling	waste paper	1 kg bio-ethanol or 1 kg waste paper	-	government	-	-	-	-	X	-	-	(Wang et al., 2012a)
57	LCA	comparison of two treatment systems for optimized reduction of greenhouse gas emissions	incineration with energy recovery	MSW	region (Northern Germany)	-	government	-	-	-	-	X	-	-	(Wittmaier et al., 2009)
58	LCA	evaluation of the environmental impacts of different leachate recirculation systems in a conventional landfill	landfilling	MSW	city (North China)	-	government	EASEWASTE	-	-	-	X	-	X	(Xing et al., 2013)
59	LCA	comparison of the existing MSW management system and different MSW management strategies	waste management system	MSW	city (Tianjin)	-	government	-	-	-	-	X	-	-	(Zhao et al., 2009a)
60	LCA	comparison of the environmental impacts of the different SWM system scenarios	waste management system	MSW	city (Hangzhou)	-	government	EASEWASTE	-	-	-	X	-	X	(Zhao et al., 2009b)
61	LCA	comparison of the current SWM system with two future waste management scenarios	waste management system	MSW	city (Beijing)	-	government	EASEWASTE	-	-	-	X	-	X	(Zhao et al., 2011b)
62	LCA	comparison of the environmental impacts of different incineration scenarios using auxiliary coal	incineration	MSW	city (Shuozhou)	-	government	EASEWASTE	-	-	-	X	-	X	(Zhao et al., 2012)
1	LCC	comparison of waste management alternatives to enlighten what are the assumptions that most influence the feasibility of each scenario and determine the ranking of options	waste management system	MSW	region (Northern Italy)	-	government	-	-	X	-	X	-	-	(Massarutto et al., 2011)
1	MCDM	comparison of different disposal methods and sites for MSW	composting, incineration, landfilling, RDF	MSW	city (Istanbul)	-	government	-	modified fuzzy TOPSIS methodology	-	X	X	-	X	(Ekmekçioğlu et al., 2010)
2	MCDM	comparison of SWM scenario relating to bio-degradable fraction of MSW to minimize the quantity of waste sent to landfills, increase energy production	anaerobic digestion, composting incineration , landfilling	organic and paper MSW	city (Sydney)	-	researchers	ELECTRE SS	ELECTRE SS (modified version of ELECTRE III)	-	-	X	-	X	(El Hanandeh et al., 2010)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
		and decrease	with energy recovery												
3	MCDM	comparison of different disposing options of plastic waste and waste recycling facilities of construction and demolition	recycling	plastic waste, C&D waste	country (Brazil)	-	government/ operators	-	-	-	X	X	-	X	(Gomes et al., 2008)
4	MCDM	to analyse the problems to find a location for hazardous waste landfill site	landfilling	hazard-ous waste	city (Ma-drid)	-	researchers	-	Joint of GIS and Multi-Criteria Evaluation	-	X	X	X	X	(Gómez-Delgado et al., 2006)
5	MCDM	comparison and ranking of different waste treatment and disposal scenarios with the developed decision support system	composting, incineration, landfilling	MSW	region (Sicily)	-	government	-	Decision Support System	X	-	X	-	X	(Haastrup et al., 1998)
6	MCDM	comparison of different options for managing waste paper	composting, gasification, incineration, landfilling, recycling	waste paper	region (Isle of Wight)	-	government	-	-	X	-	X	X	X	(Hanan et al., 2012)
7	MCDM	comparison of SWM systems with ELECTRE III	waste man-agement system	-	region (Oulu)	-	government/ researchers	ELEC-TRE III	-	X	-	X	X	X	(Hokkanen et al., 1997)
8	MCDM	comparison of waste manage-ment systems of nine areas in Dakar	waste man-agement system	MSW	hh-waste (Dakar)	-	government/ researchers	AR-GOS	-	X	-	-	X	X	(Kapepula et al., 2007)
9	MCDM	comparison of different demoli-tion waste management strate-gy	waste man-agement system	C&D waste	demolition of an old military camp (Lyon)	-	government/ researchers	ELECT R III	modified ELECTR III	X	-	X	X	X	(Roussat et al., 2009)
10	MCDM	to develop a concept to evalu-ate the social, economic and ecologic performance of a waste management system	waste man-agement system	MSW	City (Mu-nich)	-	government/ citizen	-	-		X	X	X	X	(Schütz et al., 2013)
11	MCDM	comparison of waste reduction alternatives and to integrate the experiences of cities that have adopted waste reduction strat-egies to facilitate planning of future policies	waste pre-vention	MSW	city (Taoyuan)	-	government	-	-	X	-	X	X	X	(Su et al., 2010)
12	MCDM	comparison of the environmen-tal impacts of different collec-tion methods	waste collec-tion	MSW	city (Istan-bul)	-	government/ researchers	-	-	X	-	X	X	X	(Ulukan et al., 2009)

no	assessment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	software/ tool	novelties (with respect to the assessment tool)	macro	micro	env. aspect	soc. aspect	weighting	reference
13	MCDM	comparison of different integrated solid waste management systems	composting, landfilling, incineration, sorting	MSW	city (Montreal)	-	government	-	-	X	-	X	-	X	(Vaillancourt et al., 2002)
14	MCDM	comparison of three waste management scenarios with an integrated inexact chance-constrained mixed-integer program (ICMILP)	waste management system	MSW	city (Bejing)	-	government	-	ICMILP	X	-	X	-	X	(Xi et al., 2010)
15	MCDM	to develop a novel sustainable planning approach for meeting the best sustainability interests of an e-recycling company	recycling	e-waste	e-waste recycling site	-	operators	-	fuzzy MCDM algorithm	-	X	X	X	X	(Yeh et al., 2013)
1	modified CEA	to search for the best options to treat MSW and sewage sludge considering the economic costs and fulfilment of the goals defined in Austria's Waste Management Act	waste management system	MSW, sewage sludge	country (Austria)	X	government	-	modified CEA	X	-	X	X	X	(Döberl et al., 2002)
1	multiple regression	to develop a cost function analysis for SWM for a typical developing country	waste management system	MSW	country (Developing Country)	-	government	-	-	X	-	-	-	-	(Parthan et al., 2012)
1	RA	assessment of long-term emissions of carcinogenic and non-carcinogenic air pollutants from MSWI	incineration	MSW	MSWI (Taranto)	-	government	-	-	-	-	X	-	-	(Cangialosi et al., 2008)
2	RA	to quantify and understand the behaviour of Polybrominated diphenyl ethers (PBDEs) in the atmosphere and to investigate the seasonal and diurnal variation of PBDEs	waste recycling	e-waste	e-waste recycling site (Guiyu)	-	operators/ researchers	-	-	-	-	X	-	-	(Chen et al., 2011)
3	RA	assessment of carcinogenic and non-carcinogenic effects through emissions from landfills	landfilling	non-hazardous SW	landfill site (South Italy)	-	government/ citizens	-	-	-	-	X	-	-	(Davoli et al., 2010)
4	RA	health risk assessment of dioxin emissions from MSWI	incineration	MSW	city (Antwerp)	-	government/ citizens	-	-	-	-	X	-	-	(Nouwen et al., 2001)
5	RA	to estimate environmental compatibility of the controlled landfills by applying an integrated method based on hydrogeological behaviour	landfilling	SW	landfill site (Italy)	-	government/ operators	-	-	-	-	X	-	-	(Rapti-Caputo et al., 2006)

no	assess-ment tool	goal	object of the investigation	waste type	scale	mass balance	receiver	soft-ware/ tool	novelties (with respect to the assess-ment tool)	mac-ro	mi-cro	env. as-pect	soc. as-pect	weight -ing	reference
6	RA	to estimate the total exposure of PCDD/Fs of the population living at the surroundings of the MSWI and to evaluate the health risks	incineration	MSW	region (Tarrago-na)	-	-	-	-	-	-	X	-	-	(Schuhmacher et al., 2001)
7	RA	evaluation of the bioaerosol releases from composting facilities	composting	organic waste (green waste)	composting facilities (SE Eng-land)	-	government/ operators	-	-	-	-	X	-	-	(Taha et al., 2006)
8	RA	to identify the levels of PCBs generated from e-waste recy-cling, and their potential im-pacts on the soils and vegeta-tion	recycling	e-waste	e-waste recycling site (South China)	-	government/ researchers	-	-	-	-	X	-	-	(Wang et al., 2011)
9	RA	evaluation of the nature of health risks for children living in areas influenced by lead pollu-tion from e-waste recycling and tinfoil manufacturing activities	waste recy-cling	e-waste	e-waste recycling site (Zheji-ang)	-	government/ operators	-	-	-	-	X	-	-	(Wang et al., 2012b)
10	RA	to assess the effect of uncon-trolled e-waste recycling activi-ties on the PAH contamination of soils and vegetation	waste recy-cling	e-waste	e-waste recycling site (Guang-dong)	-	government/ citizens	-	-	-	-	X	-	-	(Wang et al., 2012c)
11	RA	evaluation of the effects to human health that may result from contaminant releases from MSW combustors	incineration	MSW	Stack Emission of MSWI (1500 tons SW/day)	-	government/ researchers	-	-	-	-	X	-	-	(Zemba et al., 1996)
1	SEA	to show how SEA can be ap-plied in a waste management context to develop a regional waste management plan	waste man-agement plan	SW	region (Salzburg)	-	government/ researchers	-	-	X	-	X	X	-	(Salhofer et al., 2007)
1	spatial MFA	comparison of SWM scenarios by characterising the waste flows and building up core indicators	waste man-agement system	organic MSW	region (Cat-alonia)	X	government	-	Net Recov-ery Index, the Transport Intensity Index	X	-	X	X	-	(Font Vivanco et al., 2012)
1	statistical entropy analysis	to quantify and value the change in concentrating and diluting of heavy metals during the course of incinerator devel-opment	incineration	MSW	1 ton MSW	X	researchers	-	Substance Concentrat-ing Efficiency (SCE	-	-	X	-	X	(Rechberger et al., 2002)

X *Yes,* **-** *No*

References

Abduli, M., Naghib, A., Yonesi, M. & Akbari, A. (2011) Life Cycle Assessment (Lca) of Solid Waste Management Strategies in Tehran: Landfill and Composting Plus Landfill. *Environmental monitoring and assessment*, 178, 487-498

Accounts Commission. (2000). *Benchmarking Refuse Collection: A Review of Councils' Refuse Collection Services*, Audit Scotland, Edinburgh, Scotland

Agostinho, F., Almeida, C.M.V.B., Bonilla, S.H., Sacomano, J.B. & Giannetti, B.F. (2013) Urban Solid Waste Plant Treatment in Brazil: Is There a Net Emergy Yield on the Recovered Materials? *Resources, Conservation and Recycling*, 73, 143-155

Al Sabbagh, M.K., Velis, C.A., Wilson, D.C. & Cheeseman, C.R. (2012) Resource Management Performance in Bahrain: A Systematic Analysis of Municipal Waste Management, Secondary Material Flows and Organizational Aspects. *Waste Management & Research*, 30, 813-824

Andersen, J.K., Boldrin, A., Christensen, T.H. & Scheutz, C. (2012) Home Composting as an Alternative Treatment Option for Organic Household Waste in Denmark: An Environmental Assessment Using Life Cycle Assessment-Modelling. *Waste Management*, 32, 31-40

Arena, U., Mastellone, M.L. & Perugini, F. (2003) The Environmental Performance of Alternative Solid Waste Management Options: A Life Cycle Assessment Study. *Chemical Engineering Journal*, 96, 207-222

Banar, M., Cokaygil, Z. & Ozkan, A. (2009) Life Cycle Assessment of Solid Waste Management Options for Eskisehir, Turkey. *Waste Management*, 29, 54-62

Begum, R.A., Siwar, C., Pereira, J.J. & Jaafar, A.H. (2006) A Benefit–Cost Analysis on the Economic Feasibility of Construction Waste Minimisation: The Case of Malaysia. *Resources, Conservation and Recycling*, 48, 86-98

Benetto, E., Tiruta-Barna, L. & Perrodin, Y. (2007) Combining Lifecycle and Risk Assessments of Mineral Waste Reuse Scenarios for Decision Making Support. *Environmental Impact Assessment Review*, 27, 266-285

Bernstad, A., la Cour Jansen, J. & Aspegren, H. (2011) Life Cycle Assessment of a Household Solid Waste Source Separation Programme: A Swedish Case Study. *Waste Management & Research*, 29, 1027-1042

BiPRO. (2012) Screening of Waste Management Performance of Eu Member States. *Report submitted under the EC project “Support to Member States in improving waste management based on assessment of Member States’ performance”. Report prepared for the European Commission, DG ENV, July 2012*,

Birgisdóttir, H., Bhander, G., Hauschild, M.Z. & Christensen, T.H. (2007) Life Cycle Assessment of Disposal of Residues from Municipal Solid Waste Incineration: Recycling of Bottom Ash in Road Construction or Landfilling in Denmark Evaluated in the Road-Res Model. *Waste Management*, 27, 75-84

Björklund, A.E. & Finnveden, G. (2007) Life Cycle Assessment of a National Policy Proposal – the Case of a Swedish Waste Incineration Tax. *Waste Management*, 27, 1046-1058

Blengini, G.A., Busto, M., Fantoni, M. & Fino, D. (2012) Eco-Efficient Waste Glass Recycling: Integrated Waste Management and Green Product Development through Lca. *Waste Management*, 32, 1000-1008

Boldrin, A., Neidel, T.L., Damgaard, A., Bhander, G.S., Møller, J. & Christensen, T.H. (2011) Modelling of Environmental Impacts from Biological Treatment of Organic Municipal Waste in Easewaste. *Waste Management*, 31, 619-630

Burnley, S., Phillips, R. & Coleman, T. (2012) Carbon and Life Cycle Implications of Thermal Recovery from the Organic Fractions of Municipal Waste. *The International Journal of Life Cycle Assessment*, 17, 1015-1027

Calvo, F., Moreno, B., Ramos, Á. & Zamorano, M. (2007) Implementation of a New Environmental Impact Assessment for Municipal Waste Landfills as Tool for Planning and Decision-Making Process. *Renewable and Sustainable Energy Reviews*, 11, 98-115

Cangialosi, F., Intini, G., Liberti, L., Notarnicola, M. & Stellacci, P. (2008) Health Risk Assessment of Air Emissions from a Municipal Solid Waste Incineration Plant – a Case Study. *Waste Management*, 28, 885-895

Carlsson Reich, M. (2005) Economic Assessment of Municipal Waste Management Systems—Case Studies Using a Combination of Life Cycle Assessment (Lca) and Life Cycle Costing (Lcc). *Journal of Cleaner Production*, 13, 253-263

Chen, C., Habert, G., Bouzidi, Y., Jullien, A. & Ventura, A. (2010a) Lca Allocation Procedure Used as an Incitative Method for Waste Recycling: An Application to Mineral Additions in Concrete. *Resources, Conservation and Recycling*, 54, 1231-1240

Chen, D., Bi, X., Liu, M., Huang, B., Sheng, G. & Fu, J. (2011) Phase Partitioning, Concentration Variation and Risk Assessment of Polybrominated Diphenyl Ethers (Pbdes) in the Atmosphere of an E-Waste Recycling Site. *Chemosphere*, 82, 1246-1252

Chen, H.-W., Chang, N.-B., Chen, J.-C. & Tsai, S.-J. (2010b) Environmental Performance Evaluation of Large-Scale Municipal Solid Waste Incinerators Using Data Envelopment Analysis. *Waste Management*, 30, 1371-1381

Cherubini, F., Bargigli, S. & Ulgiati, S. (2009) Life Cycle Assessment (Lca) of Waste Management Strategies: Landfilling, Sorting Plant and Incineration. *Energy*, 34, 2116-2123

Chevalier, J., Rousseaux, P., Benoit, V. & Benadda, B. (2003) Environmental Assessment of Flue Gas Cleaning Processes of Municipal Solid Waste Incinerators by Means of the Life Cycle Assessment Approach. *Chemical Engineering Science*, 58, 2053-2064

Christensen, T.H., Gentil, E., Boldrin, A., Larsen, A.W., Weidema, B.P. & Hauschild, M. (2009) C Balance, Carbon Dioxide Emissions and Global Warming Potentials in Lca-Modelling of Waste Management Systems. *Waste Management & Research*, 27, 707-715

Cifrian, E., Galan, B., Andres, A. & Viguri, J.R. (2012) Material Flow Indicators and Carbon Footprint for Msw Management Systems: Analysis and Application at Regional Level, Cantabria, Spain. *Resources, Conservation and Recycling*, 68, 54-66

Coelho, H.M.G., Lange, L.C. & Coelho, L.M.G. (2012) Proposal of an Environmental Performance Index to Assess Solid Waste Treatment Technologies. *Waste Management*, 32, 1473-1481

Damgaard, A., Riber, C., Fruergaard, T., Hulgaard, T. & Christensen, T.H. (2010) Life-Cycle-Assessment of the Historical Development of Air Pollution Control and Energy Recovery in Waste Incineration. *Waste Management*, 30, 1244-1250

Davoli, E., Fattore, E., Paiano, V., Colombo, A., Palmiotto, M., Rossi, A.N., Il Grande, M. & Fanelli, R. (2010) Waste Management Health Risk Assessment: A Case Study of a Solid Waste Landfill in South Italy. *Waste Management*, 30, 1608-1613

De Jaeger, S., Eyckmans, J., Rogge, N. & Van Puyenbroeck, T. (2011) Wasteful Waste-Reducing Policies? The Impact of Waste Reduction Policy Instruments on Collection and Processing Costs of Municipal Solid Waste. *Waste Management*, 31, 1429-1440

den Boer, J., den Boer, E. & Jager, J. (2007) Lca-Iwm: A Decision Support Tool for Sustainability Assessment of Waste Management Systems. *Waste Management*, 27, 1032-1045

Döberl, G., Huber, R., Brunner, P.H., Eder, M., Pierrard, R., Schönbäck, W., Frühwirth, W. & Hutterer, H. (2002) Long-Term Assessment of Waste Management Options-a New, Integrated and Goal-Oriented Approach. *Waste management & research*, 20, 311-327

Dollery, B., Byrens, J., Crase, L., Akimove, A., Parsons, C., Robotti, L., Tiley, I. & Wallis, J. (2007) The Application of Performance Measurement in Australian Local Government

Ekmekçioğlu, M., Kaya, T. & Kahraman, C. (2010) Fuzzy Multicriteria Disposal Method and Site Selection for Municipal Solid Waste. *Waste Management*, 30, 1729-1736

El Hanandeh, A. & El-Zein, A. (2010) The Development and Application of Multi-Criteria Decision-Making Tool with Consideration of Uncertainty: The Selection of a Management Strategy for the Bio-Degradable Fraction in the Municipal Solid Waste. *Bioresource technology*, 101, 555-561

Emery, A., Davies, A., Griffiths, A. & Williams, K. (2007) Environmental and Economic Modelling: A Case Study of Municipal Solid Waste Management Scenarios in Wales. *Resources, Conservation and Recycling*, 49, 244-263

Feng, S., Ma, Y. & Jiang, Y. "Economic Cost-Benefit Analysis on Urban Solid Waste Categorized Collection of China." In *Energy and Environment Technology, 2009. ICEET'09. International Conference on*, 3, 279-281: IEEE, 2009.

Finnveden, G., Johansson, J., Lind, P. & Moberg, Å. (2005) Life Cycle Assessment of Energy from Solid Waste—Part 1: General Methodology and Results. *Journal of Cleaner Production*, 13, 213-229

Font Vivanco, D., Puig Ventosa, I. & Gabarrell Durany, X. (2012) Building Waste Management Core Indicators through Spatial Material Flow Analysis: Net Recovery and Transport Intensity Indexes. *Waste Management*, 32, 2496-2510

Forfas. (2010) Waste Management in Ireland Benchmarking Analysis and Policy Priorities: Update 2010.

Franchetti, M. (2013) Economic and Environmental Analysis of Four Different Configurations of Anaerobic Digestion for Food Waste to Energy Conversion Using Lca For: A Food Service Provider Case Study. *Journal of Environmental Management*, 123, 42-48

Fruergaard, T., Hyks, J. & Astrup, T. (2010) Life-Cycle Assessment of Selected Management Options for Air Pollution Control Residues from Waste Incineration. *Science of The Total Environment*, 408, 4672-4680

Geng, Y., Tsuyoshi, F. & Chen, X. (2010) Evaluation of Innovative Municipal Solid Waste Management through Urban Symbiosis: A Case Study of Kawasaki. *Journal of Cleaner Production*, 18, 993-1000

Gentil, E.C., Gallo, D. & Christensen, T.H. (2011) Environmental Evaluation of Municipal Waste Prevention. *Waste Management*, 31, 2371-2379

Giugliano, M., Cernuschi, S., Grosso, M. & Rigamonti, L. (2011) Material and Energy Recovery in Integrated Waste Management Systems. An Evaluation Based on Life Cycle Assessment. *Waste Management*, 31, 2092-2101

Gomes, C.F.S., Nunes, K.R.A., Helena Xavier, L., Cardoso, R. & Valle, R. (2008) Multicriteria Decision Making Applied to Waste Recycling in Brazil. *Omega*, 36, 395-404

Gómez-Delgado, M. & Tarantola, S. (2006) Global Sensitivity Analysis, Gis and Multi-Criteria Evaluation for a Sustainable Planning of a Hazardous Waste Disposal Site in Spain. *International Journal of Geographical Information Science*, 20, 449-466

Government of India. (2009) Position Paper on the Solid Waste Management Sector in India. *Department of Economic Affairs Ministry of Finance*,

Gunamantha, M. & Sarto. (2012) Life Cycle Assessment of Municipal Solid Waste Treatment to Energy Options: Case Study of Kartamantul Region, Yogyakarta. *Renewable Energy*, 41, 277-284

Gurauskienė, I. & Stasiškienė, Ž. (2011) Application of Material Flow Analysis to Estimate the Efficiency of E-Waste Management Systems: The Case of Lithuania. *Waste Management & Research*, 29, 763-777

Haastrup, P., Maniezzo, V., Mattarelli, M., Mazzeo Rinaldi, F., Mendes, I. & Paruccini, M. (1998) A Decision Support System for Urban Waste Management. *European Journal of Operational Research*, 109, 330-341

Hanan, D., Burnley, S. & Cooke, D. (2012) A Multi-Criteria Decision Analysis Assessment of Waste Paper Management Options. *Waste Management*,

Herva, M., Hernando, R., Carrasco, E.F. & Roca, E. (2010) Development of a Methodology to Assess the Footprint of Wastes. *Journal of Hazardous Materials*, 180, 264-273

Herva, M. & Roca, E. (2013) Ranking Municipal Solid Waste Treatment Alternatives Based on Ecological Footprint and Multi-Criteria Analysis. *Ecological Indicators*, 25, 77-84

Hiraki, T. & Akiyama, T. (2009) Exergetic Life Cycle Assessment of New Waste Aluminium Treatment System with Co-Production of Pressurized Hydrogen and Aluminium Hydroxide. *International Journal of Hydrogen Energy*, 34, 153-161

Hogg, D. & Consulting, E.R. (2002) Costs for Municipal Waste Management in the Eu. *Final Report to Directorate General Environment, European Commission*,

Hokkanen, J. & Salminen, P. (1997) Choosing a Solid Waste Management System Using Multicriteria Decision Analysis. *European Journal of Operational Research*, 98, 19-36

Hong, J., Li, X. & Zhaojie, C. (2010) Life Cycle Assessment of Four Municipal Solid Waste Management Scenarios in China. *Waste Management*, 30, 2362-2369

Hong, R.J., Wang, G.F., Guo, R.Z., Cheng, X., Liu, Q., Zhang, P.J. & Qian, G.R. (2006) Life Cycle Assessment of Bmt-Based Integrated Municipal Solid Waste Management: Case Study in Pudong, China. *Resources, Conservation and Recycling*, 49, 129-146

Huang, Y.-T., Pan, T.-C. & Kao, J.-J. (2011) Performance Assessment for Municipal Solid Waste Collection in Taiwan. *Journal of Environmental Management*, 92, 1277-1283

Ichinose, D., Yamamoto, M. & Yoshida, Y. (2013) Productive Efficiency of Public and Private Solid Waste Logistics and Its Implications for Waste Management Policy. *IATSS Research*, 36, 98-105

Iriarte, A., Gabarrell, X. & Rieradevall, J. (2009) Lca of Selective Waste Collection Systems in Dense Urban Areas. *Waste Management*, 29, 903-914

Jamasb, T. & Nepal, R. (2010) Issues and Options in Waste Management: A Social Cost–Benefit Analysis of Waste-to-Energy in the Uk. *Resources, Conservation and Recycling*, 54, 1341-1352

Jamelske, E. & Kipperberg, G. (2006) A Contingent Valuation Study and Benefit-Cost Analysis of the Switch to Automated Collection of Solid Waste with Single Stream Recycling in Madison, Wisconsin. *Public works management & policy*, 11, 89-103

Jeswani, H.K., Smith, R.W. & Azapagic, A. (2013) Energy from Waste: Carbon Footprint of Incineration and Landfill Biogas in the Uk. *The International Journal of Life Cycle Assessment*, 18, 218-229

Kapepula, K.-M., Colson, G., Sabri, K. & Thonart, P. (2007) A Multiple Criteria Analysis for Household Solid Waste Management in the Urban Community of Dakar. *Waste management*, 27, 1690-1705

Karmperis, A.C., Sotirchos, A., Aravossis, K. & Tatsiopoulos, I.P. (2012) Waste Management Project's Alternatives: A Risk-Based Multi-Criteria Assessment (Rbmca) Approach. *Waste management*, 32, 194-212

Kaufman, S.M., Krishnan, N. & Themelis, N.J. (2010) A Screening Life Cycle Metric to Benchmark the Environmental Sustainability of Waste Management Systems. *Environmental Science & Technology*, 44, 5949-5955

Khoo, H.H. (2009) Life Cycle Impact Assessment of Various Waste Conversion Technologies. *Waste Management*, 29, 1892-1900

Kim, M.-H. & Kim, J.-W. (2010) Comparison through a Lca Evaluation Analysis of Food Waste Disposal Options from the Perspective of Global Warming and Resource Recovery. *Science of The Total Environment*, 408, 3998-4006

Klang, A., Vikman, P.-Å. & Brattebø, H. (2003) Sustainable Management of Demolition Waste—an Integrated Model for the Evaluation of Environmental, Economic and Social Aspects. *Resources, Conservation and Recycling*, 38, 317-334

Komly, C.-E., Azzaro-Pantel, C., Hubert, A., Pibouleau, L. & Archambault, V. (2012) Multiobjective Waste Management Optimization Strategy Coupling Life Cycle Assessment and Genetic Algorithms: Application to Pet Bottles. *Resources, Conservation and Recycling*, 69, 66-81

Kondo, Y. & Nakamura, S. (2004) Evaluating Alternative Life-Cycle Strategies for Electrical Appliances by the Waste Input-Output Model. *The International Journal of Life Cycle Assessment*, 9, 236-246

Kong, D., Shan, J., Iacoboni, M. & Maguin, S.R. (2012) Evaluating Greenhouse Gas Impacts of Organic Waste Management Options Using Life Cycle Assessment. *Waste Management & Research*, 30, 800-812

Koroneos, C.J. & Nanaki, E.A. (2012) Integrated Solid Waste Management and Energy Production - a Life Cycle Assessment Approach: The Case Study of the City of Thessaloniki. *Journal of Cleaner Production*, 27, 141-150

Kumar, S., Gawaikar, V., Gaikwad, S. & Mukherjee, S. (2004) Cost–Benefit Analysis of Landfill System with Gas Recovery for Municipal Solid Waste Management: A Case Study. *International journal of environmental studies*, 61, 637-650

Lavee, D. (2007) Is Municipal Solid Waste Recycling Economically Efficient? *Environmental Management*, 40, 926-943

Lavee, D. & Khatib, M. (2010) Benchmarking in Municipal Solid Waste Recycling. *Waste Management*, 30, 2204-2208

Lei, K. & Wang, Z. (2008) Municipal Wastes and Their Solar Transformities: An Emergy Synthesis for Macao. *Waste Management*, 28, 2522-2531

Liang, S., Zhang, T. & Xu, Y. (2012) Comparisons of Four Categories of Waste Recycling in China's Paper Industry Based on Physical Input–Output Life-Cycle Assessment Model. *Waste Management*, 32, 603-612

Lundie, S. & Peters, G.M. (2005) Life Cycle Assessment of Food Waste Management Options. *Journal of Cleaner Production*, 13, 275-286

Manfredi, S. & Christensen, T.H. (2009) Environmental Assessment of Solid Waste Landfilling Technologies by Means of Lca-Modeling. *Waste Management*, 29, 32-43

Manfredi, S., Christensen, T.H., Scharff, H. & Jacobs, J. (2010) Environmental Assessment of Low-Organic Waste Landfill Scenarios by Means of Life-Cycle Assessment Modelling (Easewaste). *Waste Management & Research*, 28, 130-140

Manfredi, S., Tonini, D. & Christensen, T.H. (2011) Environmental Assessment of Different Management Options for Individual Waste Fractions by Means of Life-Cycle Assessment Modelling. *Resources, Conservation and Recycling*, 55, 995-1004

Marques, R.C. & Simões, P. (2009) Incentive Regulation and Performance Measurement of the Portuguese Solid Waste Management Services. *Waste Management & Research*, 27, 188-196

Massarutto, A., Carli, A.d. & Graffi, M. (2011) Material and Energy Recovery in Integrated Waste Management Systems: A Life-Cycle Costing Approach. *Waste Management*, 31, 2102-2111

Mastellone, M.L., Brunner, P.H. & Arena, U. (2009) Scenarios of Waste Management for a Waste Emergency Area. *Journal of Industrial Ecology*, 13, 735-757

Mendes, M.R., Aramaki, T. & Hanaki, K. (2003) Assessment of the Environmental Impact of Management Measures for the Biodegradable Fraction of Municipal Solid Waste in São Paulo City. *Waste Management*, 23, 403-409

Menikpura, S., Gheewala, S.H. & Bonnet, S. (2012) Framework for Life Cycle Sustainability Assessment of Municipal Solid Waste Management Systems with an Application to a Case Study in Thailand. *Waste Management & Research*, 30, 708-719

Merrild, H., Damgaard, A. & Christensen, T.H. (2008) Life Cycle Assessment of Waste Paper Management: The Importance of Technology Data and System Boundaries in Assessing Recycling and Incineration. *Resources, Conservation and Recycling*, 52, 1391-1398

Miliūte, J. & Staniškis, J.K. (2010) Application of Life-Cycle Assessment in Optimisation of Municipal Waste Management Systems: The Case of Lithuania. *Waste management & Research*, 28, 298-308

Moberg, Å., Finnveden, G., Johansson, J. & Lind, P. (2005) Life Cycle Assessment of Energy from Solid Waste—Part 2: Landfilling Compared to Other Treatment Methods. *Journal of Cleaner Production*, 13, 231-240

Moutavtchi, V., Stenis, J., Hogland, W. & Shepeleva, A. (2010) Solid Waste Management by Application of the Wamed Model. *Journal of Material Cycles and Waste Management*, 12, 169-183

Moutavtchi, V., Stenis, J., Hogland, W., Shepeleva, A. & Andersson, H. (2008) Application of the Wamed Model to Landfilling. *Journal of Material Cycles and Waste Management*, 10, 62-70

Ning, S.-K., Chang, N.-B. & Hung, M.-C. Comparative Streamlined Life Cycle Assessment for Two Types of Municipal Solid Waste Incinerator. *Journal of Cleaner Production*,

Niskanen, A., Manfredi, S., Christensen, T.H. & Anderson, R. (2009) Environmental Assessment of Ämmässuo Landfill (Finland) by Means of Lca-Modelling (Easewaste). *Waste management & Research*, 27, 542-550

Nouwen, J., Cornelis, C., De Fré, R., Wevers, M., Viaene, P., Mensink, C., Patyn, J., Verschaeve, L., Hooghe, R., Maes, A., Collier, M., Schoeters, G., Van Cleuvenbergen, R. & Geuzens, P. (2001) Health Risk Assessment of Dioxin Emissions from Municipal Waste Incinerators: The Neerlandquarter (Wilrijk, Belgium). *Chemosphere*, 43, 909-923

Parthan, S.R., Milke, M.W., Wilson, D.C. & Cocks, J.H. (2012) Cost Function Analysis for Solid Waste Management: A Developing Country Experience. *Waste Management & Research*, 30, 485-491

Pires, A., Chang, N.-B. & Martinho, G. (2011) Reliability-Based Life Cycle Assessment for Future Solid Waste Management Alternatives in Portugal. *The International Journal of Life Cycle Assessment*, 16, 316-337

Qu, L., Zhang, T. & Liang, S. (2013) Waste Management of Urban Agglomeration on a Life Cycle Basis. *Resources, Conservation and Recycling*, 78, 47-53

Quina, M.J., Bordado, J.C.M. & Quinta-Ferreira, R.M. (2011) Environmental Impact of Apc Residues from Municipal Solid Waste Incineration: Reuse Assessment Based on Soil and Surface Water Protection Criteria. *Waste Management*, 31, 1984-1991

Rapti-Caputo, D., Sdao, F. & Masi, S. (2006) Pollution Risk Assessment Based on Hydrogeological Data and Management of Solid Waste Landfills. *Engineering Geology*, 85, 122-131

Rechberger, H. & Brunner, P.H. (2002) A New, Entropy Based Method to Support Waste and Resource Management Decisions. *Environmental science & technology*, 36, 809-816

Riber, C., Bhander, G.S. & Christensen, T.H. (2008) Environmental Assessment of Waste Incineration in a Life-Cycle-Perspective (Easewaste). *Waste Management & Research*, 26, 96-103

Rigamonti, L., Grosso, M. & Sunseri, M.C. (2009) Influence of Assumptions About Selection and Recycling Efficiencies on the Lca of Integrated Waste Management Systems. *The International Journal of Life Cycle Assessment*, 14, 411-419

Rives, J., Rieradevall, J. & Gabarrell, X. (2010) Lca Comparison of Container Systems in Municipal Solid Waste Management. *Waste Management*, 30, 949-957

Rogge, N. & De Jaeger, S. (2012) Evaluating the Efficiency of Municipalities in Collecting and Processing Municipal Solid Waste: A Shared Input Dea-Model. *Waste Management*, 32, 1968-1978

Rogge, N. & De Jaeger, S. (2013) Measuring and Explaining the Cost Efficiency of Municipal Solid Waste Collection and Processing Services. *Omega*, 41, 653-664

Roussat, N., Dujet, C. & Méhu, J. (2009) Choosing a Sustainable Demolition Waste Management Strategy Using Multicriteria Decision Analysis. *Waste Management*, 29, 12-20

Saer, A., Lansing, S., Davitt, N.H. & Graves, R.E. Life Cycle Assessment of a Food Waste Composting System: Environmental Impact Hotspots. *Journal of Cleaner Production*,

Salhofer, S., Wassermann, G. & Binner, E. (2007) Strategic Environmental Assessment as an Approach to Assess Waste Management Systems. Experiences from an Austrian Case Study. *Environmental Modelling & Software*, 22, 610-618

Sanchez, I. "Efficiency of Solid Waste Collection in Spain." In *III International Conference on waste management and the environment. Wit press*, 593-601, 2006.

Schmidt, J.H., Holm, P., Merrild, A. & Christensen, P. (2007) Life Cycle Assessment of the Waste Hierarchy – a Danish Case Study on Waste Paper. *Waste Management*, 27, 1519-1530

Schuhmacher, M., Meneses, M., Xifró, A. & Domingo, J.L. (2001) The Use of Monte-Carlo Simulation Techniques for Risk Assessment: Study of a Municipal Waste Incinerator. *Chemosphere*, 43, 787-799

Schütz, N., Thörner, T., Reh, K., Stenzel, F., Franke, M. & Faulstich, M. (2013) Neue Herausforderungen Für Die Kommunale Abfallwirtschaft. *Müll und Abfall*, 08, 420-426

Sciubba, E. (2003) Extended Exergy Accounting Applied to Energy Recovery from Waste: The Concept of Total Recycling. *Energy*, 28, 1315-1334

Simões, P., De Witte, K. & Marques, R.C. (2010) Regulatory Structures and Operational Environment in the Portuguese Waste Sector. *Waste Management*, 30, 1130-1137

Slagstad, H. & Brattebø, H. (2012) Lca for Household Waste Management When Planning a New Urban Settlement. *Waste Management*, 32, 1482-1490

Song, Q., Wang, Z. & Li, J. (2013) Sustainability Evaluation of E-Waste Treatment Based on Emergy Analysis and the Lca Method: A Case Study of a Trial Project in Macau. *Ecological Indicators*, 30, 138-147

Song, Q., Wang, Z., Li, J. & Duan, H. (2012) Sustainability Evaluation of an E-Waste Treatment Enterprise Based on Emergy Analysis in China. *Ecological Engineering*, 42, 223-231

Su, J.-P., Hung, M.-L., Chao, C.-W. & Ma, H.-w. (2010) Applying Multi-Criteria Decision-Making to Improve the Waste Reduction Policy in Taiwan. *Waste Management & Research*, 28, 20-28

Tabata, T., Hishinuma, T., Ihara, T. & Genchi, Y. (2011) Life Cycle Assessment of Integrated Municipal Solid Waste Management Systems, Taking Account of Climate Change and Landfill Shortage Trade-Off Problems. *Waste Management & Research*, 29, 423-432

Taha, M.P.M., Drew, G.H., Longhurst, P.J., Smith, R. & Pollard, S.J.T. (2006) Bioaerosol Releases from Compost Facilities: Evaluating Passive and Active Source Terms at a Green Waste Facility for Improved Risk Assessments. *Atmospheric Environment*, 40, 1159-1169

Tanskanen, J.-H. (2000) Strategic Planning of Municipal Solid Waste Management. *Resources, Conservation and Recycling*, 30, 111-133

Tin, A.M., Wise, D.L., Su, W.-H., Reutergardh, L. & Lee, S.-K. (1995) Cost—Benefit Analysis of the Municipal Solid Waste Collection System in Yangon, Myanmar. *Resources, Conservation and Recycling*, 14, 103-131

Tonini, D. & Astrup, T. (2012) Life-Cycle Assessment of a Waste Refinery Process for Enzymatic Treatment of Municipal Solid Waste. *Waste Management*, 32, 165-176

Tulokhonova, A. & Ulanova, O. (2013) Assessment of Municipal Solid Waste Management Scenarios in Irkutsk (Russia) Using a Life Cycle Assessmentintegrated Waste Management Model. *Waste Management & Research*,

Tunesi, S. (2011) Lca of Local Strategies for Energy Recovery from Waste in England, Applied to a Large Municipal Flow. *Waste Management*, 31, 561-571

Turconi, R., Butera, S., Boldrin, A., Grosso, M., Rigamonti, L. & Astrup, T. (2011) Life Cycle Assessment of Waste Incineration in Denmark and Italy Using Two Lca Models. *Waste Management & Research*, 29, S78-S90

Ulukan, H.Z. & Kop, Y. "Multi-Criteria Decision Making (Mcdm) of Solid Waste Collection Methods Using Life Cycle Assessment (Lca) Outputs." In *Computers & Industrial Engineering, 2009. CIE 2009. International Conference on*, 584-589: IEEE, 2009.

Vaillancourt, K. & Waaub, J.-P. (2002) Environmental Site Evaluation of Waste Management Facilities Embedded into Eugène Model: A Multicriteria Approach. *European Journal of Operational Research*, 139, 436-448

Varžinskas, V., Staniškis, J.K. & Knašytė, M. (2012) Decision-Making Support System Based on Lca for Aseptic Packaging Recycling. *Waste Management & Research*, 30, 931-939

Wang, J.B., Wang, M.-S., Wu, E.M.-Y., Chang-Chien, G.-P. & Lai, Y.-C. (2008) Approaches Adopted to Assess Environmental Impacts of Pcdd/F Emissions from a Municipal Solid Waste Incinerator. *Journal of Hazardous Materials*, 152, 968-975

Wang, L., Templer, R. & Murphy, R.J. (2012a) A Life Cycle Assessment (Lca) Comparison of Three Management Options for Waste Papers: Bioethanol Production, Recycling and Incineration with Energy Recovery. *Bioresource Technology*, 120, 89-98

Wang, X., Miller, G., Ding, G., Lou, X., Cai, D., Chen, Z., Meng, J., Tang, J., Chu, C., Mo, Z. & Han, J. (2012b) Health Risk Assessment of Lead for Children in Tinfoil Manufacturing and E-Waste Recycling Areas of Zhejiang Province, China. *Science of The Total Environment*, 426, 106-112

Wang, Y., Luo, C.-L., Li, J., Yin, H., Li, X.-D. & Zhang, G. (2011) Characterization and Risk Assessment of Polychlorinated Biphenyls in Soils and Vegetations near an Electronic Waste Recycling Site, South China. *Chemosphere*, 85, 344-350

Wang, Y., Tian, Z., Zhu, H., Cheng, Z., Kang, M., Luo, C., Li, J. & Zhang, G. (2012c) Polycyclic Aromatic Hydrocarbons (Pahs) in Soils and Vegetation near an E-Waste Recycling Site in South China: Concentration, Distribution, Source, and Risk Assessment. *Science of The Total Environment*, 439, 187-193

Weng, Y.-C. & Fujiwara, T. (2011) Examining the Effectiveness of Municipal Solid Waste Management Systems: An Integrated Cost–Benefit Analysis Perspective with a Financial Cost Modeling in Taiwan. *Waste Management*, 31, 1393-1406

Wilson, D.C., Rodic, L., Scheinberg, A., Velis, C.A. & Alabaster, G. (2012) Comparative Analysis of Solid Waste Management in 20 Cities. *Waste Management & Research*, 30, 237-254

Wittmaier, M., Langer, S. & Sawilla, B. (2009) Possibilities and Limitations of Life Cycle Assessment (Lca) in the Development of Waste Utilization Systems – Applied Examples for a Region in Northern Germany. *Waste Management*, 29, 1732-1738

Xi, B., Su, J., Huang, G., Qin, X., Jiang, Y., Huo, S., Ji, D. & Yao, B. (2010) An Integrated Optimization Approach and Multi-Criteria Decision Analysis for Supporting the Waste-Management System of the City of Beijing, China. *Engineering Applications of Artificial Intelligence*, 23, 620-631

Xing, W., Lu, W., Zhao, Y., Zhang, X., Deng, W. & Christensen, T.H. (2013) Environmental Impact Assessment of Leachate Recirculation in Landfill of Municipal Solid Waste by Comparing with Evaporation and Discharge (Easewaste). *Waste Management*, 33, 382-389

Yeh, C.-H. & Xu, Y. (2013) Sustainable Planning of E-Waste Recycling Activities Using Fuzzy Multicriteria Decision Making. *Journal of Cleaner Production*,

Yuan, F., Shen, L.-y. & Li, Q.-m. (2011a) Emergy Analysis of the Recycling Options for Construction and Demolition Waste. *Waste Management*, 31, 2503-2511

Yuan, H.P., Shen, L.Y., Hao, J.J.L. & Lu, W.S. (2011b) A Model for Cost–Benefit Analysis of Construction and Demolition Waste Management Throughout the Waste Chain. *Resources, Conservation and Recycling*, 55, 604-612

Zemba, S.G., Green, L.C., Crouch, E.A.C. & Lester, R.R. (1996) Quantitative Risk Assessment of Stack Emissions from Municipal Waste Combustors. *Journal of Hazardous Materials*, 47, 229-275

Zhao, W., der Voet, E.v., Zhang, Y. & Huppes, G. (2009a) Life Cycle Assessment of Municipal Solid Waste Management with Regard to Greenhouse Gas Emissions: Case Study of Tianjin, China. *Science of The Total Environment*, 407, 1517-1526

Zhao, W., Huppes, G. & van der Voet, E. (2011a) Eco-Efficiency for Greenhouse Gas Emissions Mitigation of Municipal Solid Waste Management: A Case Study of Tianjin, China. *Waste Management*, 31, 1407-1415

Zhao, Y., Christensen, T.H., Lu, W., Wu, H. & Wang, H. (2011b) Environmental Impact Assessment of Solid Waste Management in Beijing City, China. *Waste Management*, 31, 793-799

Zhao, Y., Wang, H.-T., Lu, W.-J., Damgaard, A. & Christensen, T.H. (2009b) Life-Cycle Assessment of the Municipal Solid Waste Management System in Hangzhou, China (Easewaste). *Waste Management & Research*, 27, 399-406

Zhao, Y., Xing, W., Lu, W., Zhang, X. & Christensen, T.H. (2012) Environmental Impact Assessment of the Incineration of Municipal Solid Waste with Auxiliary Coal in China. *Waste Management*, 32, 1989-1998

ARTICLE II:

MATERIAL FLOW ANALYSIS AS A DECISION SUPPORT TOOL FOR WASTE MANAGEMENT: A LITERATURE REVIEW

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Journal of Industrial Ecology 2015, 19, (5), pp 753-764
DOI: 10.1111/jiec.12354

Material Flow Analysis as a Decision Support Tool for Waste Management

A Literature Review

Astrid Allesch and Paul H. Brunner

Keywords:
environmental decision making
mass balance
material flow analysis (MFA)
resource flows
substance flow analysis (SFA)
waste management

Supporting information is available on the *JIE* Web site

Summary

This article reviews, categorizes, and evaluates the objectives, means, and results of the application of material flow analysis (MFA) in waste management. It identifies those areas where MFA methodologies are most successful in supporting waste management decisions. The focus of this review is on the distinction between MFA on the level of goods and on the level of substances. Based on 83 reviewed studies, potentials, strengths, and weaknesses are investigated for the two levels of MFA when applied for analysis, evaluation, and improvement of waste management systems. The differences are discussed in view of effectiveness, applicability, and data availability. The results show that MFA on the level of goods are instrumental for understanding how waste management systems function, facilitating the connections of stakeholders, authorities, and waste management companies. The substance level is essential to assess qualitative aspects regarding resources and environment. Knowledge about the transformation, transport, and storage of valuable and hazardous substances forms the base for identifying both resource potentials and risks for human health and the environment. The results of this review encourage the application of MFA on both levels of goods and substances for decision making in waste management. Because of the mass balance principle, this combination has proven to be a powerful tool for comprehensively assessing if a chosen system reaches designated waste management goals.

Introduction

Material flow analysis (MFA) is a tool to analyze the transformation, transportation, or storage of materials within a defined system (Brunner and Rechberger 2004). It has been applied in various fields, such as medicine (Santorio 1737), social systems (Fischer-Kowalski 1998), and urban metabolism (Baccini and Brunner 1991). MFA is increasingly applied in industrial ecology, and has become a fast developing field of research with mounting policy relevance (Bringezu and Moriguchi 2002). The growing use of MFA can be attributed to resource-, environmental-, economic-, and health-related demands. Among others, it serves to fulfill higher recycling rates and reduce losses of potential secondary raw materials as demanded by the European Commission (EC 2014). Ecological consequences on a regional (e.g., eutrophication) or global scale (e.g., greenhouse gas emission) are minimized with the implementation of national laws or international agreements. The use of chemical substances is controlled by REACH Regulation (EC 2006) to protect human health and the environment. Sociopolitical and legal actions are common; to ensure their success and effectiveness, it is necessary to understand the properties of the systems at stake.

MFA provides a comprehensive and systematic account of a defined physical system to support decision makers. Owing to the different conceptual backgrounds, a diversity of

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DOI: 10.1111/jiec.12354

Editor managing review: Ester van der Voet

Volume 19, Number 5

MFA concepts has been developed (Bringezu and Moriguchi 2002). The approaches differ in terms of (1) scale of the system evaluated (e.g., whole economy, specific parts of the economy, regions, industrial plants, and private households), (2) materials investigated (goods and/or substances), and (3) databases used (e.g., material flows derived from national or international econometric statistics, physical substance flows measured by specific sampling, and analysis campaigns). Regarding methodologies, the main principle of all MFA approaches is the mass balance: The sum of all inputs into a system has to be equal to all outputs plus changes in stocks.

An MFA investigation requires a system defined by system boundaries in time and space and material flows linking processes (Brunner and Rechberger 2004). A process is defined as transformation, transport, or storage of one or more materials. Flows are the ratio of mass per time (e.g., tonnes per year), and are sometimes given as mass per time and cross-section (e.g., tonnes per capita and year). The term material serves as an umbrella term for both substances and goods.

Within the field of MFA, a subdivision into investigations of goods and substances can be discerned (Brunner and Rechberger 2004).

- MFA on the level of goods is the analysis of flows and stocks of goods. Goods are economic entities with a positive or negative economic value for example computers, waste of electrical and electronic equipment (WEEE), municipal solid waste (MSW), and cement. All flows of goods within a system are investigated.
- MFA on the level of substances provides an analysis of flows and stocks of substances. Substances are materials composed of uniform units, such as chemical elements (composed of identical atoms, e.g., silver and phosphorous [P]) or compounds (composed of identical molecules, e.g., water and benzene). All substance flows within a system are investigated, often together with the corresponding goods; this type of MFA is sometimes referred to as substance flow analysis.
- MFA on the level of goods and substances regards the flows and stocks of goods and substances. Selected substances and related goods are investigated.

The goal of this study is to look into the application of MFA for analysis and evaluation of waste management (WM). The potentials of MFA on the level of goods and substances are individually assessed, and the differences are discussed in view of effectiveness, applicability, and data availability. In addition, this study aims at providing a base for goal-oriented decision making in WM. With respect to the precautionary principle and sustainability issues, the following goals are generally accepted for WM and have been incorporated into legislation in several countries: (1) protection of humans and the environment; (2) conservation of resources; and (3) aftercare-free waste management, resulting in no burdens for future generations. These general goals are often specified in more detail. The so-called waste hierarchy of prevention, prepare for reuse, recycle, recover other value (e.g., energy), and disposal, has been developed as a means to reach those goals. Based on the assumption that it is essential to know flows and stocks of goods and substances through a WM system in order evaluate its performance, the reviewed studies are characterized by: (1) materials investigated (goods and/or substances); (2) goal within the study; (3) scale of system evaluated; (4) processes and flows observed; and (5) origin of data and data uncertainties.

Materials and Methods

This study is based on an extended literature research comprising articles in journals until November 2014. The following databases have been scanned: Science Direct, Wiley Online Library, and SAGE Publications. Additionally, Google Scholar has been used to retrieve more information. The keywords used for the literature search included "material flow analysis" and "waste management." After a prereview of the collected articles, 83 studies have been reviewed in detail. In all of them, goals, methodologies, means, and results of MFA applications have been categorized in general as well as concerning WM (see supporting information SI on the Journal's website).

In contrast to other studies, this review considers only MFA studies with a clear focus on WM. MFA is well suited to provide fundamental knowledge about material stocks; together with periodic analysis and life span estimations, this information serves to assess future off-flows from stocks, such as future waste generation or change in waste composition. However, due to the focus of this review, the aspect of how resource management can inform waste management has not been taken into account. There are other excellent reviews of MFA applications, such as Chen and Graedel (2012a) concentrating on anthropogenic flows and cycles of elements, or Binder (2007) discussing the coupling of MFA with social science modeling approaches.

MFA terms and definitions are used according to the *Practical Handbook of Material Flow Analysis* (Brunner and Rechberger (2004).

Results and Discussion

Goods and Substances Investigated

Among the 83 reviewed studies, approximately 25% focused on the level of goods, 50% on the substance level, and 25% started with goods and further proceeded to substances. Table 1 gives an overview of the studies examined and lists the investigated goods and substances. On the substances level, either inorganic substances (metals or nonmetals), organic substances (by carbon [C]), compounds (e.g., polyvinylchloride [PVC]), or mixture of substances were evaluated.

Most studies on the goods level focus on municipal solid and electronic waste. Further, the flows of biological, construction and demolition, and industrial and plastic waste are evaluated. Twenty of the reviewed studies provide an MFA on goods and substances for the same system; on the level of goods, primarily MSW and plastic waste, and on the level of substances, metals

Table 1 Applied MFA in the reviewed studies (n = 83) on the level of goods and/or substances

MFA	*Goods*	*Substances*	*#*	*References*
Good level	Bio-, garden-, food-, wood waste	—	4	(Bergeron 2014; Betz et al. 2015; Lang et al. 2006a; Lang et al. 2006b)
	C&D wastes		1	(Nasrullah et al. 2014a)
	C&I waste		1	(Nasrullah et al. 2014b)
	MSW, residual waste		5	(Al Sabbagh et al. 2012; Binder and Mosler 2007; Döberl et al. 2002; Masood et al. 2014; Stanic-Maruna and Fellner 2012)
	plastic waste, tires, PVC		3	(Bogucka et al. 2008; Jacob et al. 2014; Kleijn et al. 2000)
	General		1	(Eckelman and Chertow 2009)
	WEEE, computer, TV sets		5	(Gurauskienė and Stasiškienė 2011; Kahhat and Williams 2012; Liu et al. 2006; Steubing et al. 2010; Streicher-Porte et al. 2005)
Good and substance level	Bio-, garden-, food-, wood waste	Mixture	2	(Andersen et al. 2011, 2012)
	Bottom ash	Metals	1	(Allegrini et al. 2014)
	C&D wastes	Mixture	2	(Brunner and Stämpfli 1993; Schachermayer et al. 2000)
	General	Mixture	1	(Brunner and Baccini 1992)
	MSW, residual waste	Metals	1	(Morf et al. 2000)
		Mixture	6	(Arena and Di Gregorio 2013; Brunner and Mönch 1986; Mastellone et al. 2009; Rotter et al. 2004; Stanisavljevic and Brunner 2014; Tonini et al. 2014)
		Organic	1	(Arena and Di Gregorio 2014a)
	Plastic waste, tires, PVC	Mixture	2	(Arena and Di Gregorio 2014b; Mastellone et al. 2012)
		Organic	2	(Arena et al. 2011; Di Gregorio and Zaccariello 2012)
	WEEE, computer, TV sets	Metals	1	(Chancerel et al. 2009)
Substance level	Main focus on substance level; (though usually based on good flows)	Compounds	3	(Eriksson et al. 2008; Nakamura et al. 2009; Vyzinkarova and Brunner 2013)
		Metals	28	(Asari et al. 2008; Asari and Sakai 2013; Cain et al. 2007; Chen et al. 2013; Chen and Graedel 2012b; Guo et al. 2010; Huang et al. 2014; Kral et al. 2014; Krook et al. 2007; Kuo et al. 2007; Lanzano et al. 2006; Long et al. 2013; Månsson et al. 2009; Morf et al. 2013; Oguchi et al. 2013; Oguchi et al. 2012; Rechberger and Graedel 2002; Saurat and Bringezu 2008; Spatari et al. 2002; Spatari et al. 2003; Spatari et al. 2005; Tanimoto et al. 2010; Vexler et al. 2004; Zhang et al. 2008; Themelis and Gregory 2001; Nakajima et al. 2008; Modaresi and Müller 2012; Graedel et al. 2011)
		Mixture	1	(Morf et al. 2007)
		Nonmetals	12	(Bi et al. 2013; Chen et al. 2015; Cooper and Carliell-Marquet 2013; Fan et al. 2009; Li et al. 2010; Ma et al. 2012, 2013; Ott and Rechberger 2012; Schmid Neset et al. 2008; Senthilkumar et al. 2014; Senthilkumar et al. 2012; Yuan et al. 2011)

Note: # = number of studies; WEEE = waste of electrical and electronic equipment; C&D = construction and demolition; C&I = commercial and industrial; MSW = municipal solid waste; PVC = polyvinylchloride; TV = television.

Table 2 Goals of the reviewed studies (n = 83)

Goal	*Level of goods*	*Level of goods and substances*	*Level of substances*	*Total*	*%*
Performance evaluation	8	9	22	39	47
System analysis	1	0	10	11	13
Comparison of WM systems	3	5	7	15	18
Early recognition	4	1	3	8	10
Scenario analysis	4	4	2	10	12
Total	**20**	**19**	**44**	**83**	**100**

Note: WM = waste management.

and C are analyzed. MFA on the substance level focus on metals (n = 28) and nonmetals (n = 12), mixtures (n = 1), and compounds (n = 3). Primarily investigated substances are P and copper (Cu), followed by zinc and mercury. Three studies aim at organic compounds (polybrominated diphenyl ether, Parabens, or PVC).

Goals of the Studies

MFA is carried out on multiple levels. The goals are manifold and range from Chinese P metabolism of the prehuman period (Fan et al. 2009) to the evaluation of air gasification behavior of mixed plastic wastes (Al Sabbagh et al. 2012).

Every reviewed study has its own individual goals. Some of the goals are:

- Performance evaluation: To assess and evaluate the performance of a current waste management system to obtain information about the distribution of materials (focus on related impacts and whether a system reaches set goals)
- System analysis: To describe a WM system for further assessments (focus on quantifying flows and stocks)
- Comparison of WM systems: To compare different management systems or technologies
- Early recognition: To early recognize beneficial or harmful changes of flows and stocks, for example, future accumulations or depletions of substances within a system
- Scenario analysis: To evaluate and optimize WM systems

In table 2, different goals in relation to the MFA methodology on the level of goods and/or substances are summarized.

In WM, MFA is most often used for performance evaluation of current systems (47%). Approximately 20% of all studies are aiming at the comparison of WM or treatment systems, for example, to compare different waste treatment plants. The goal of 13% of the studies is system analysis; either for qualitative assessments through interpretation or to serve as inventory for further evaluations such as life cycle assessment (LCA). The other studies apply MFA for predictions or scenario analyses. Indicators are used to assess the efficiency (e.g., resource, energy, or collection efficiency) or evaluate emissions (gaseous to atmosphere, or liquid to groundwater and surface water). Scenario analyses are carried out in ten studies, primarily to optimize different MSW management systems. To early recognize the need for future changes in WM strategy or treatment system, eight studies focus on the future generation of waste or on future material flows.

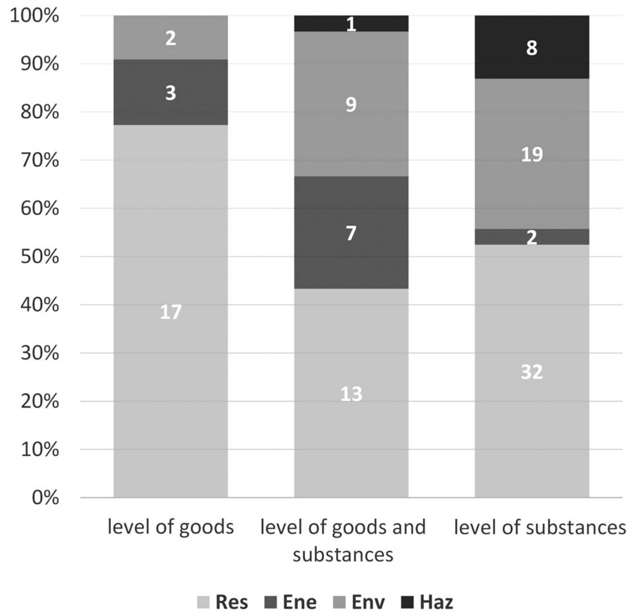

Figure 1 Comparison of the aspects considered in the various MFAs in relation to the investigated materials (n = 83). MFA = material flow analysis; Res = resource potential; Ene = energetic performance; Env = environmental consequences; Haz = release of potential hazardous substances.

MFA creates an inventory of flows, stocks, and treatment processes and hence provides knowledge and understanding about a WM system. However, an MFA alone cannot actually assess a system in view of certain goals, such as resource conservation, or protection of human health. For such purposes, the MFA has to be combined with further assessment methods such as risk assessment or exergy/entropy considerations. The reviewed studies focus on the following aspects with regard to evaluation of MFA results:

- The resource potential is quantified to identify sources and pathways of valuable materials. Recycling potentials, reuse options, and reduction of landfill volumes are often investigated.
- The environmental consequences are investigated by quantifying emissions to the hydrosphere, atmosphere, and pedosphere. Often, effects such as eutrophication and climate change are included.
- The release of potentially hazardous substances to the environment or the incorporation of such substances in products are evaluated to take into account risks for the environment and human health.

- The energy performance of WM and treatment is assessed to reduce energy consumption or to improve energy efficiency by new or advanced technologies.

Figure 1 shows the number of applications of MFA on the level of goods or substances in relation to the considered aspects. Some studies consider more than one aspect.

Approximately 75% of the reviewed studies apply MFA to assess resource potential. The goal is to analyze the dependence of a regional economy on imported goods and substances and explore recovery potentials. MFA on the level of goods (n = 17) is primarily used to provide an overview of the connections of stakeholders, authorities, and WM companies and identify losses and accumulations of resources. Looking at both goods and substances, 13 MFAs are aiming at identifying resource potential by quantifying mass flow rates of wastes and their main constituents (chemical elements). In 32 of the reviewed studies, MFA on the substance level is carried out to identify sources, pathways, and sinks of single elements (e.g., P and Cu); particularly, analyses of whole economies are focusing on the evaluation of resource potential. Environmental aspects are in the focus of one third of the reviewed studies. Especially, studies on the substance level quantify environmental consequences of emissions to soil, air, and water (n = 19). Potential hazardous substance emissions are investigated on the substance level (n = 8), with the goal to construct a picture of sources and pathways, estimate possible impacts, and identify necessary actions for policy makers. On the level of goods, the hazardous aspect was not—and cannot be—considered. Twelve studies focus on the energetic performance either to evaluate energy generation of individual plants (e.g., by comparing different input materials) or assess energy efficiency of WM systems. Six studies provide an energy flow diagram based on the applied MFA. One third of the reviewed studies have investigated two or more aspects (resource potential, energetic performance, environmental consequences, or release of potential hazardous substances). Most often, resource potentials and environmental consequences are considered. Most studies applying MFA on the level of goods focus on a single aspect. In contrast, one third of the reviewed studies providing MFA on the substance level and half of the reviewed studies focusing on goods and substances have considered two or more aspects.

Systems and System Boundaries of Studies Investigated

The definition of the temporal, spatial, and/or thematic system boundaries is crucial. Commonly, one year is chosen as the temporal boundary. Spatially, the system is defined by geographical, hydrological, or administrative boundaries. If investigating an economic sector or a company, the system boundaries are often defined thematically (e.g., municipal WM or treatment plant). In the reviewed studies, the thematic system boundaries can be categorized into four areas:

i. WM as an integral part of the national economy; WM is just one fragment (whole economy—waste management embedded)
ii. WM systems considering MSW (MSW management)
iii. WM systems considering a specific waste fraction other than MSW (waste fraction management)
iv. Waste treatment plants (waste treatment plant).

Table 3 Application of MFA in relation to the thematic and geographical system boundary in the reviewed studies (n = 83)

Thematic boundary	*Geo. boundary*	*Level of goods*	*Level of goods and substances*	*Level of substances*	*Total*
Whole economy—waste management embedded	City			6	6
	Region	1		3	4
	Country	4	1	16	21
	EU			6	6
	Continent			2	2
	Global			1	1
MSW management	City	2	1	1	4
	Region		2		2
	Country	3			3
	—		1		1
Waste fraction management	City	4		1	5
	Country	4			4
	Global			1	1
Waste treatment plant	—	2	14	7	23
Total		**20**	**19**	**44**	**83**

Note: MSW = municipal solid waste; EU = European Union.

The thematic system boundaries (i to iii) can be further categorized geographically, such as global, continents, countries, regions, or cities. Approximately 40 studies focus on material flows of a whole economy. Twenty studies investigate WM systems (ten MSW, ten waste fraction), and 23 studies apply MFA for waste treatment plants (see table 3).

The level of goods is often investigated in order to depict the structure of a sector. In the case of WM, the goal is for example to optimize recycling processes or transport routes. The analysis of a system on the level of goods and substances serves primarily as a characterization of the elemental composition of inputs into a treatment plant, as well as their transfer to outputs. MFA on the substance level is commonly applied to quantify the overall flows of that substance through a large section of the economy—including waste management—with the goal to identify and link sources, pathways, and sinks.

In many of the reviewed studies, system boundaries are not explicitly defined, and hence it is unclear where the investigated system begins and ends. In approximately one quarter of the studies, the environmental components, such as hydrosphere, lithosphere, and atmosphere, are included within the system boundaries, but are not actually analyzed, balanced, and treated as the other processes of the system. The reason for this is the lack of information on environmental components,

Table 4 Amount of investigated substances in relation to the thematic system boundary

Thematic system boundary	*No. of substances*	*No. of studies*
Whole economy—waste management embedded	1	31
	2–5	3
	>10	1
MSW management	1	1
	2–5	2
	6–10	2
Waste fraction management	1	1
	6–10	1
Waste treatment plant	1	4
	2–5	7
	6–10	6
	>10	4

Note: MSW = municipal solid waste.

Table 5 Amount of investigated inflows, outflows, and processes (n = 83)

No. of inflows	*No. of studies*	*No. of outflows*	*No. of studies*	*No. of processes*	*No. of studies*
1	25	*1*	3	*1*	7
2–5	42	2–5	37	2–5	30
6–10	14	6–10	23	6–10	31
>10	2	>10	20	>10	15
Total	**83**	**Total**	**83**	**Total**	**83**

which are difficult to investigate and balance. Owing to the fact that MFA is a systematic account of a defined physical system, every process within the system boundary has to be balanced according to the mass balance principle. A solution for this dilemma of lack of data and necessity to include environmental components is to position the environmental processes outside the MFA system boundaries. Material flows from and to the environment can be considered as imports and exports, such as consumption of and emissions to air, or use of and leachate to groundwater.

Methodology of Studies Investigated

Mass Balance Principle

The fundamental principle of MFA is the conservation of matter: Inflows into an MFA system equal the outflows plus changes in stocks to consider accumulation and depletion. Every MFA system as well as each process within the system has to be balanced according to the mass balance principle. Approximately 80% of the reviewed studies take the mass balance principle into account; all MFA investigating both goods and substances are among those 80%.

Quantity of Substances Investigated

The substance level has been investigated in 63 studies. Approximately 60% of them focus on one substance, especially investigations focusing on pathways through the whole economy. If the goal is to manage single waste fractions, or to evaluate and optimize waste treatment processes, commonly more than one substance is analyzed (see table 4).

Number of substances analyzed and aspects considered (resource potential, environmental consequences, release of potential hazardous substances, or energetic performances) do not necessarily correlate. In studies with one or more than ten substances, primarily one aspect has been considered (resource potential = 20; energetic performance = 1; environmental consequences = 4; release of potentially hazardous substances = 1).

In relation to the substances investigated, the following aspects are considered: MFA studies about metals most often investigate resource potentials. Looking at organic substances, environmental impacts are in the foreground, and other nonmetals are taken into account for investigating in both resource and environmental issues.

Complexity of the System Investigated

The complexity of the reviewed MFA varies significantly. The amount of the considered inflows, outflows, and processes are represented in table 5.

In general, several studies exhibit a high complexity, comprising a large number of flows and processes requiring computational methods and corresponding software. In contrast, approximately 25 of the reviewed MFAs—often studies on waste treatment plants—start with one inflow only. Primarily two to five inflows are investigated.

The studies differ substantially in relation to the number of processes investigated. Studies comprising a few (one to five) processes often only focus on production, fabrication/manufacture, use, and WM. If more than five processes are analyzed, a variety of processes, such as people, animals, construction, machinery, landfills, and wastewater treatment, are among them.

On the backend of MFA systems, most often two to ten outflows have been analyzed. Outflows appear to correlate with the goals of the studies. Outflows most often considered, such as raw materials, finished products, old scrap, residues, and recycled materials, serve to provide information about the resource potential. If environmental impacts and releases of potential hazardous substances are in focus, outflows such as emissions to air, water, and land are analyzed (e.g., landfill gas, landfill leachate, and pollutant carrier). Outflows such as biogas, waste to energy, syngas, ashes, and air pollution control residues are often linked to the evaluation of energetic performance.

Data Considered and Uncertainty in the Studies Investigated

Data quality is the specific characteristic of data as expressed through information about the data, such as information on its uncertainty, its reliability, its completeness, and its age (Weidema and Wesnæs 1996). For the interpretation of MFA results, information about data quality is crucial. Also, if MFA is used to support WM policy decisions, it is indispensable to know the uncertainties of the underlying data and thus results. Uncertain data pose a risk for misperception and speculation (Hedbrant and Sörme 2001). For instance: Decision makers often have the choice between a new technology with high uncertainty owing to lacking experience, and old technology with little or no uncertainty owing to a long track record. If the uncertainties of the two cases are not known, decisions are inclined to be biased. In general, MFA is well suited to supply comprehensive information about uncertainties, too.

The majority (65%) of the data of the reviewed studies have been collected by literature research. Either physical material flows have been assessed or econometric data have been taken from statistics and translated into physical flows. In approximately 20% of the studies—particularly about treatment processes—material flows have been measured. Roughly, one third used a combination of methods such as literature research, personal interviews, and measurements to obtain data. Emissions to air and water were often calculated through models.

Owing to the diversity of information sources, the varying quality and availability of data, MFA results are inherently uncertain (Laner et al. 2014). No matter whether data are collected either through literature or by measurement, uncertainty should be stated in the MFA. In MFA practice, data are often scarce, incomplete, or even missing. Thus, numerical values may have to be extracted from empirical evidence (e.g., measurements), up- or downscaled, transformed from other systems to apply to the investigated system, quantified using expert judgment, or assumed using educated guesses and plausible reasoning (Laner et al. 2014).

In 20% of the reviewed MFA studies, uncertainties in flows and stocks are quantified. Approximately one third discusses or mentions uncertainties in a qualitative way, but do not quantify the uncertainty for each flow and stock. Half of the reviewed studies do not specify data with uncertainties: So far, waste-related MFA studies analyzing whole regional economies mention uncertainties, but do not actually describe them. Quantification of uncertainties is more common when investigating treatment plants. Although uncertainty treatment of data collected at a single plant may be less resource consuming, MFA for whole economies should also take into account such treatment. Based on their literature review, Laner and colleagues (2014) suggest a step-wise procedure to systematically consider uncertainty in MFA.

Results and Deductions Based on the Studies Investigated

The studies included in this review differ in relation to the systems investigated and goals defined, and thus their results and conclusions cover a broad range of issues.

The studies focusing on MSW management are mainly carried out on the level of goods, or on both goods and substances (Supporting Information on the Web: #: 1, 7, 13, 26, 49, 50, 73, 74, 79, and 83). General conclusions in view of their goals are mainly suggestions for organizational changes, such as better involvement of stakeholders, or shifting waste flows to other treatment options. Studies focusing on waste fractions other than MSW are mainly applied on the level of goods (Supporting Information on the Web: #: 11, 14, 34, 38, 40, 41, 44, 52, 75, and 76). Investigations on biogenic waste result in strategic advice for improving marketing of products and provide general information about losses (e.g., nutrients). Studies on WEEE identify the need for data to predict future e-waste generation as a key issue. These MFAs for MSW or waste fraction management are carried out to provide insight into WM and allow visualization of a given WM system with all related inputs, stocks, and outputs.

Approximately 20 studies focusing on waste treatment plants (Supporting Information on the Web: #: 2 to 6, 8, 16, 18, 20, 21, 25, 39, 45, 51, 53 to 55, 58 to 61, 64, and 66) are mainly carried out on the level of goods and substances, or substances only. Their purpose is to identify the distribution of substances during waste treatment. Process emissions are determined by substance concentrations in wastes; product quality is evaluated and recovery efficiencies are quantified to fulfill the goals resource conservation and environmental protection. MFA is applied in 15 studies on thermal waste treatment, either to compare different incinerators or waste to energy plants on economic and technological aspects, or to identify elemental composition of inputs and their transfer to outputs. Studies investigating energy aspects suggest technological improvements, such as oxygen-enriched combustion air or treatment options such as presorting steps to ensure high-energy efficiencies. Other studies focus on the resource potential of residues of thermal treatment plants and assess the recovery of valuable metals from bottom ash and air pollution residues. These studies differ in their conclusions depending on the system boundaries and waste input: Some find a lack of precious metal enrichment in residues and suggest presorting whereas other studies conclude that many valuable substances can be recovered economically from bottom ash and air pollution control residues.

Approximately 40 of the reviewed MFAs take into account the level of substances for whole economies, emphasizing waste management as an important embedded part (Supporting Information on the Web: #: 9,10,12,15,17,19,22 to 24,27 to 33,35 to 37,42, 43,46 to 48,56,57,62,63,65,67 to 72,77,78,80 to 82). These MFAs focus on resource management and environmental impacts by analyzing stocks and flows. The results of 11 studies focusing on P-flows conclude that there is a large P-discharge to water bodies. They recommend to reduce the application of P-fertilizer and redesign agricultural systems.

The knowledge about the in-use stock, its emissions, and expected lifetime is fundamental for waste management planning, and thus several MFA studies investigate the change of anthropogenic metal stocks over time. Dynamic MFA models are provided to predict future waste flows and emissions by Kleijn and colleagues (2000) and Van der Voet and colleagues (2002).

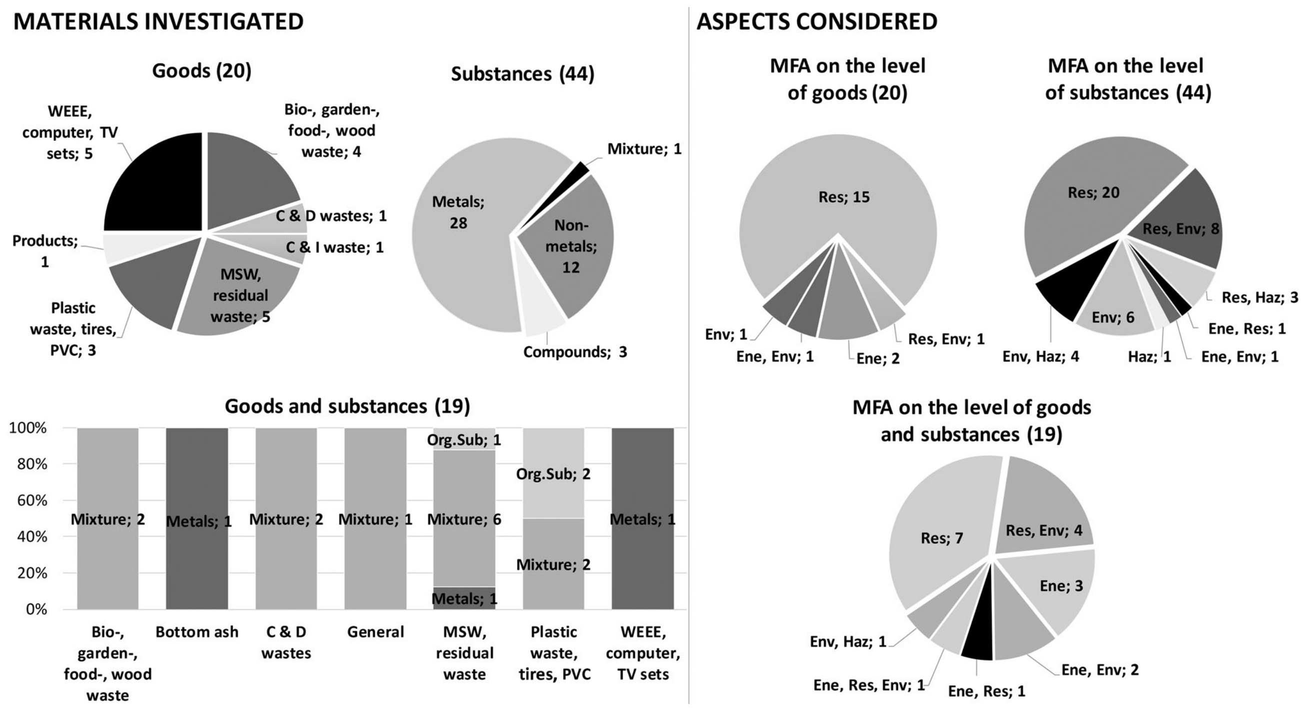

Figure 2 Materials investigated and aspects considered (n = 83). Org.Sub = organic substances; Res = resource potential; Ene = energetic performance; Env = environmental consequences; Haz = release of potential hazardous substances.

In summary, MFAs are carried out to comprehensively analyze flows, stocks, and processes within defined system boundaries. They illuminate connections between system inputs, processes, and system outputs in a mass balanced way and thus foster general understanding and control of waste management. MFAs on the level of goods have proven to be useful for decisions such as capacity planning or selection of collection and treatment concepts. Studies applying MFA on the level of goods and substances mainly provide information on the strategic level, but are also useful for environmental impact statements, technical decisions about design of treatment plants, or exploitation of resource recovery potentials. MFA on the level of substances are carried out to gain insights into the flows and into the subsequent accumulation of harmful or beneficial stocks of waste-derived materials in the anthroposphere and environment.

Conclusions and Recommendations for Goal-Oriented Decision Making in Waste Management

The review of 83 studies shows that during the last two decades, MFA has become a common, widely used tool to analyze waste management systems on different levels (goods and substances) and with various goals. The main goal of an MFA is to describe a defined system and establish a flow and stock diagram for individual materials based on the mass balance principle (Baccini and Brunner 1991). The results of this review corroborate the successful application of MFA methodology for the following purposes: (1) to reduce the complexity of comprehensive waste management systems; (2) for managing wastes, resulting in secondary resources, and substance flows to the environment; (3) to model the interrelation between the regional/national economy and waste management; and (4) to provide background information in aggregated form on the composition and changes of the physical structure of socioeconomic systems for waste management (Bringezu and Moriguchi 2002; Eurostat 2009; Fischer-Kowalski et al. 2011).

Figure 2 categorizes the reviewed MFA studies regarding materials investigated and aspects considered, subdivided into the three levels “MFA on goods,” “MFA on substances and goods,” and “MFA on substances.”

Based on the presented results of this review, the following recommendations are suggested for application of MFA in WM.

MFA on the level of goods is highly useful for understanding WM systems. It represents a tool for analyzing, controlling, and managing material flows within a system. For decision making in WM, it is essential to know the quantity of waste to be treated (inflows), how this waste is transformed, transported, or stored (processes), and what kind of materials are leaving (outflows) or are accumulated in the system (stocks). MFA on the level of goods is also a valuable means to implement regulatory mechanisms. Literature examples are assessments of collection efficiencies, recycling rates, and amounts of materials treated and landfilled. On the level of goods, primary resources can be conserved by pointing out the potential in secondary resources of wastes. It is recommended to use MFA to support communication and facilitate transparency between the various groups engaged in WM decision making: Visualizations of the flows of goods and the changes of stocks over time facilitates greatly the development of a common discussion basis for stakeholders from public, industrial, and administrative sectors.

Yet, the level of goods does not include enough qualitative information. In addition to mere bulk material flows, it is highly recommended to select key substances and balance these key substances throughout the system. This allows answering questions regarding the accumulation and depletion of beneficial as well as hazardous substances in goods. The level of substances is indispensable to evaluate whether waste management goals are fulfilled. A main advantage that has been described in some of the reviewed articles is that the balance principle forces experts to consider all flows, also those that sometimes are neglected (e.g., because they are not regulated). Characterizing the substance composition of inflows and the transfer to possible products by a mass balance approach can ensure that materials reclaimed or recycled do not present a greater risk than comparable primary resources. A mass balance also avoids that potentially harmful substances are hidden or accumulated somewhere in the system, thus preventing pollution of the environment or of secondary resources. Therefore, MFA on the substance level is a key tool for decision making in view of the goals protection of humans and the environment, conservation of resources, and aftercare-free WM (Brunner and Ma 2009).

Based on our review, we conclude that an MFA performed on the level of both goods and substances is most appropriate to support WM decisions. This combination is an indispensable tool for assessing whether a given WM system reaches a set goal in a comprehensive way. MFA of goods and respectively substances have their strength and weaknesses, but together (goods and substances) they provide profound and transparent knowledge for decision makers. Because a combined approach on the level of goods and substances takes advantage of the same system definitions and analysis, the effort to perform a combined MFA is less resource consuming than for two individual MFAs. The results of MFA can be used as a well-grounded inventory for LCA or other evaluation methodologies and serve as a basis for management decisions. Further, MFA with a focus on resource management can provide valuable information on the in-use stock and future end-of-life flows from stocks for decision makers in the fields of resource and waste management.

It is recommended to define MFA system boundaries carefully and explicitly. For the beneficiaries of the results, it is essential to know clearly which elements (flows, stocks, and processes) are within the systems boundaries and are balanced and which are situated outside the boundaries and thus are not balanced. It is equally important to estimate uncertainties of used data and obtained results. A transparent and clear presentation of uncertainties is of great importance to inform stakeholders in an impartial way and will result in well-founded, goal-oriented decisions.

In summary, this review shows the high potential of MFA to support goal-oriented WM if both levels of goods and substances are taken into account.

Acknowledgments

The authors declare that there is no conflict of interest. The valuable comments of three anonymous reviewers have been instrumental in improving this article and are highly acknowledged.

References

Al Sabbagh, M. K., C. A. Velis, D. C. Wilson, and C. R. Cheeseman. 2012. Resource management performance in Bahrain: A systematic analysis of municipal waste management, secondary material flows and organizational aspects. *Waste Management & Research* 30(8): 813–824.

Allegrini, E., A. Maresca, M. E. Olsson, M. S. Holtze, A. Boldrin, and T. F. Astrup. 2014. Quantification of the resource recovery potential of municipal solid waste incineration bottom ashes. *Waste Management* 34(9): 1627–1636.

Andersen, J. K., A. Boldrin, T. H. Christensen, and C. Scheutz. 2011. Mass balances and life cycle inventory of home composting of organic waste. *Waste Management* 31(9–10): 1934–1942.

Andersen, J. K., A. Boldrin, T. H. Christensen, and C. Scheutz. 2012. Home composting as an alternative treatment option for organic household waste in Denmark: An environmental assessment using life cycle assessment-modelling. *Waste Management* 32(1): 31–40.

Arena, U. and F. Di Gregorio. 2013. Element partitioning in combustion- and gasification-based waste-to-energy units. *Waste Management* 33(5): 1142–1150.

Arena, U. and F. Di Gregorio. 2014a. A waste management planning based on substance flow analysis. *Resources, Conservation and Recycling* 85: 54–66.

Arena, U. and F. Di Gregorio. 2014b. Energy generation by air gasification of two industrial plastic wastes in a pilot scale fluidized bed reactor. *Energy* 68: 735–743.

Arena, U., F. Di Gregorio, C. Amorese, and M. L. Mastellone. 2011. A techno-economic comparison of fluidized bed gasification of two mixed plastic wastes. *Waste Management* 31(7): 1494–1504.

Asari, M. and S.-I. Sakai. 2013. Li-ion battery recycling and cobalt flow analysis in Japan. *Resources, Conservation and Recycling* 81: 52–59.

Asari, M., K. Fukui, and S.-I. Sakai. 2008. Life-cycle flow of mercury and recycling scenario of fluorescent lamps in Japan. *Science of The Total Environment* 393(1): 1–10.

Baccini, P. and P. H. Brunner. 1991. *Metabolism of the anthroposphere*. Berlin-Heidelberg-New York: Springer-Verlag.

Bergeron, F. C. 2014. Assessment of the coherence of the Swiss waste wood management. *Resources, Conservation and Recycling* 91: 62–70.

Betz, A., J. Buchli, C. Göbel, and C. Müller. 2015. Food waste in the Swiss food service industry—Magnitude and potential for reduction. *Waste Management* 35: 218–226.

Bi, J., Q. Chen, L. Zhang, and Z. Yuan. 2013. Quantifying phosphorus flow pathways through socioeconomic systems at the county level in China. *Journal of Industrial Ecology* 17(3): 452–460.

Binder, C. R. 2007. From material flow analysis to material flow management part I: Social sciences modeling approaches coupled to MFA. *Journal of Cleaner Production* 15(17): 1596–1604.

Binder, C. R. and H.-J. Mosler. 2007. Waste-resource flows of short-lived goods in households of Santiago de Cuba. *Resources, Conservation and Recycling* 51(2): 265–283.

Bogucka, R., I. Kosinska, and P. H. Brunner. 2008. Setting priorities in plastic waste management—Lessons learned from material flow analysis in Austria and Poland. *Polimery* 53(1): 55–59.

Bringezu, S. and Y. Moriguchi. 2002. Material flow analysis. In *A handbook of industrial ecology*, edited by R. U. Ayres and L. W. Ayres. Chelten ham, UK: Edward Elgar.

Brunner, P. H. and H. Mönch. 1986. The flux of metals through municipal solid waste incinerators. *Waste Management & Research* 4(1): 105–119.

Brunner, P. H. and P. Baccini. 1992. Regional material management and environmental protection. *Waste Management & Research* 10(2): 203–212.

Brunner, P. H. and D. M. Stämpfli. 1993. Material balance of a construction waste sorting plant. *Waste Management & Research* 11(1): 27–48.

Brunner, P. H. and H. Rechberger. 2004. *Practical handbook of material flow analysis*. Boca Raton, FL, USA: CRC.

Brunner, P. H. and H.-W. Ma. 2009. Substance Flow Analysis: An indispensable tool for goal-oriented waste management. *Journal of Industrial Ecology* 13(1): 11–14.

Cain, A., S. Disch, C. Twaroski, J. Reindl, and C. R. Case. 2007. Substance flow analysis of mercury intentionally used in products in the United States. *Journal of Industrial Ecology* 11(3): 61–75.

Chancerel, P., C. E. M. Meskers, C. Hagelüken, and V. S. Rotter. 2009. Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. *Journal of Industrial Ecology* 13(5): 791–810.

Chen, G., N. Zhang, W. Ma, V. S. Rotter, and Y. Wang. 2015. Investigation of chloride deposit formation in a 24 MWe waste to energy plant. *Fuel* 140: 317–327.

Chen, P.-C., H.-J. Su, and H.-W. Ma. 2013. Trace anthropogenic arsenic in Taiwan—Substance flow analysis as a tool for environmental risk management. *Journal of Cleaner Production* 53: 13–21.

Chen, W.-Q. and T. E. Graedel. 2012a. Anthropogenic cycles of the elements: A critical review. *Environmental Science & Technology* 46(16): 8574–8586.

Chen, W.-Q. and T. E. Graedel. 2012b. Dynamic analysis of aluminum stocks and flows in the United States: 1900–2009. *Ecological Economics* 81: 92–102.

Cooper, J. and C. Carliell-Marquet. 2013. A substance flow analysis of phosphorus in the UK food production and consumption system. *Resources, Conservation and Recycling* 74: 82–100.

Di Gregorio, F. and L. Zaccariello. 2012. Fluidized bed gasification of a packaging derived fuel: Energetic, environmental and economic performances comparison for waste-to-energy plants. *Energy* 42(1): 331–341.

Döberl, G., R. Huber, P. H. Brunner, M. Eder, R. Pierrard, W. Schönbäck, W. Frühwirth, and H. Hutterer. 2002. Long-term assessment of waste management options—A new, integrated and goal-oriented approach. *Waste Management & Research* 20(4): 311–327.

EC (European Commission). 2006. Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency. Brussels: European Commission.

EC (European Commission). 2014. Proposal for a Directive of the European Parliament and of the Council amending Directives 2008/98/EC on waste, 94/62/EC on packaging and packaging waste, 1999/31/EC on the landfill of waste, 2000/53/EC on end-of-life vehicles, 2006/66/EC on batteries and accumulators and waste batteries and accumulators, and 2012/19/EU on waste electrical and electronic equipment. Brussels: European Commission.

Eckelman, M. J. and M. R. Chertow. 2009. Using material flow analysis to illuminate long-term waste management solutions in Oahu, Hawaii. *Journal of Industrial Ecology* 13(5): 758–774.

Eriksson, E., H. R. Andersen, and A. Ledin. 2008. Substance flow analysis of parabens in Denmark complemented with a survey of presence and frequency in various commodities. *Journal of Hazardous Materials* 156(1–3): 240–259.

Eurostat. 2009. *Economy wide material flow accounts: Compilation guidelines for reporting to the 2009 Eurostat questionnaire*. Luxembourg: European Communities.

Fan, Y., S. Hu, D. Chen, Y. Li, and J. Shen. 2009. The evolution of phosphorus metabolism model in China. *Journal of Cleaner Production* 17(9): 811–820.

Fischer-Kowalski, M. 1998. Society's metabolism. *Journal of Industrial Ecology* 2(1): 61–78.

Fischer-Kowalski, M., F. Krausmann, S. Giljum, S. Lutter, A. Mayer, S. Bringezu, Y. Moriguchi, H. Schütz, H. Schandl, and H. Weisz. 2011. Methodology and indicators of economy-wide material flow accounting. *Journal of Industrial Ecology* 15(6): 855–876.

Graedel, T. E., J. Allwood, J. P. Birat, M. Buchert, C. Hagelüken, B. K. Reck, S. F. Sibley, and G. Sonnemann. 2011. What do we know about metal recycling rates? *Journal of Industrial Ecology* 15(3): 355–366.

Guo, X., J. Zhong, Y. Song, and Q. Tian. 2010. Substance flow analysis of zinc in China. *Resources, Conservation and Recycling* 54(3): 171–177.

Gurauskienė, I. and Ž. Stasiškienė. 2011. Application of material flow analysis to estimate the efficiency of e-waste management systems: The case of Lithuania. *Waste Management & Research* 29(7): 763–777.

Hedbrant, J. and L. Sörme. 2001. Data vagueness and uncertainties in urban heavy-metal data collection. *Water, Air and Soil Pollution: Focus* 1(3–4): 43–53.

Huang, C.-L., J. Vause, H.-W. Ma, Y. Li, and C.-P. Yu. 2014. Substance flow analysis for nickel in mainland China in 2009. *Journal of Cleaner Production* 84: 450–458.

Jacob, P., P. Kashyap, T. Suparat, and C. Visvanathan. 2014. Dealing with emerging waste streams: Used tyre assessment in Thailand using material flow analysis. *Waste Management & Research* 32(9): 918–926.

Kahhat, R. and E. Williams. 2012. Materials flow analysis of e-waste: Domestic flows and exports of used computers from the United States. *Resources, Conservation and Recycling* 67: 67–74.

Kleijn, R., R. Huele, and E. van der Voet. 2000. Dynamic substance flow analysis: The delaying mechanism of stocks, with the case of PVC in Sweden. *Ecological Economics* 32(2): 241–254.

Kral, U., C.-Y. Lin, K. Kellner, H.-W. Ma, and P. H. Brunner. 2014. The copper balance of cities. *Journal of Industrial Ecology* 18(3): 432–444.

Krook, J., A. Mårtensson, and M. Eklund. 2007. Evaluating waste management strategies—A case of metal-contaminated waste wood. *Resources, Conservation and Recycling* 52(1): 103–118.

Kuo, N.-W., H.-W. Ma, Y.-M. Yang, T.-Y. Hsiao, and C.-M. Huang. 2007. An investigation on the potential of metal recovery from the municipal waste incinerator in Taiwan. *Waste Management* 27(11): 1673–1679.

Laner, D., H. Rechberger, and T. Astrup. 2014. Systematic evaluation of uncertainty in material flow analysis. *Journal of Industrial Ecology* 18(6): 859–870.

Lang, D. J., C. R. Binder, R. W. Scholz, K. Schleiss, and B. Stäubli. 2006a. Impact factors and regulatory mechanisms for material flow management: Integrating stakeholder and scientific perspectives: The case of bio-waste delivery. *Resources, Conservation and Recycling* 47(2): 101–132.

Lang, D. J., C. R. Binder, M. Stauffacher, C. Ziegler, K. Schleiss, and R. W. Scholz. 2006b. Material and money flows as a means for industry analysis of recycling schemes: A case study of regional bio-waste management. *Resources, Conservation and Recycling* 49(2): 159–190.

Lanzano, T., M. Bertram, M. De Palo, C. Wagner, K. Zyla, and T. E. Graedel. 2006. The contemporary European silver cycle. *Resources, Conservation and Recycling* 46(1): 27–43.

Li, S., Z. Yuan, J. Bi, and H. Wu. 2010. Anthropogenic phosphorus flow analysis of Hefei City, China. *Science of the Total Environment* 408(23): 5715–5722.

Liu, X., M. Tanaka, and Y. Matsui. 2006. Generation amount prediction and material flow analysis of electronic waste: A case study in Beijing, China. *Waste Management & Research* 24(5): 434–445.

Long, Y.-Y., Y.-J. Feng, S.-S. Cai, W.-X. Ding, and D.-S. Shen. 2013. Flow analysis of heavy metals in a pilot-scale incinerator for residues from waste electrical and electronic equipment dismantling. *Journal of Hazardous Materials* 261: 427–434.

Ma, D., S. Hu, D. Chen, and Y. Li. 2012. Substance flow analysis as a tool for the elucidation of anthropogenic phosphorus metabolism in China. *Journal of Cleaner Production* 29–30: 188–198.

Ma, D., S. Hu, D. Chen, and Y. Li. 2013. The temporal evolution of anthropogenic phosphorus consumption in China and its environmental implications. *Journal of Industrial Ecology* 17(4): 566–577.

Månsson, N., B. Bergbäck, and L. Sörme. 2009. Phasing out cadmium, lead, and mercury. *Journal of Industrial Ecology* 13(1): 94–111.

Masood, M., C. Y. Barlow, and D. C. Wilson. 2014. An assessment of the current municipal solid waste management system in Lahore, Pakistan. *Waste Management & Research* 32(9): 834–847.

Mastellone, M. L., P. H. Brunner, and U. Arena. 2009. Scenarios of waste management for a waste emergency area. *Journal of Industrial Ecology* 13(5): 735–757.

Mastellone, M. L., L. Zaccariello, D. Santoro, and U. Arena. 2012. The O_2-enriched air gasification of coal, plastics and wood in a fluidized bed reactor. *Waste Management* 32(4): 733–742.

Modaresi, R. and D. B. Müller. 2012. The role of automobiles for the future of aluminum recycling. *Environmental Science & Technology* 46(16): 8587–8594.

Morf, L. S., P. H. Brunner, and S. Spaun. 2000. Effect of operating conditions and input variations on the partitioning of metals in a municipal solid waste incinerator. *Waste Management and Research* 18(1): 4–15.

Morf, L. S., J. Tremp, R. Gloor, F. Schuppisser, M. Stengele, and R. Taverna. 2007. Metals, non-metals and PCB in electrical and electronic waste—Actual levels in Switzerland. *Waste Management* 27(10): 1306–1316.

Morf, L. S., R. Gloor, O. Haag, M. Haupt, S. Skutan, F. D. Lorenzo, and D. Böni. 2013. Precious metals and rare earth elements in municipal solid waste—Sources and fate in a Swiss incineration plant. *Waste Management* 33(3): 634–644.

Nakajima, K., K. Matsubae-Yokoyama, S. Nakamura, S. Itoh, and T. Nagasaka. 2008. Substance flow analysis of zinc associated with iron and steel cycle in Japan, and environmental assessment of EAF Dust Recycling Process. *ISIJ International* 48(10): 1478–1483.

Nakamura, S., K. Nakajima, Y. Yoshizawa, K. Matsubae-Yokoyama, and T. Nagasaka. 2009. Analyzing polyvinyl chloride in Japan with the waste input-output material flow analysis model. *Journal of Industrial Ecology* 13(5): 706–717.

Nasrullah, M., P. Vainikka, J. Hannula, M. Hurme, and J. Kärki. 2014a. Mass, energy and material balances of SRF production process. Part 2: SRF produced from construction and demolition waste. *Waste Management* 34(11): 2163–2170.

Nasrullah, M., P. Vainikka, J. Hannula, M. Hurme, and J. Kärki. 2014b. Mass, energy and material balances of SRF production process. Part 1: SRF produced from commercial and industrial waste. *Waste Management* 34(8): 1398–1407.

Oguchi, M., H. Sakanakura, and A. Terazono. 2013. Toxic metals in WEEE: Characterization and substance flow analysis in waste treatment processes. *Science of the Total Environment* 463–464: 1124–1132.

Oguchi, M., H. Sakanakura, A. Terazono, and H. Takigami. 2012. Fate of metals contained in waste electrical and electronic equipment in a municipal waste treatment process. *Waste Management* 32(1): 96–103.

Ott, C. and H. Rechberger. 2012. The European phosphorus balance. *Resources, Conservation and Recycling* 60: 159–172.

Rechberger, H. and T. E. Graedel. 2002. The contemporary European copper cycle: Statistical entropy analysis. *Ecological Economics* 42(1–2): 59–72.

Rotter, V. S., T. Kost, J. Winkler, and B. Bilitewski. 2004. Material flow analysis of RDF-production processes. *Waste Management* 24(10): 1005–1021.

Santorio, S. 1737. *Medicina statica: Being the aphorisms of sanctorius*. 5th ed. London: T. Longman and J. Newton.

Saurat, M. and S. Bringezu. 2008. Platinum group metal flows of Europe, part 1. *Journal of Industrial Ecology* 12(5–6): 754–767.

Schachermayer, E., T. Lahner, and P. H. Brunner. 2000. Assessment of two different separation techniques for building wastes. *Waste Management & Research* 18(1): 16–24.

Schmid Neset, T.-S., H.-P. Bader, R. Scheidegger, and U. Lohm. 2008. The flow of phosphorus in food production and consumption—Linköping, Sweden, 1870–2000. *Science of the Total Environment* 396(2–3): 111–120.

Senthilkumar, K., T. Nesme, A. Mollier, and S. Pellerin. 2012. Conceptual design and quantification of phosphorus flows and balances at the country scale: The case of France. *Global Biogeochemical Cycles* 26(2): GB2008.

Senthilkumar, K., A. Mollier, M. Delmas, S. Pellerin, and T. Nesme. 2014. Phosphorus recovery and recycling from waste: An appraisal based on a French case study. *Resources, Conservation and Recycling* 87: 97–108.

Spatari, S., M. Bertram, K. Fuse, T. E. Graedel, and H. Rechberger. 2002. The contemporary European copper cycle: 1 year stocks and flows. *Ecological Economics* 42(1–2): 27–42.

Spatari, S., M. Bertram, K. Fuse, T. E. Graedel, and E. Shelov. 2003. The contemporary European zinc cycle: 1-year stocks and flows. *Resources, Conservation and Recycling* 39(2): 137–160.

Spatari, S., M. Bertram, R. B. Gordon, K. Henderson, and T. E. Graedel. 2005. Twentieth century copper stocks and flows in North America: A dynamic analysis. *Ecological Economics* 54(1): 37–51.

Stanic-Maruna, I. and J. Fellner. 2012. Solid waste management in Croatia in response to the European Landfill Directive. *Waste Management & Research* 30(8): 825–838.

Stanisavljevic, N. and P. H. Brunner. 2014. Combination of material flow analysis and substance flow analysis: A powerful approach for decision support in waste management. *Waste Management & Research* 32(8): 733–744.

Steubing, B., H. Böni, M. Schluep, U. Silva, and C. Ludwig. 2010. Assessing computer waste generation in Chile using material flow analysis. *Waste Management* 30(3): 473–482.

Streicher-Porte, M., R. Widmer, A. Jain, H.-P. Bader, R. Scheidegger, and S. Kytzia. 2005. Key drivers of the e-waste recycling system: Assessing and modelling e-waste processing in the informal sector in Delhi. *Environmental Impact Assessment Review* 25(5): 472–491.

Tanimoto, A. H., X. Gabarrell Durany, G. Villalba, and A. C. Pires. 2010. Material flow accounting of the copper cycle in Brazil. *Resources, Conservation and Recycling* 55(1): 20–28.

Themelis, N. J. and A. F. Gregory. 2001. Sources and material balance of mercury in the New York-New Jersey. New York: New York Academy of Sciences.

Tonini, D., G. Dorini, and T. F. Astrup. 2014. Bioenergy, material, and nutrients recovery from household waste: Advanced material, substance, energy, and cost flow analysis of a waste refinery process. *Applied Energy* 121: 64–78.

Van der Voet, E., R. Kleijn, R. Huele, M. Ishikawa, and E. Verkuijlen. 2002. Predicting future emissions based on characteristics of stocks. *Ecological Economics* 41(2): 223–234.

Vexler, D., M. Bertram, A. Kapur, S. Spatari, and T. E. Graedel. 2004. The contemporary Latin American and Caribbean copper cycle: 1 year stocks and flows. *Resources, Conservation and Recycling* 41(1): 23–46.

Vyzinkarova, D. and P. H. Brunner. 2013. Substance flow analysis of wastes containing polybrominated diphenyl ethers. *Journal of Industrial Ecology* 17(6): 900–911.

Weidema, B. P. and M. S. Wesnæs. 1996. Data quality management for life cycle inventories—An example of using data quality indicators. *Journal of Cleaner Production* 4(3–4): 167–174.

Yuan, Z., X. Liu, H. Wu, L. Zhang, and J. Bi. 2011. Anthropogenic phosphorus flow analysis of Lujiang County, Anhui Province, Central China. *Ecological Modelling* 222(8): 1534–1543.

Zhang, H., P.-J. He, and L.-M. Shao. 2008. Implication of heavy metals distribution for a municipal solid waste management system—A case study in Shanghai. *Science of the Total Environment* 402(2–3): 257–267.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information outlines the literature review of the 83 studies that were examined for this article.

Table S1: Summary of Literature Review

SUPPORTING INFORMATION FOR:

Allesch, A. and P.H. Brunner. 2015. Material flow analysis as a decision support tool for waste management: A literature review. *Journal of Industrial Ecology.*

Summary

This supporting information outlines the literature review of the 83 studies that were examined for this article.

Table S1: Summary of Literature Review

SI #	Reference	System boundary		*Allocated Topic*	Materials		Goal	*Allocated Goal*	Aspects				Data		Flows and Processes		
		Geo.	*Them.*		*Goods*	*Substances*			*Ene*	*Res*	*Env*	*Tox*	*Collection*	*Uncertainty*	*Inflows*	*Outflows*	*Processes*
1	(Al Sabbagh et al. 2012)	Country	MSW Management	MSW Management	MSW		-to offer a complete and systematic account of the MSW in the Kingdom of Bahrain -to compare the results to averages for low-, middle- and high-income cities -to quantify resource flows	Comparison		y			Literature, measurement, interviews	n (mentioned)	6-10	6-10	2-5
2	(Allegrini et al. 2014)		Bottom ash recovery facility	waste treatment plant	Bottom ash	Fe, NFe	-to quantify recovery efficiencies -determination of the resource potential -to offer a platform for future environmental assessments of incineration technologies and metal recovery	Performance evaluation		y			Literature, measurement	y	1	>10	6-10
3	(Andersen et al. 2010)		Composting plant (garden waste)	waste treatment plant	Garden waste	C, N, P, Cr, Cd	-to offer a detailed LCI of the garden waste composting plant in Aarhus, Denmark	Performance evaluation		y	y		Measurement	y	2-5	6-10	2-5
4	(Andersen et al. 2011)		Home composting (Food and garden waste)	waste treatment plant	Food and garden waste	C, VS, N, K, P, Cd, Cr, Cu and Pb	-to provide a comprehensive LCI of single-family as a starting point for making environmental assessment -to present the composition and assess the quality of the final compost product	Performance evaluation		y	y		Measurement	y	2-5	2-5	2-5
5	(Arena and Di Gregorio 2013)		Waste to energy plant	waste treatment plant	Residual waste	Al, C, Cl, Pb	-to compare two WtE plants -to dedicated the partitioning of low-boiling-point heavy metals and to their concentration in output solid streams with reference to reuse or disposal Scenario analysis	Comparison		y			Literature	n	6-10	2-5	2-5
6	(Arena and Di Gregorio 2014a)		Fluidized bed gasification (plastic wastes)	waste treatment plant	Plastic waste	Al, C, Cl, Pb, S, Ca, Mg, K, Fe, Zn	-to evaluate the air gasification behavior of two mixed plastic wastes -to define a suitable plant configuration and some related design solutions for a fully sustainable energy generation	Comparison	y				Measurement	n	2-5	2-5	2-5
7	(Arena and Di Gregorio 2014b)	Region	MSW Management	MSW Management	MSW	C	-to quantify the mass flow rates of wastes and their main chemical elements in order	Scenario analysis	y	y	y		Literature	n	2-5	>10	6-10
8	(Arena et al. 2011)		Fluidized bed gasification	waste treatment plant	Plastic waste	C	-a techno-economic C of fluidized bed gasification of two mixed plastic wastes	Comparison	y				Measurement	n	2-5	2-5	2-5
9	(Asari et al. 2008)	Country	Whole mercury economy	whole economy		Hg	-to describe the current management of mercury-containing hazardous household wastes and discuss how to control them -to promote further discussion of future management systems	Scenario analysis		y		y	Literature	n	2-5	6-10	6-10
10	(Asari and Sakai 2013)	Country	Whole cobalt economy	whole economy		Co	-to investigate the flow of small rechargeable batteries in Japan	Early recognition		y			Literature, measurement	n	2-5	>10	2-5
11	(Betz et al. 2015)	Country	Food waste management	waste fraction management	Food		-to provide general information about food loss in the food service industry -to assess the level of waste, the reasons for its accumulation	Comparison		y			Measurement	n (mentioned)	1	2-5	6-10

SI #	Reference	System boundary		*Allocated Topic*	Materials		Goal	*Allocated Goal*	Aspects				Data		Flows and Processes		
		Geo.	*Them.*		*Goods*	*Substances*			*Ene*	*Res*	*Env*	*Tox*	*Collection*	*Uncertainty*	*Inflows*	*Outflows*	*Processes*
12	(Bi et al. 2013)	Region	Whole phosphorus economy	whole economy		P	-to conduct a county-level SFA of P flows	Performance evaluation		y	y		Literature, interviews	n (discussed)	2-5	2-5	6-10
13	(Binder and Mosler 2007)	City	MSW Management	MSW Management	MSW		-to investigate how the WM sector is organized and how high the recycling rates are -to compare Cuba with other developing countries -to investigate the role of the informal sector	Performance evaluation		y			personal interviews	n	1	1	6-10
14	(Bergeron 2014)	Country	Waste wood management	waste fraction management	General		-to assess the coherence of waste wood management in Switzerland	Scenario analysis	y	y			Literature	n	6-10	>10	>10
15	(Bogucka et al. 2008)	Country	Whole plastic economy	whole economy	Plastic		to recognize potentially valuable as well as hazardous plastic waste stocks -to design of future plastic materials in the view of multiple recycling and final disposal	Early recognition		y			Literature	n	2-5	6-10	6-10
16	(Brunner and Stämpfli 1993)		C&D sorting plant	waste treatment plant	C&D Waste	SiO, Ca, Fe, H_20, C_{org}, S, CI, Mg, Al, K, Zn, Cu, Pb, As, Cd, Hg	-to present a material balance of a commercially operating, full-scale construction waste sorting plant -to assess the efficiency of the plant to eliminate selected elements from the main product stream	Performance evaluation		y			Measurement	n	1	>10	>10
17	(Brunner and Baccini 1992)	Country	Whole economy	whole economy	General	P, Pb	-to demonstrate the approach Switzerland has taken to define the objectives of waste management -to present a method to determine the material input into a regional anthroposphere in order to assess future waste fluxes	Early recognition		y			Literature	n	6-10	2-5	6-10
18	(Brunner and Mönch 1986)		Incinerator	waste treatment plant	MSW	C, S, Cl, F, Fe, Cu, Zn, Pb, Cd, Hg	-to determine material balances of elements in different MSW incinerators -to examine if material balance is changed by varying combustion conditions	Performance evaluation		y	y		Measurement	y	1	2-5	1
19	(Cain et al. 2007)	Country	Whole economy (fluorescent lamps)	whole economy		Hg	-to develop improved estimates of the environmental releases caused by mercury-containing products -to provide policy-makers with a better understanding of opportunities for reducing releases of mercury to estimate the likely impacts of options that would decrease mercury use or improve management of mercury containing wastes	Performance evaluation			y	y	Literature (economic data)	n (mentioned)	1	>10	>10
20	(Chancerel et al. 2009)		Pre-processing (WEEE)	waste treatment plant	WEEE	Ag, Au, Pd, Co, Al, Fe	-to quantify the flows of precious metals in and out of a pre-processing facility for WEEE -to determine implications for process optimization -to illustrate the necessity of applying	Performance evaluation		y			Literature	y	1	>10	2-5

SI #	Reference	System boundary		*Allocated Topic*	Materials		Goal	*Allocated Goal*	Aspects				Data		Flows and Processes		
		Geo.	*Them.*		*Goods*	*Substances*			*Ene*	*Res*	*Env*	*Tox*	*Collection*	*Uncertainty*	*Inflows*	*Outflows*	*Processes*
							SFA on a process level to create a holistic approach to systems optimization										
21	(Chen et al. 2015)		Waste to energy plant	waste treatment plant		Cl	-to obtain information concerning chlorine distribution in the WTE plant -to characterize the chemical composition of deposit at different locations and identify deposit chemistry	Performance evaluation		y			Measurement	n	1	2-5	1
22	(Chen et al. 2013)	Country	Whole arsen economy	whole economy		As	-to construct a comprehensive picture of health risk due to total emissions of anthropogenic arsenic - contribute to the design and management of industrial systems	Performance evaluation			y	y	Literature (economic data)	n (mentioned)	6-10	2-5	6-10
23	(Chen and Graedel 2012)	Country	Whole aluminum economy	whole economy		Al	-to quantify how much aluminum has entered, left, passed through, and accumulated in the U.S. anthroposphere -to provide a detailed perspective on prospective future for aluminium in the United States	Early recognition		y			Literature	n (discussed)	2-5	>10	>10
24	(Cooper and Carliell-Marquet 2013)	Country	Whole phosphorus economy	whole economy		P	-to determine the UK's reliance on imported phosphorus, identify areas of inefficient use and quantify losses within potentially recoverable waste streams -to discuss measures that could be implemented in the development of a closed-loop phosphorus management system in the UK	Performance evaluation		y			Literature	yes	1	6-10	>10
25	(Di Gregorio and Zaccariello 2012)		Fluidized bed gasification (plastic wastes)	waste treatment plant	Plastic waste	C	-to evaluate and compare the environmental, energetic and economic (EEE) Performance evaluations of the most promising design configurations for an industrial application of gasification-based PDF-to-energy generators	Comparison	y		y		Measurement	n	2-5	2-5	2-5
26	(Döberl et al. 2002)	Country	MSW Management	MSW Management	MSW		-to search for the best options to treat MSW and sewage sludge considering both – economic costs and fulfilment of the goals defined in Austria's Waste Management Act	Scenario analysis			y		Literature	n (mentioned)	6-10	>10	6-10
27	(Eckelman and Chertow 2009)	Region	Whole economy	whole economy	General		-to provide a multilevel, quantitative picture of material flows on the island of Oahu as a means of highlighting the sustainability issues and opportunities that the island faces	Performance evaluation		y			Literature (economic data)	n	2-5	2-5	2-5
28	(Eriksson et al. 2008)	Country	Whole parabens economy	whole economy	General	parabens	-to identify and quantify the sources and pathways for transporting parabens within the technosphere/urban environment -to identify necessary actions to be taken in order to limit paraben occurrence and distribution	System analysis			y	y	Literature, Interviews	n (discussed)	>10	>10	>10
29	(Fan et al.	Countr	Whole	whole		P	-to build different models of phosphorus	Comparison		y	y		Literature	n	2-5	2-5	>10

SI #	Reference	System boundary		Allocated Topic	Materials		Goal	Allocated Goal	Aspects				Data		Flows and Processes		
		Geo.	Them.		Goods	Substances			Ene	Res	Env	Tox	Collection	Uncertainty	Inflows	Outflows	Processes
	2009)	y	phosphorus economy	economy			metabolism for the following three periods: the pre-human period, traditional agricultural period and modern industrial period -to describe the evolution process of the phosphorus cycle in China - to provide a long-term perspective from which to learn how phosphor resources should be used										
30	(Graedel et al. 2011)	Global	Whole metal economy	whole economy		V, Vr, Mn, Fe, Ni, Nb, Mo, Mg, Al, Ti, Co, Cu, Zn, Sn, Pb, Ru, Rh, Pd, Ag, Os, Ir, Pt, Au, Li, Be, B, Sc, Ga, Ge, As, Se, Sr, Y, Zr, Cd, In, Sb, Te, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm Yb, Lu, Hf, Ta, W, Re, Hf, Tl, Bi	- to discuss definitions of recycling statistics, review recycling information, identify information gaps, and discuss the implications of our results - to summarize available information (rather than to generate new data), highlight information gaps,	Performance evaluation		y			Literature	n (mentioned)	1	2-5	6-10
31	(Guo et al. 2010)	Country	Whole zinc economy	whole economy		Zn	-to explain the situation of the flow and recycling of metallic zinc, and would provide guidance for the high-comprehensive utility of zinc resource	Performance evaluation		y			Literature	n	2-5	2-5	2-5
32	(Gurauskienė and Stasiškienė 2011)	Country	Whole WEEE economy	whole economy	WEEE		-to show the importance of the estimation of national EEE flows discovering real efficiency of the system, a potential to increase it and possible measures stakeholders could take to achieve it in e-waste	Performance evaluation		y			Literature	n	2-5	6-10	6-10
33	(Huang et al. 2014)	Region	Whole nickel economy	whole economy		Ni	-to attempt a thorough integrated nickel flow analysis at the country level -to discuss the role which SFA results can play in the derivation of sustainability indicators and analysis of environmental burden shifting	Performance evaluation		y			Literature (economic data)	n (mentioned)	6-10	2-5	2-5
34	(Jacob et al. 2014)	Country	Waste tire management	waste fraction management	Tires		-to quantify the present flows, accumulations, existing reuse, recycling, treatment and disposal practices of waste tires at a macro level in Thailand -to assess current flows and stocks of waste tires to facilitate appropriate policy direction -to encourage policy makers to expand the role of producer responsibility	System analysis		y			Literature, Interviews	n	2-5	>10	2-5
35	(Kahhat and Williams 2012)	Country	Whole computer economy	whole economy	Computer		to develop and implement a method to quantify flows and exports of used and scrap electronics for a nation	Scenario analysis		y			Literature	n (discussed)	2-5	2-5	2-5

SI #	Reference	System boundary		*Allocated Topic*	Materials		Goal	*Allocated Goal*	Aspects				Data		Flows and Processes		
		Geo.	*Them.*		*Goods*	*Substances*			*Ene*	*Res*	*Env*	*Tox*	*Collection*	*Uncertainty*	*Inflows*	*Outflows*	*Processes*
36	(Kleijn et al. 2000)	Country	Whole pvc economy	whole economy	PVC		'-to estimate future outflows on the basis of information on current stock	Early recognition		y			Literature	n	2-5	1	1
37	(Kral et al. 2014)	City	Whole copper economy	whole economy		Cu	-to develop a methodology to analyze and evaluate the Cu flows and stocks -to present and compare the results of a Cu flow and stock between two cities on the basis of selected indicators -to compare the metabolic differences between cities for improving decision making	Comparison		y	y		Literature	y	2-5	>10	6-10
38	(Krook et al. 2007)	City	Waste wood management	waste fraction management		Heavy metals (As, Cr, Pb, Cu, Zn, Hg, Ni, Cd)	-to evaluate how different upstream strategies influence the arising of pollution and resource problems downstream the waste management system	Performance evaluation	y	y			Literature	n	6-10	6-10	2-5
39	(Kuo et al. 2007)		MSW incinerator	waste treatment plant		Cr, Cu, Fe, Cd, Al, Zn, Pb	-to identify distribution of metals and to estimate the amount of these metals that can be potentially recovered from incineration residues	Performance evaluation		y			Literature	n	1	2-5	1
40	(Lang et al. 2006a)	City	Bio-waste management	waste fraction management	Bio-waste		-to identify the crucial physical flow of bio-waste delivery to centralized transformation facilities in Canton Zurich -to investigate how the impact factors interact and create mechanisms that crucially influenced the development of the material flows	Performance evaluation		y			Literature	y	6-10	>10	>10
41	(Lang et al. 2006b)	City	Bio-waste management	waste fraction management	Bio-waste		-to determine the economic status and market interdependencies of an entire recycling industry - to develop effective strategies to improve the product market	Performance evaluation		y			Literature	y	6-10	>10	>10
42	(Lanzano et al. 2006)	EU	Whole silver economy	whole economy		Ag	-to assess the overall flow patterns of the silver cycle -to establish the amount entering silver reservoirs -to assess the amount of silver used in Europe -to light target areas for policy makers	Performance evaluation		y			Literature	n	2-5	1	6-10
43	(Li et al. 2010)	City	Whole phosphorus economy	whole economy		P	-to examine phosphorus flow and its connection to water pollution in the city of Hefei,	Performance evaluation			y		Literature	n	2-5	6-10	6-10
44	(Liu et al. 2006)	City	WEEE management	waste fraction management	WEEE		-to predict the annual obsolete amount of the five kinds of electronic appliances generated from Beijing urban households and analyse their flow after the end of the useful phase.	Early recognition		y			Literature	n	1	2-5	>10
45	(Long et al. 2013)		Incinerator for residues of WEEE	waste treatment plant		Cu, Zn, Pb, Ni, Cd	-to estimate the heavy metal transfer behavior in the incineration system and provide reference values for the management of WEEE solid waste	Performance evaluation			y	y	Measurement	n	1	6-10	2-5

SI #	Reference	System boundary		*Allocated Topic*	Materials		Goal	*Allocated Goal*	Aspects				Data		Flows and Processes		
		Geo.	*Them.*		*Goods*	*Substances*			*Ene*	*Res*	*Env*	*Tox*	*Collection*	*Uncertainty*	*Inflows*	*Outflows*	*Processes*
46	(Ma et al. 2012)	Country	Whole phosphorus economy	whole economy		P	-to account the change traits of China's anthropogenic P metabolism from a socioeconomic viewpoint -to discuss the annual and aggregate accumulation of P into natural reservoirs and identify the human-induced stocks with the greatest potential for the secondary recovery	Comparison		y			Literature	n (discussed)	2-5	2-5	6-10
47	(Ma et al. 2013)	Country	Whole phosphorus economy	whole economy		P	-to quantify and explore the temporal evolution of China's P consumption in main metabolic nodes from 1984 to 2008 -to discuss the environmental implications for both surface waters and natural soil	Comparison		y	y		Literature	n (mentioned)	2-5	2-5	2-5
48	(Månsson et al. 2009)	City	Whole economy	whole economy		Cd, Pb, Hg	-to study the effect of large stocks of metals which have accumulated in the urban technosphere in Stockholm, Sweden, in 1995 and in 2002–2003	Early recognition			y		Literature	n (mentioned)	2-5	6-10	2-5
49	(Masood et al. 2014)	City	MSW Management	MSW Management	MSW		-to characterize the SWM system in Lahore in a format that can be compared with the data from other cities in developing countries.	Performance evaluation		y			Literature, interviews	n	1	6-10	6-10
50	(Mastellone et al. 2009)	Region	MSW Management	MSW Management	MSW	C, Cd	-to quantify and assess six waste management Scenario analysiss d by means of substance flow analysis	Scenario analysis	y		y		Literature	n (mentioned)	6-10	>10	2-5
51	(Mastellone et al. 2012)		Fluidized bed gasification (plastic wastes)	waste treatment plant	Plastic waste	C, H	-to investigate the effect of a gasifying stream composed by air enriched with pure oxygen on the Performance evaluation of the co-gasification process of coal, plastics and wood fed as a mixture in the gasifier.	Performance evaluation	y				Literature	n	2-5	2-5	2-5
52	(Modaresi and Müller 2012)	Global	Aluminum Recycling (Automobiles)	waste fraction management		Al	-to develop a dynamic model of global vehicle stock shaping the boundary conditions for aluminum recycling -to assess most effective interventions to ensure that all recoverable scrap will find a useful application	Performance evaluation		y			Literature	n (mentioned)	2-5	2-5	2-5
53	(Morf et al. 2013)		MSW incinerator	waste treatment plant		Ag, Au, Ba, Be, Bi, Co, Ga, Gd, Ge, Hf, In, Li, Mo, Nb, Nd, Pb, Pr, Pt, Rb, Rh, Ru, Sc, Se, Sr, Ta, Te, Tl, V, W, Y, Zr	-to characterize of the elemental composition of MSW and the transfer into the outputs of the MSWI	System analysis		y			Measurement	y	1	6-10	2-5
54	(Morf et al. 2007)		WEEE treatment plant	waste treatment plant		Al, Sb, Pb, Cd, Cr, Fe, Cu, Ni, Hg, Zn, Sn, Cl, P, PCB sum	-to characterize the actual chemical composition and contents of specific pollutants of WEEE -to determine the separation efficiency of the hand-sorting and mechanical recycling process regarding resources	Performance evaluation		y		y	Measurement	y	1	>10	2-5

SI #	Reference	System boundary		Allocated Topic	Materials		Goal	Allocated Goal	Aspects				Data		Flows and Processes		
		Geo.	*Them.*		*Goods*	*Substances*			*Ene*	*Res*	*Env*	*Tox*	*Collection*	*Uncertainty*	*Inflows*	*Outflows*	*Processes*
							and potential toxic substances										
55	(Morf et al. 2000)		MSW incinerator	waste treatment plant	MSW	Cu, Zn, Pb, Cd	-to investigate a full-scal MSW incinerator -to analyze effects on waste input variations on CU, Zn, Cd and Pb	Performance evaluation		y			Measurement	y	1	6-10	1
56	(Nakajima et al. 2008)	Country	Whole zinc economy	whole economy		Zn	-to identify the material flow of zinc associated with steel production - to estimate the environmental effects (energy consumption and CO_2 emission reduction) of some intermediate dust treatment processes	Performance evaluation	y		y		Literature	n	2-5	2-5	6-10
57	(Nakamura et al. 2009)	Country	Whole PVC economy	whole economy	PVC	PVC	-to analyze PVC flows in Japan	System analysis		y			Literature	n	2-5	6-10	
58	(Nasrullah et al. 2014a)		Solid recovered fuel production process	waste treatment plant	C&I wastes		-to analyze the material flows and their characteristics in the various streams of material produced in SRF production process produced from C & I waste	Performance evaluation	y				Measurement	n	1	6-10	1
59	(Nasrullah et al. 2014b)		Solid recovered fuel production process	waste treatment plant	C & D wastes		-to analyze the material flows and their characteristics in the various streams of material produced in SRF production process produced from C & D.	Performance evaluation	y				Measurement	n	1	6-10	1
60	(Oguchi et al. 2013)		WEEE treatment plant	waste treatment plant		54 metals	-to characterize substance flows of toxic metals in WEEE -to examine the relative importance of various types of WEEE in terms of managing both toxic and valuable metals -to investigate the distribution behavior of metals in a typical process for MSW thermal treatment	Comparison				y	Literature	n	1	2-5	2-5
61	(Oguchi et al. 2012)		WEEE treatment plant	waste treatment plant		54 metals	-to investigate the distribution ratios and substance flows of 54 metals contained in WEEE during municipal waste treatment	Comparison		y			Literature	n (discussed)	1	2-5	2-5
62	(Ott and Rechberger 2012)	EU	Whole phosphorus economy	whole economy		P	-to develop an SFA model for the EU15 and adopt it to the special requirements for an EU15 wide analysis	System analysis		y			Literature	y	6-10	6-10	2-5
63	(Rechberger and Graedel 2002)	EU	Whole copper economy	whole economy		Cu	-to introduce an alternative and useful method for evaluating material flows	Scenario analysis		y	y		Literature	n (discussed)	2-5	2-5	6-10
64	(Rotter et al. 2004)		Refuse-derived fuels production of MSW	waste treatment plant	Residual waste	Cl, Pb, Cd	-to evaluate the possibilities of modifying the chemical characteristics of refuse-derived fuels that are processed from residual household waste by mechanical operations -to achieve and assure quality targets for relevant chemical concentrations	Scenario analysis			y	y	Literature	n	1	2-5	2-5
65	(Saurat and Bringezu 2008)	EU	Whole platinum proup metal	whole economy		PGM	-to analyze the Platinum Group Metal flows to, from, and through Europe and the related environmental impacts	Performance evaluation			y		Literature (economic data)	n	2-5	>10	>10

SI #	Reference	System boundary		Allocated Topic	Materials		Goal	Allocated Goal	Aspects				Data		Flows and Processes		
		Geo.	*Them.*		*Goods*	*Substances*			*Ene*	*Res*	*Env*	*Tox*	*Collection*	*Uncertainty*	*Inflows*	*Outflows*	*Processes*
			flows economy														
66	(Schachermayer et al. 2000)		C & D sorting plant	waste treatment plant	C & D wastes	S, Si, Zn	-to present original results of a mass balance of a wet construction waste sorting plant -to present an assessment of two different separation techniques for C & D wastes with respect to their potential to produce suitable secondary building materials	Comparison		y			Measurement	n (discussed)	2-5	6-10	6-10
67	(Schmid Neset et al. 2008)	City	Whole phosphorus economy	whole economy		P	-to answer, how the flow of phosphorus changed, which were and are the main flows, and how changes in consumption, agricultural production and waste handling influence the reuse of this resource	Comparison		y	y		Literature	n (discussed)	2-5	6-10	6-10
68	(Senthilkumar et al. 2014)	Country	Whole phosphorus economy	whole economy		P	-to quantify P flows along the food processing, household wastewater and municipal waste chains at the country scale -to quantify P recovery, P recycling and P losses at various stages of the waste streams -to identify opportunities for improved P resource recycling	Performance evaluation		y	y		Literature	n (mentioned)	1	2-5	6-10
69	(Senthilkumar et al. 2012)	Country	Whole phosphorus economy	whole economy		P	-to identify and quantify P flows, stocks and balances across and within different sectors in France -to quantify the French P efficiency of crops and animals, as well as P recovery and recycling from waste management systems and to identify opportunities for improvement -to understand how closed the P flows in France are and their consequences for soil and water compartments.	Performance evaluation		y	y		Literature	n (mentioned)	2-5	2-5	>10
70	(Spatari et al. 2002)	EU	Whole copper economy	whole economy		Cu	-to estimate the amount of copper leaving the economy in waste, determine the amount recovered, and to assess the amount stored in specific reservoirs	System analysis		y			Literature	n	2-5	2-5	6-10
71	(Spatari et al. 2003)	EU	Whole zinc economy	whole economy		Zn	-to examine the quantity of zinc used in the 1990s, to estimate the amount leaving the economy as discarded waste -to determine the amount recovered, and to assess the amount stored in specific reservoirs	System analysis		y			Literature	n	2-5	6-10	2-5
72	(Spatari et al. 2005)	continent	Whole copper economy	whole economy		Cu	-to estimate the accumulation of copper-bearing products in use and in waste reservoirs in North America over the period 1900– 1999.	System analysis		y			Literature	n (discussed)	2-5	2-5	6-10
73	(Stanic-Maruna and Fellner	Country	MSW Management	MSW Management	MSW		-to show the past and present situation of waste management in Croatia,	Scenario analysis		y	y		Literature	n	6-10	6-10	2-5

SI #	Reference	System boundary		Allocated Topic	Materials		Goal	Allocated Goal	Aspects				Data		Flows and Processes		
		Geo.	Them.		Goods	Substances			Ene	Res	Env	Tox	Collection	Uncert ainty	Inflows	Outflo ws	Process es
	2012)						-to analyze the transposition of the Landfill Directive into Croatian law -to evaluate the country's waste management plan by investigating different Scenario analysis of future waste management.										
74	(Stanisavljevic and Brunner 2014)	City	MSW Management	MSW Management	MSW	C, Cd	-to demonstrate how a combination of MFA, SFA and Scenario analysis modelling can be used as a base for goal-oriented evaluation and optimization of waste management systems	Scenario analysis		y	y		Literature	y	2-5	>10	6-10
75	(Steubing et al. 2010)	Countr y	Computer waste management	waste fraction management	Computer		to provide data with regard to the generation of e-waste to the decision makers in Chile using the method of material flow analysis	Early recognition		y			Literature (economic data)	n	2-5		6-10
76	(Streicher-Porte et al. 2005)	City	E-waste management	waste fraction management	WEEE		-to identify key drivers within the WEEE managing system -to assess the informal sector of the recycling industry in Delhi	Comparison		y			Literature	n	2-5	>10	>10
77	(Tanimoto et al. 2010)	Countr y	Whole copper economy	whole economy		Cu	-to quantify the flow of copper in Brazil in 2005, throughout its life cycle, including stages of production, consumption and final disposal	System analysis		y			Literature	n (discus sed)	2-5	2-5	6-10
78	(Themelis and Gregory 2001)	Regio n	Whole mercury economy	whole economy		Hg	-to quantify the sources of past and present emissions of mercury in the Hudson-Raritan basin -to establish an order-of-magnitude material balance of sources and sinks of mercury in the period 1880-2000 -recommend measures that may be taken to decrease mercury contamination	Performance evaluation			y		Literature	n (menti oned)	>10	>10	>10
79	(Tonini et al. 2014)		MSW Management	MSW Management	MSW	C, C_{foss}, N, P, K, Fe, and Al	- to characterize the outputs of a pilotscale waste refinery process -to develop a mathematical optimization model to evaluate the potential for recovery -to evaluate the quality of the digestate left after anaerobic digestion -to estimate the costs of the waste refinery solution compared with alternative waste management systems.	Performance evaluation	y	y			Measureme nt	y	1	6-10	6-10
80	(Vexler et al. 2004)	contin ent	Whole copper economy	whole economy		Cu	-to examine the quantity of copper used in the 1990s, to estimate the amount of copper leaving the economy in waste, determine the amount recovered, and to assess the amount stored in specific reservoirs	System analysis		y			Literature	n	2-5	2-5	6-10
81	(Vyzinkarova and Brunner 2013)	City	Whole (cPentaBDE, cOctaBDE) economy	whole economy		cPentaBDE, cOctaBDE	-to identify sources, pathways, and sinks -to determine fractions of cPentaBDE and cOctaBDE that reach final sinks -to develop recommendations for goal-	Performance evaluation		y		y	Literature	y	2-5	2-5	2-5

SI #	Reference	System boundary		*Allocated Topic*	Materials		Goal	*Allocated Goal*	Aspects				Data		Flows and Processes		
		Geo.	*Them.*		*Goods*	*Substances*			*Ene*	*Res*	*Env*	*Tox*	*Collection*	*Uncertainty*	*Inflows*	*Outflows*	*Processes*
							oriented waste management in order to ensure minimum recycling and maximum transfer of POP-PBDEs to final sinks.										
82	(Yuan et al. 2011)	City	Whole phosphorus economy	whole economy		P	-to develop a phosphorus-flow analytical model to trace the pathways of this limiting nutrient throughout Lujiang's socioeconomic system	System analysis			y		Literature	n (mentioned)	6-10	6-10	6-10
83	(Zhang et al. 2008)	City	MSW Management	MSW Management		Pa, Wo, Pu, Gl, Pl, Te, Me, Cd	-to analyze the occurrence and distribution of heavy metals in MSW -to discuss their implications for the integrated MSW management system in mega-cities	Performance evaluation			y		Measurement	y	1	2-5	6-10

Note: y = yes; n = no; Geo. = geographical system boundary, Them. = thematic system boundary; Res = resource potential; Ene = energetic Performance evaluation; Env = environmental consequences; Haz = release of potential hazardous substances; C & D wastes = Construction and demolition wastes; C & I = Commercial and industrial wastes; WEEE = waste of electrical and electronic equipment; MSW = Municipal solid waste

References

Al Sabbagh, M. K., C. A. Velis, D. C. Wilson, and C. R. Cheeseman. 2012. Resource management performance in Bahrain: a systematic analysis of municipal waste management, secondary material flows and organizational aspects. *Waste Management & Research* 30(8): 813-824.

Allegrini, E., A. Maresca, M. E. Olsson, M. S. Holtze, A. Boldrin, and T. F. Astrup. 2014. Quantification of the resource recovery potential of municipal solid waste incineration bottom ashes. *Waste Management* 34(9): 1627-1636.

Andersen, J. K., A. Boldrin, T. H. Christensen, and C. Scheutz. 2010. Mass balances and life-cycle inventory for a garden waste windrow composting plant (Aarhus, Denmark). *Waste Management & Research* 28(11): 1010-1020.

Andersen, J. K., A. Boldrin, T. H. Christensen, and C. Scheutz. 2011. Mass balances and life cycle inventory of home composting of organic waste. *Waste Management* 31(9–10): 1934-1942.

Arena, U. and F. Di Gregorio. 2013. Element partitioning in combustion- and gasification-based waste-to-energy units. *Waste Management* 33(5): 1142-1150.

Arena, U. and F. Di Gregorio. 2014a. Energy generation by air gasification of two industrial plastic wastes in a pilot scale fluidized bed reactor. *Energy* 68: 735-743.

Arena, U. and F. Di Gregorio. 2014b. A waste management planning based on substance flow analysis. *Resources, Conservation and Recycling* 85: 54-66.

Arena, U., F. Di Gregorio, C. Amorese, and M. L. Mastellone. 2011. A techno-economic comparison of fluidized bed gasification of two mixed plastic wastes. *Waste Management* 31(7): 1494-1504.

Asari, M. and S.-i. Sakai. 2013. Li-ion battery recycling and cobalt flow analysis in Japan. *Resources, Conservation and Recycling* 81: 52-59.

Asari, M., K. Fukui, and S.-i. Sakai. 2008. Life-cycle flow of mercury and recycling scenario of fluorescent lamps in Japan. *Science of The Total Environment* 393(1): 1-10.

Bergeron, F. C. 2014. Assessment of the coherence of the Swiss waste wood management. *Resources, Conservation and Recycling* 91: 62-70.

Betz, A., J. Buchli, C. Göbel, and C. Müller. 2015. Food waste in the Swiss food service industry – Magnitude and potential for reduction. *Waste Management* 35: 218-226.

Bi, J., Q. Chen, L. Zhang, and Z. Yuan. 2013. Quantifying Phosphorus Flow Pathways Through Socioeconomic Systems at the County Level in China. *Journal of Industrial Ecology* 17(3): 452-460.

Binder, C. R. and H.-J. Mosler. 2007. Waste-resource flows of short-lived goods in households of Santiago de Cuba. *Resources, Conservation and Recycling* 51(2): 265-283.

Bogucka, R., I. Kosinska, and P. H. Brunner. 2008. Setting priorities in plastic waste management-lessons learned from material flow analysis in Austria and Poland. *Polimery* 53(1): 55-59.

Brunner, P. H. and H. Mönch. 1986. The flux of metals through municipal solid waste incinerators. *Waste Management & Research* 4(1): 105-119.

Brunner, P. H. and P. Baccini. 1992. Regional material management and environmental protection. *Waste Management & Research* 10(2): 203-212.

Brunner, P. H. and D. M. Stämpfli. 1993. Material balance of a construction waste sorting plant. *Waste Management & Research* 11(1): 27-48.

Cain, A., S. Disch, C. Twaroski, J. Reindl, and C. R. Case. 2007. Substance Flow Analysis of Mercury Intentionally Used in Products in the United States. *Journal of Industrial Ecology* 11(3): 61-75.

Chancerel, P., C. E. M. Meskers, C. Hagelüken, and V. S. Rotter. 2009. Assessment of Precious Metal Flows During Preprocessing of Waste Electrical and Electronic Equipment. *Journal of Industrial Ecology* 13(5): 791-810.

Chen, G., N. Zhang, W. Ma, V. S. Rotter, and Y. Wang. 2015. Investigation of chloride deposit formation in a 24MWe waste to energy plant. *Fuel* 140: 317-327.

Chen, P.-C., H.-J. Su, and H.-W. Ma. 2013. Trace anthropogenic arsenic in Taiwan—substance flow analysis as a tool for environmental risk management. *Journal of Cleaner Production* 53: 13-21.

Chen, W.-Q. and T. E. Graedel. 2012. Dynamic analysis of aluminum stocks and flows in the United States: 1900–2009. *Ecological Economics* 81: 92-102.

Cooper, J. and C. Carliell-Marquet. 2013. A substance flow analysis of phosphorus in the UK food production and consumption system. *Resources, Conservation and Recycling* 74: 82-100.

Di Gregorio, F. and L. Zaccariello. 2012. Fluidized bed gasification of a packaging derived fuel: energetic, environmental and economic performances comparison for waste-to-energy plants. *Energy* 42(1): 331-341.

Döberl, G., R. Huber, P. H. Brunner, M. Eder, R. Pierrard, W. Schönbäck, W. Frühwirth, and H. Hutterer. 2002. Long-term assessment of waste management options - a new, integrated and goal-oriented approach. *Waste Management & Research* 20(4): 311-327.

Eckelman, M. J. and M. R. Chertow. 2009. Using Material Flow Analysis to Illuminate Long-Term Waste Management Solutions in Oahu, Hawaii. *Journal of Industrial Ecology* 13(5): 758-774.

Eriksson, E., H. R. Andersen, and A. Ledin. 2008. Substance flow analysis of parabens in Denmark complemented with a survey of presence and frequency in various commodities. *Journal of Hazardous Materials* 156(1–3): 240-259.

Fan, Y., S. Hu, D. Chen, Y. Li, and J. Shen. 2009. The evolution of phosphorus metabolism model in China. *Journal of Cleaner Production* 17(9): 811-820.

Graedel, T. E., J. Allwood, J. P. Birat, M. Buchert, C. Hagelüken, B. K. Reck, S. F. Sibley, and G. Sonnemann. 2011. What do we know about metal recycling rates? *Journal of Industrial Ecology* 15(3): 355-366.

Guo, X., J. Zhong, Y. Song, and Q. Tian. 2010. Substance flow analysis of zinc in China. *Resources, Conservation and Recycling* 54(3): 171-177.

Gurauskienė, I. and Ž. Stasiškienė. 2011. Application of material flow analysis to estimate the efficiency of e-waste management systems: the case of Lithuania. *Waste Management & Research* 29(7): 763-777.

Huang, C.-L., J. Vause, H.-W. Ma, Y. Li, and C.-P. Yu. 2014. Substance flow analysis for nickel in mainland China in 2009. *Journal of Cleaner Production* 84: 450-458.

Jacob, P., P. Kashyap, T. Suparat, and C. Visvanathan. 2014. Dealing with emerging waste streams: Used tyre assessment in Thailand using material flow analysis. *Waste Management & Research* 32(9): 918-926.

Kahhat, R. and E. Williams. 2012. Materials flow analysis of e-waste: Domestic flows and exports of used computers from the United States. *Resources, Conservation and Recycling* 67: 67-74.

Kleijn, R., R. Huele, and E. van der Voet. 2000. Dynamic substance flow analysis: the delaying mechanism of stocks, with the case of PVC in Sweden. *Ecological Economics* 32(2): 241-254.

Kral, U., C.-Y. Lin, K. Kellner, H.-w. Ma, and P. H. Brunner. 2014. The Copper Balance of Cities. *Journal of Industrial Ecology* 18(3): 432-444.

Krook, J., A. Mårtensson, and M. Eklund. 2007. Evaluating waste management strategies—A case of metal-contaminated waste wood. *Resources, Conservation and Recycling* 52(1): 103-118.

Kuo, N.-W., H.-W. Ma, Y.-M. Yang, T.-Y. Hsiao, and C.-M. Huang. 2007. An investigation on the potential of metal recovery from the municipal waste incinerator in Taiwan. *Waste Management* 27(11): 1673-1679.

Lang, D. J., C. R. Binder, R. W. Scholz, K. Schleiss, and B. Stäubli. 2006a. Impact factors and regulatory mechanisms for material flow management: Integrating stakeholder and scientific perspectives: The case of bio-waste delivery. *Resources, Conservation and Recycling* 47(2): 101-132.

Lang, D. J., C. R. Binder, M. Stauffacher, C. Ziegler, K. Schleiss, and R. W. Scholz. 2006b. Material and money flows as a means for industry analysis of recycling schemes: A case study of regional bio-waste management. *Resources, Conservation and Recycling* 49(2): 159-190.

Lanzano, T., M. Bertram, M. De Palo, C. Wagner, K. Zyla, and T. E. Graedel. 2006. The contemporary European silver cycle. *Resources, Conservation and Recycling* 46(1): 27-43.

Li, S., Z. Yuan, J. Bi, and H. Wu. 2010. Anthropogenic phosphorus flow analysis of Hefei City, China. *Science of The Total Environment* 408(23): 5715-5722.

Liu, X., M. Tanaka, and Y. Matsui. 2006. Generation amount prediction and material flow analysis of electronic waste: a case study in Beijing, China. *Waste Management & Research* 24(5): 434-445.

Long, Y.-Y., Y.-J. Feng, S.-S. Cai, W.-X. Ding, and D.-S. Shen. 2013. Flow analysis of heavy metals in a pilot-scale incinerator for residues from waste electrical and electronic equipment dismantling. *Journal of Hazardous Materials* 261: 427-434.

Ma, D., S. Hu, D. Chen, and Y. Li. 2012. Substance flow analysis as a tool for the elucidation of anthropogenic phosphorus metabolism in China. *Journal of Cleaner Production* 29–30: 188-198.

Ma, D., S. Hu, D. Chen, and Y. Li. 2013. The Temporal Evolution of Anthropogenic Phosphorus Consumption in China and Its Environmental Implications. *Journal of Industrial Ecology* 17(4): 566-577.

Månsson, N., B. Bergbäck, and L. Sörme. 2009. Phasing Out Cadmium, Lead, and Mercury. *Journal of Industrial Ecology* 13(1): 94-111.

Masood, M., C. Y. Barlow, and D. C. Wilson. 2014. An assessment of the current municipal solid waste management system in Lahore, Pakistan. *Waste Management & Research* 32(9): 834-847.

Mastellone, M. L., P. H. Brunner, and U. Arena. 2009. Scenarios of Waste Management for a Waste Emergency Area. *Journal of Industrial Ecology* 13(5): 735-757.

Mastellone, M. L., L. Zaccariello, D. Santoro, and U. Arena. 2012. The O2-enriched air gasification of coal, plastics and wood in a fluidized bed reactor. *Waste Management* 32(4): 733-742.

Modaresi, R. and D. B. Müller. 2012. The role of automobiles for the future of aluminum recycling. *Environmental science & technology* 46(16): 8587-8594.

Morf, L. S., P. H. Brunner, and S. Spaun. 2000. Effect of operating conditions and input variations on the partitioning of metals in a municipal solid waste incinerator. *Waste Management and Research* 18(1): 4-15.

Morf, L. S., J. Tremp, R. Gloor, F. Schuppisser, M. Stengele, and R. Taverna. 2007. Metals, non-metals and PCB in electrical and electronic waste – Actual levels in Switzerland. *Waste Management* 27(10): 1306-1316.

Morf, L. S., R. Gloor, O. Haag, M. Haupt, S. Skutan, F. D. Lorenzo, and D. Böni. 2013. Precious metals and rare earth elements in municipal solid waste – Sources and fate in a Swiss incineration plant. *Waste Management* 33(3): 634-644.

Nakajima, K., K. Matsubae-Yokoyama, S. Nakamura, S. Itoh, and T. Nagasaka. 2008. Substance flow analysis of zinc associated with iron and steel cycle in Japan, and environmental assessment of EAF Dust Recycling Process. *ISIJ international* 48(10): 1478-1483.

Nakamura, S., K. Nakajima, Y. Yoshizawa, K. Matsubae-Yokoyama, and T. Nagasaka. 2009. Analyzing Polyvinyl Chloride in Japan With the Waste Input−Output Material Flow Analysis Model. *Journal of Industrial Ecology* 13(5): 706-717.

Nasrullah, M., P. Vainikka, J. Hannula, M. Hurme, and J. Kärki. 2014a. Mass, energy and material balances of SRF production process. Part 1: SRF produced from commercial and industrial waste. *Waste Management* 34(8): 1398-1407.

Nasrullah, M., P. Vainikka, J. Hannula, M. Hurme, and J. Kärki. 2014b. Mass, energy and material balances of SRF production process. Part 2: SRF produced from construction and demolition waste. *Waste Management* 34(11): 2163-2170.

Oguchi, M., H. Sakanakura, and A. Terazono. 2013. Toxic metals in WEEE: Characterization and substance flow analysis in waste treatment processes. *Science of The Total Environment* 463–464: 1124-1132.

Oguchi, M., H. Sakanakura, A. Terazono, and H. Takigami. 2012. Fate of metals contained in waste electrical and electronic equipment in a municipal waste treatment process. *Waste Management* 32(1): 96-103.

Ott, C. and H. Rechberger. 2012. The European phosphorus balance. *Resources, Conservation and Recycling* 60: 159-172.

Rechberger, H. and T. E. Graedel. 2002. The contemporary European copper cycle: statistical entropy analysis. *Ecological Economics* 42(1–2): 59-72.

Rotter, V. S., T. Kost, J. Winkler, and B. Bilitewski. 2004. Material flow analysis of RDF-production processes. *Waste Management* 24(10): 1005-1021.

Saurat, M. and S. Bringezu. 2008. Platinum Group Metal Flows of Europe, Part 1. *Journal of Industrial Ecology* 12(5-6): 754-767.

Schachermayer, E., T. Lahner, and P. H. Brunner. 2000. Assessment of two different separation techniques for building wastes. *Waste Management & Research* 18(1): 16-24.

Schmid Neset, T.-S., H.-P. Bader, R. Scheidegger, and U. Lohm. 2008. The flow of phosphorus in food production and consumption — Linköping, Sweden, 1870–2000. *Science of The Total Environment* 396(2–3): 111-120.

Senthilkumar, K., T. Nesme, A. Mollier, and S. Pellerin. 2012. Conceptual design and quantification of phosphorus flows and balances at the country scale: The case of France. *Global Biogeochemical Cycles* 26(2).

Senthilkumar, K., A. Mollier, M. Delmas, S. Pellerin, and T. Nesme. 2014. Phosphorus recovery and recycling from waste: An appraisal based on a French case study. *Resources, Conservation and Recycling* 87: 97-108.

Spatari, S., M. Bertram, K. Fuse, T. E. Graedel, and H. Rechberger. 2002. The contemporary European copper cycle: 1 year stocks and flows. *Ecological Economics* 42(1–2): 27-42.

Spatari, S., M. Bertram, K. Fuse, T. E. Graedel, and E. Shelov. 2003. The contemporary European zinc cycle: 1-year stocks and flows. *Resources, Conservation and Recycling* 39(2): 137-160.

Spatari, S., M. Bertram, R. B. Gordon, K. Henderson, and T. E. Graedel. 2005. Twentieth century copper stocks and flows in North America: A dynamic analysis. *Ecological Economics* 54(1): 37-51.

Stanic-Maruna, I. and J. Fellner. 2012. Solid waste management in Croatia in response to the European Landfill Directive. *Waste Management & Research* 30(8): 825-838.

Stanisavljevic, N. and P. H. Brunner. 2014. Combination of material flow analysis and substance flow analysis: A powerful approach for decision support in waste management. *Waste Management & Research* 32(8): 733-744.

Steubing, B., H. Böni, M. Schluep, U. Silva, and C. Ludwig. 2010. Assessing computer waste generation in Chile using material flow analysis. *Waste Management* 30(3): 473-482.

Streicher-Porte, M., R. Widmer, A. Jain, H.-P. Bader, R. Scheidegger, and S. Kytzia. 2005. Key drivers of the e-waste recycling system: Assessing and modelling e-waste processing in the informal sector in Delhi. *Environmental Impact Assessment Review* 25(5): 472-491.

Tanimoto, A. H., X. Gabarrell Durany, G. Villalba, and A. C. Pires. 2010. Material flow accounting of the copper cycle in Brazil. *Resources, Conservation and Recycling* 55(1): 20-28.

Themelis, N. J. and A. F. Gregory. 2001. Sources and Material Balance of Mercury in the New York-New Jersey Harbor. *Report to the New York Academy of Sciences*: 17-19.

Tonini, D., G. Dorini, and T. F. Astrup. 2014. Bioenergy, material, and nutrients recovery from household waste: Advanced material, substance, energy, and cost flow analysis of a waste refinery process. *Applied Energy* 121: 64-78.

Vexler, D., M. Bertram, A. Kapur, S. Spatari, and T. E. Graedel. 2004. The contemporary Latin American and Caribbean copper cycle: 1 year stocks and flows. *Resources, Conservation and Recycling* 41(1): 23-46.

Vyzinkarova, D. and P. H. Brunner. 2013. Substance Flow Analysis of Wastes Containing Polybrominated Diphenyl Ethers. *Journal of Industrial Ecology* 17(6): 900-911.

Yuan, Z., X. Liu, H. Wu, L. Zhang, and J. Bi. 2011. Anthropogenic phosphorus flow analysis of Lujiang County, Anhui Province, Central China. *Ecological Modelling* 222(8): 1534-1543.

Zhang, H., P.-J. He, and L.-M. Shao. 2008. Implication of heavy metals distribution for a municipal solid waste management system — a case study in Shanghai. *Science of The Total Environment* 402(2–3): 257-267.

ARTICLE III:

MATERIAL FLOW ANALYSIS AS A TOOL TO IMPROVE WASTE MANAGEMENT SYSTEMS: THE CASE OF AUSTRIA

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Environmental Science & Technology 2017, 51 (1), pp 540–551
DOI: 10.1021/acs.est.6b04204

Environmental Science & Technology
Article
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Material Flow Analysis as a Tool to improve Waste Management Systems: The Case of Austria

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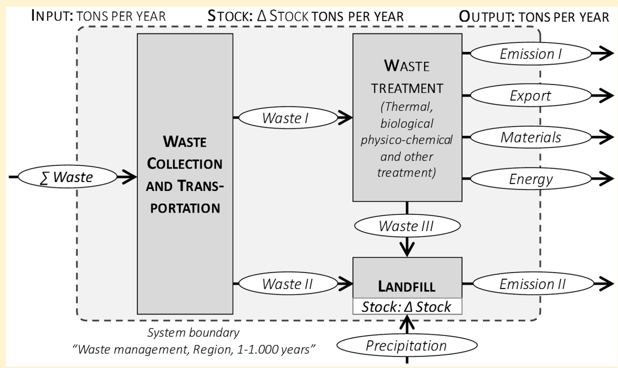
Supporting Information

ABSTRACT: This paper demonstrates the power of material flow analysis (MFA) for designing waste management (WM) systems and for supporting decisions with regards to given environmental and resource goals. Based on a comprehensive case study of a nationwide WM-system, advantages and drawbacks of a mass balance approach are discussed. Using the software STAN, a material flow system comprising all relevant inputs, stocks and outputs of wastes, products, residues, and emissions is established and quantified. Material balances on the level of goods and selected substances (C, Cd, Cr, Cu, Fe, Hg, N, Ni, P, Pb, Zn) are developed to characterize this WM-system. The MFA results serve well as a base for further assessments. Based on given goals, stakeholders engaged in this study selected the following seven criteria for evaluating their WM-system: (i) waste input into the system, (ii) export of waste (iii) gaseous emissions from waste treatment plants, (iv) long-term gaseous and liquid emissions from landfills, (v) waste being recycled, (vi) waste for energy recovery, (vii) total waste landfilled. By scenario analysis, strengths and weaknesses of different measures were identified. The results reveal the benefits of a mass balance approach due to redundancy, data consistency, and transparency for optimization, design, and decision making in WM.



INTRODUCTION

In most countries, goals of waste management (WM) are based on the precautionary principle and sustainability. They aim at protecting human health and environment, conservation of resources, and aftercare-free waste treatment and landfilling without jeopardizing future generations.[1] Today, WM-systems have reached different levels of development. A screening of WM performances of EU Member States shows that especially high developed countries like Austria, Netherland, Denmark, and Germany have achieved high standards.[2] For future development of WM in such countries, the question arises, how to assess and improve current WM-systems. Various assessments methods like cost-benefit-analysis, environmental impact assessment, multicriteria-decision-making, life cycle assessment and life cycle costing are available to point out strength and weakness of a WM-system, and to identify strategies for future development.[3−6] Independent of the applied assessment method, a consistent, transparent and unambiguous database is required to analyze and manage material flows.

Material flow analysis (MFA) has become an increasingly applied method providing a system-oriented view of interlinked processes and flows to support strategic and priority-oriented decisions and to design management measures. MFA have a long history in various fields.[7] Fischer-Kowalski, and Fischer-Kowalski and Hüttler[8,9] have presented a review on the history of MFA from 1860 to 1998 showing the rapidly growing development and analytical and policy interest in MFA. MFA studies offer a big picture view of industrial processes.[10] A general form to visualize MFA is shown in Figure 1 with processes depicted from left to right. Chen and Graedel[11] provided a critical review of elements to characterize material flows of specific materials with anthropogenic cycles. MFA provides a comprehensive overview of a material system and its interaction with the surroundings. It is highly instrumental for linking the anthroposphere with the environment. Thus, it serves for early recognition, priority setting, to analyze and improve effectiveness of measures, and to design efficient material management strategies in view of sustainability.[12] MFA are carried out on multiple levels. Many are focusing on metal flows of whole economies[13−33] to quantify accumulations and environmental releases. An overview of MFA in the bibliographic database for sciences (Scopus)[34] shows an increasing use of MFA since 1992 with a peak in the year 2010. The main subject areas of interests are engineering, materials science, and chemical and environmental engineering. A similar trend can be observed in the field of WM. Especially, MFA for municipal solid WM is often carried out[35−44] to account flows within the

Received: August 19, 2016
Revised: November 17, 2016
Accepted: November 21, 2016
Published: December 12, 2016

DOI: 10.1021/acs.est.6b04204
Environ. Sci. Technol. 2017, 51, 540−551

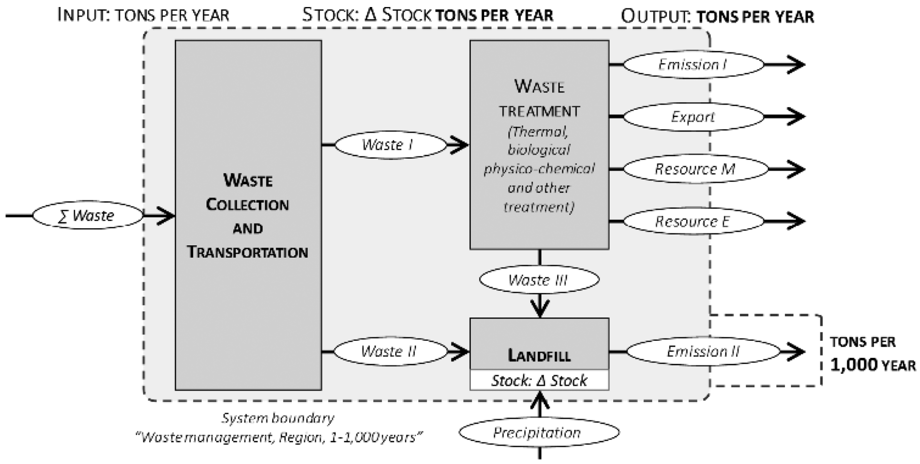


Figure 1. MFA, system and its elements as a mass-balanced base for further evaluation.

system or to the environment. MFA facilitates the understanding of the structure and functioning of metabolic processes, and supports the analysis of the throughput of process chains.[45] WM can be seen as a "throughput economy", with inputs from the market and consumption and with outputs to the market and to the environment.[3,11]

The objectives of this study are (i) to demonstrate how MFA can be used as tool to design WM-systems, (ii) to point out how MFA can be applied as a base for assessment of WM-systems in view of given objectives, and (iii) to support goal-oriented WM decisions in general. A case study from Austria is presented exemplifying the comprehensive MFA approach. The following three questions are addressed: (1) What is the main unique advantage of applying MFA to facilitate WM decisions? (2) Which information and criteria can be derived from MFA and how can these results support assessments of WM-systems? (3) How can MFA be applied in a case study to identify future improvements of an already highly developed WM-system?

MATERIALS AND METHODS

Establishing a Mass Balance by MFA. The goal of MFA is to establish a mass balance for a system of study. The sum of all inputs into the system must equal all outputs plus changes in stock. The mass balance principle applies on the level of goods (e.g., wastes, air, off-gas, products, etc.) as well as substances (elements or chemical compounds). It must be observed for every process and for the total system. Depending on the focus of a study, MFA can be carried out as a static or dynamic mass-balance approach. To evaluate the changes over time within a system, dynamic models provide information about changes in stocks and flows. Dynamic models are carried out to capture time-dependent aspects such as the development of the in-use stock and the associated postconsumer flows.[14] Müller et al.[46] have shown that dynamic MFA with the focus on metals are useful for providing knowledge of stocks and flows. Static models provide insight into investigated systems for a specific time. Therefore, they allow assessing current states of a system. In this study a static MFA for the year 2012 is carried out. The advantage of a static modeling approach is that accounting requires reported or measured data sets (inputs, outputs, and stocks) and these are often available for past years.[20] Further, if a data set for one year only is aimed at, the available financial resources can be concentrated on this year, resulting in more data and smaller uncertainties of the resulting mass balances for this year. Terms used in this study are described in Table 1 and correspond with those presented in the Practical Handbook of Material Flow Analysis.[47]

Table 1. Terminology of MFA

terms	descriptions
substances	substances are any (chemical) element or compound composed of uniform units (atoms, molecules).
goods	goods are any economic entities of matter with a positive or negative economic value and are made up of one or several substances.
materials	material serves as an umbrella term for both substances and goods
processes	processes are defined as the transformation, transport, or storage of materials.
flows	flows are defined as a mass flow rate with the ratio of mass per time.
transfer coefficients	transfer coefficients describe the partitioning of materials in a process
system	system is the actual object of investigation. it links flows and stocks of materials and substances by processes, and is limited by system boundaries defined in space and time.

The mass-balance based approach provides a well-founded, reproducible, and transparent database for evaluating WM-systems. The choice of thematic and spatial boundaries of the investigated system is crucial for impartial assessment, and for interpreting the data and results generating transparent information for stakeholders and the public. A literature review on MFA in the field of WM[48] reveals the high potential of MFA to support goal-oriented WM if both levels of goods and substances are taken into account. MFA on the level of goods is instrumental for understanding the functioning of WM as a whole (processes and connection between processes). It presents an excellent tool for analyzing, controlling and managing flows of wastes, recycling products, and residues. Also, the level of goods corresponds to the economic level, because each flow of goods can be associated with a monetary value. MFA on the level of substances is essential to assess aspects regarding the quality of material flows, such as resource flows or emissions to the environment. It serves to evaluate the transformation, transport, and storage of valuable and hazardous substances, and thus forms the base for identifying both resource potentials and risks for human health and the environment. In order to evaluate a WM-system in a comprehensive way, material flows beginning with waste input into the system, continuing with collection, transportation, treatment, and ending with recycling,

DOI: 10.1021/acs.est.6b04204
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Table 2. MFA Based Criteria for Assessment

flows	description	decision support criteria: MFA on the level of goods	decision support criteria: MFA on the level of substances	note
$\sum$ *waste*	total waste input into the system.	reduction of waste generation [t $year^{-1}$]	reduction of hazardous substances in waste generated [mg/kg]	to conserve resources and reduce environmental impacts through WM (outside the sphere of influence of WM)
export	export of waste leaving the investigated geographical system.	reduction of exports of waste [t $year^{-1}$]	reduction of exports of waste with hazardous or beneficial substances [mg/kg]	to conserve resources (beneficial substances) and provide treatment autarky (hazardous substances)
emission I	gaseous emissions from waste treatment plants.	reduction of emissions from waste treatment plant [t $year^{-1}$]	reduction of air pollutants and climate relevant gases, e.g., SO_2, NO_x, CO_2, N_20, CH_4 [t $year^{-1}$]	to protect environment, improve air quality and ensure achievement of legal objectives
emission II	long-term gaseous and liquid emissions from landfills over a time period of 1.000 years.	reduction of long-term emissions from landfills [t $year^{-1}$]	reduction of gaseous emissions, e.g., CO_2, CH_4, [t 1−1000 $year^{-1}$] reduction of leachate load, e.g., TOC, NH_4, Cd, Cr, Fe, Hg, Pb [t 1−1000 $year^{-1}$]	to provide after care free waste treatment and to ensure that only such waste remains as can be stored without danger to future generations
resource M	reused or (treated) waste suitable for material recycling.	increase secondary raw material generation [t $year^{-1}$]	reduction of hazardous substances in secondary raw material, e.g., Cd, Cr, Cu, Ni, Hg, Pb, Zn [mg/kg]	to conserve resources (raw materials) and ensure in case of recycling that materials reclaimed do not present a greater risk than comparable primary raw materials
resource E	treated waste used for energy recovery in non-wm-plants (only substitute fuels)	increase energy recovery [t $year^{-1}$]		to conserve resources (energy)
waste II and waste III	wastes landfilled.	reduction of landfill volume [t $year^{-1}$]	reduction of hazardous or beneficial substances to landfills, e.g., Cr, Cd, Cu, Hg, Ni, Pb, Zn [mg/kg]	to conserve resources (landfill volume) and that only such waste remains as can be stored without danger to future generation

DOI: 10.1021/acs.est.6b04204
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Table 3. Waste Generated and Included in the Assessment

waste generated		substance concentration [mg/kg]										
waste groups	[kilo tons]	Cd	C	Fe	N	P	Cr	Cu	Hg	Ni	Pb	Zn
biogenic waste	1490	0.3	183 000	3150	9650	1730	7	21	0.1	7	19	72
bulky waste	330	35	164 000	608	1210	81	353	210	0.2	4	1280	767
construction and demolition waste (C&D)	6290	0.3	75 800	8120	193		27	24	0.1	18	37	48
drosses, slags and metallic dusts	262	26	301 000	43 000		22 900	295	2170	12	144	12 900	11 600
glass waste	297	0.2	3000	11 800			3370	1		1	1	6
incineration residues	328	111	12 400	14 800	490	6790	270	1190	8.8	3590	3390	9600
lime mud	22	0.2					9	9	0.1	4	6	19
metal waste	2110	8.8	10 700	631 000	45	267	1810	23 500		75 200	574	1680
oils and oil contaminated waste	332	1.9	284 000	23 000	2180	2290	166	128	3.1	56	26	455
other waste	369	24	5830	54 700	3580	394	14 200	1820	12	22 400	24 800	17 900
paper waste	2050	2.0	350 000	2020	3650	105	19	47	0.2	96	17	22
plastic waste	350	29	583 000	9540	5650	668	81	54	2.1	18	252	199
residual waste	1960	6.1	203 000	21 200	7270	1000	180	727	0.4	54	296	713
textile waste	41	2.4	376 000	2170	23 500	764	172	254	0.3	7	147	462
waste electrical, electronic equipment (WEEE)	80	11	154 000	150 000	2030	273	14 500	11 800	1.1	6920	5080	1100
wood waste	995	0.3	460 000	443	4080	121	8	198	0.1	14	18	85
total	**17 300**	**6.5**	**162 000**	**86 300**	**2730**	**860**	**703**	**3130**	**0.8**	**9760**	**963**	**1090**

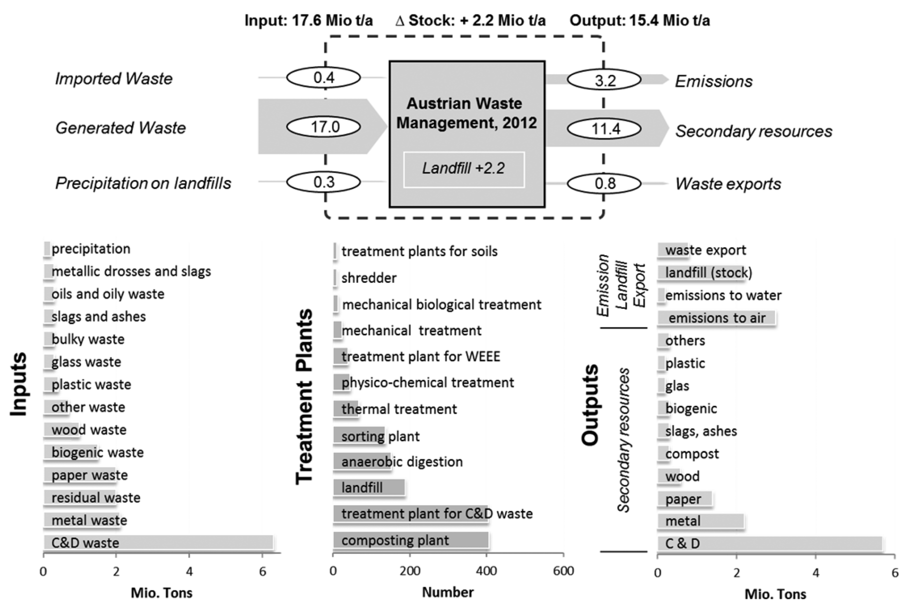

Figure 2. MFA-System representing Austrian WM of 2012.

landfilling and emissions, need to be assessed and linked on both levels of goods and substances. Figure 1 provides a general template to design WM-systems with MFA. One of the central point is the focus on the mass balance principle to provide a complete database on the level of goods as well as on the level of substances. The description of the mass flows is provided in Table 2.

In Austria WM goals are based on the precautionary principle and sustainability. They aim at (i) protection of humans, animals and plants, (ii) reduction of greenhouse gases and air pollution, (iii) conservation of resources, (iv) production of recycled materials that do not present a greater risk than comparable primary materials, and (v) remaining waste that can be stored without jeopardizing future generations.[1] Based on a survey and value judgment of Austrian WM stakeholders, different criteria were identified to fulfill these goals. Table 2 shows seven criteria, where MFA and relating material flows provide a base for further assessment methods and support goal-oriented WM. Every criterion is assessed individually. For a complete evaluation of a WM-system, it is necessary to take into account dependencies and even contradictions between these criteria, too. This has not been performed in the present study, which serves to present the MFA approach only.

The method presented is based on (i) the mass-balance-principle to ensure that all inputs are equal to the outputs and stock changes (Figure 1), (ii) goal-oriented seven criteria (Table 2) according to the Austrian WM act and (iii) a stakeholder survey. Depending on the WM-system in focus this approach needs specifications with regard to the MFA system and evaluation criteria. Other goals and stakeholders value-choices will lead to different criteria.

DOI: 10.1021/acs.est.6b04204
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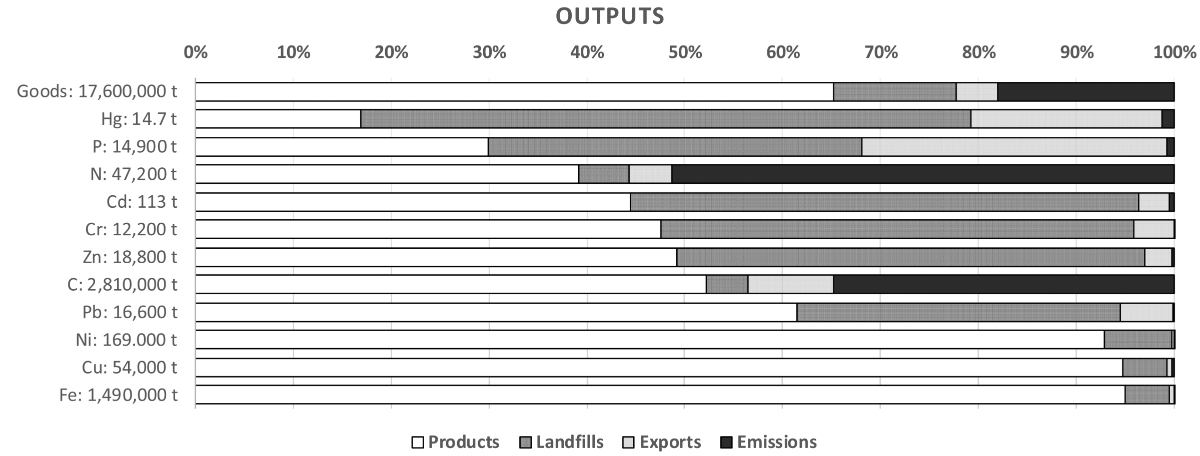

Figure 3. MFA: Inputs, outputs, stocks, and releases to the environment for selected substances.

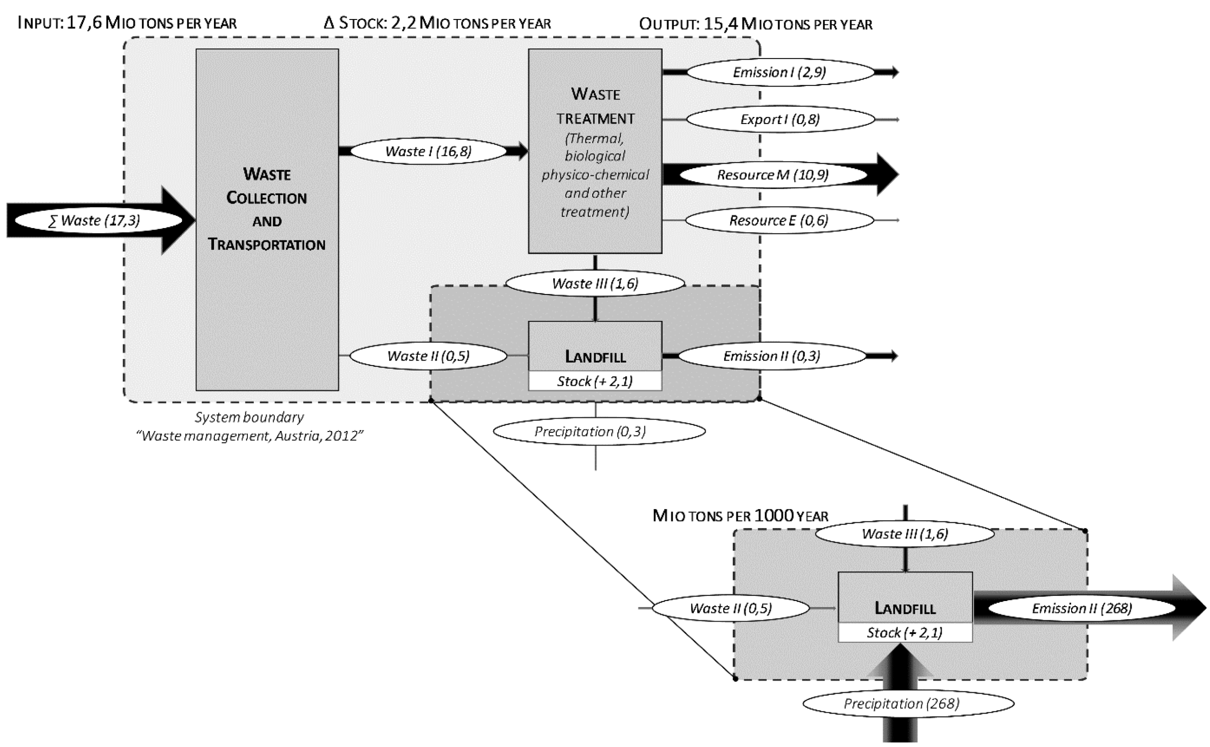

Figure 4. MFA as a base for assessment, Case Study Austria.

Scope and System Boundary. For this case study, the system boundaries in subject, space and time are Austrian WM with all its processes (collection, treatment, recycling, incineration, landfilling etc.), material flows, recycling products, residues, and emissions; the national boundary of Austria; and the year 2012. The following substances were selected for mass balancing: C, Cd, Cr, Cu, Fe, Hg, N, Ni, P, Pb, and Zn. These substances are of interest, because on the one hand they are useful as resources, and on the other hand they may act as hazardous substances and are of potential harm to the environment. A static approach is applied to evaluate the Austrian WM-system. The year 2012 was chosen because at the start of the project the best and most complete data set was available for this point in time. The inputs into the WM-system are domestic as well as imported wastes, and precipitation falling on landfills. The outputs, measured respectively calculated by transfer coefficients, are secondary products for material or energy recovery, exported waste, and emissions to the environment. The transfer coefficients describe the partitioning of materials in a process.[47] Landfills are defined as long-term stocks within the WM-system, and are the only stocks in this model. The temporal system boundary is one year for all WM processes and subsequent flows before landfilling. For the investigation of long-term effects, the temporal boundary for the biogeochemical reactor "landfill" and its in- and outputs is 1000 years.[38] Data uncertainties are calculated and estimated based on Laner et al.[49] For data collection, a comprehensive search was carried out including official statistics, stakeholder interviews and literature reviews. In total, over 100 processes of collection, recycling, treatment, and disposal, and about 300 flows of wastes, residues, secondary products, and emissions have been taken into account[50] and quantified. The software tool STAN 2.5 is used to perform MFA.[51] For considering data uncertainties, the calculation algorithm uses mathematical tools

DOI: 10.1021/acs.est.6b04204
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Table 4. MFA Based Criteria, Case Study Austria

flow		goods [kilo tons]	unit	C	Cd	N	P	Fe	Cr	Cu	Hg	Ni	Pb	Zn
		current state												
			substances											
input (1y)	**∑ waste**	17 300	[t year^{-1}]	2 810 000	113	47 200	14 900	1 490 000	12 200	54 000	15	169 000	16 600	18 800
	precipitation	268		not calculated (n.c.)										
stock (1y)	**waste II and waste III**	2190	[mg/kg]	54 700	27	1110	2600	30 600	2680	1100	4	5270	2510	4100
output (1y)	**emissions I**	2900	[t year^{-1}]	977 000	1	24 200	113	219	4	153	0.2	19	22	47
	export	751	[mg/kg]	326 000	5	2680	6160	9910	670	369	4	639	1190	687
	resources M	10 900		111 000	4	1470	397	130 000	530	4690	0.2	14 400	935	846
	resources E	563		466 000	5	4360	229	3090	20	168	0.5	14	49	69
	emissions II	270	[t year^{-1}]	927	8.7×10^{-04}	1.3×10^{00}	1.0×10^{-02}	3.1×10^{-01}	9.5×10^{-04}	(n.c.)	8.1×10^{-05}	(n.c.)	1.7×10^{-04}	2.7×10^{-03}
	landfill gas	2		926	not calculated (n.c.)									
	leachate load	1.9×10^{-03}		3.3×10^{-01}	8.7×10^{-04}	1.3×10^{00}	1.0×10^{-02}	3.1×10^{-01}	9.5×10^{-04}	(n.c.)	8.1×10^{-05}	(n.c.)	1.7×10^{-04}	2.7×10^{-03}
	evaporation, surface runoff	268		not calculated (n.c.)										
changes in viewing long-term effects (1000 years)	**precipitation**	268 000	[t 1000 year^{-1}]	not calculated (n.c.)										
	stock	2180		115 000	58	2350	5590	66 300	5870	2410	8	11 500	5490	8970
	emissions II	268 000		5640	0.1	91	90	700	2	(n.c.)	1	(n.c.)	1	15
	landfill gas	13		5310	not calculated (n.c.)									
	leachate load	1		331	0.1	91	90	700	2	(n.c.)	1	(n.c.)	1	15
	evaporation, surface runoff	268 000		not calculated (n.c.)										

DOI: 10.1021/acs.est.6b04204
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such as data reconciliation, error propagation and gross error detection. The calculation algorithm of STAN allows to make use of redundant information to reconcile uncertain "conflicting" data (with data reconciliation) and subsequently to compute unknown variables including their uncertainties (with error propagation).[52] Especially, error propagation is essential for compiling different types of plants.

Database and Modeling. In 2012, Austria with 8.4 million inhabitants has generated 48.7 million tons of waste (5800 kg/inhabitant). About 30 million tons consist of uncontaminated excavation material (50% landfilled and 50% backfilled). This waste and some other waste fractions are not included in the case study. Seventeen million tons of waste are considered in detail, comprising about 500 different waste fractions. For the MFA, these 500 waste fractions were merged into selected waste groups with similar substance concentrations. Data uncertainty was considered, too. Based on an approach to characterize uncertainty of MFA[49] data quality is evaluated with respect to reliability, completeness, temporal, and geographical correlation. For evaluation of expert estimates, only one data quality dimension is used. Table 3 shows an aggregated overview of the investigated waste groups and associated substance concentrations.

By literature search and the use of own data from previous work, the transfer coefficients, describing the partitioning of materials in a process,[47] are defined for every waste treatment plant. In 2012, about 1.500 WM plants—most of them composting plants and treatment plants for C&D waste—were in service in Austria. Due to the large number of different plants, transfer coefficients have been compiled for 32 plant types to calculate the transfer of the total waste input (excluding other raw materials) into a plant to a specific output on the level of goods and selected substances. Long-term gaseous emissions were calculated for landfills for residues from mechanical biological treatment (MBT) based on Tabasaran and Rettenberger[53] long-term leachate concentrations of TOC and NH_4–N after t years are modeled, based on the mobilizable substance potential of the landfilled waste.[54] For metals and phosphorus, a constant substance concentration over time in the leachate is assumed. Detailed information on input quantities, substance concentrations and transfer coefficients are provided in Brunner et al.[50] and in the Supporting Information.

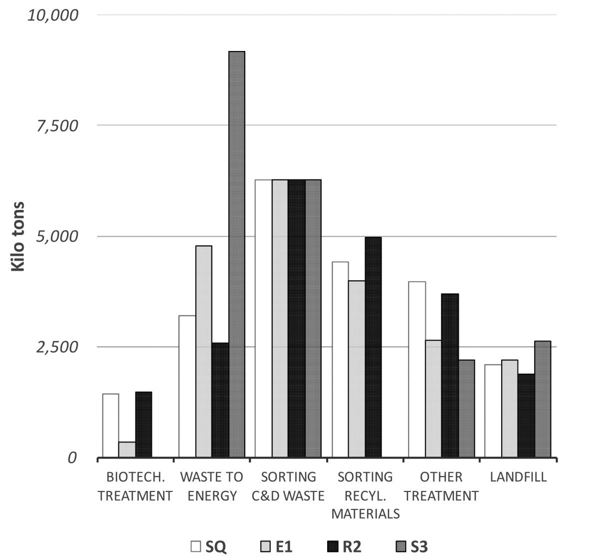

Figure 5. Scenario Analysis: Variation of waste treatment.

RESULTS

MFA as a Base for Decision Making. The total input into the investigated system is about 17 million tons of waste. Figure 2 shows an overview of the MFA on the level of goods, and gives details about inputs, outputs and stocks in million tons per year. About 65% of the waste is transferred into secondary products for material or energy recovery. Secondary products for material recovery include materials for reuse or ready for recycling without treatment (1.1 million tons) and treated waste which can be directly used as substitution of raw materials (9.8 million tons). The treatment of construction and demolition (C&D) waste for recycling provides the major share with about 6 million tons followed by metals with about 2 million tons. Secondary products for energy recovery are plastic and wood waste processed to refuse-derived-fuels fulfilling the end-of-waste criteria (0.6 million tons). About 15% of the total

Table 5. Description of Scenarios

scenarios	key aspect	changes	motivation
economy (E1)	reducing costs	no separate household collection of metals, textiles, biogenic waste, plastics	reduce cost for citizens, reduce costs for collection and transportation
		Plastic waste is incinerated	Collection and treatment of plastics is costly
		WEEE are incinerated	Collection and treatment of WEEE is costly
		no mechanical or mechanical and biological treatment	MBT and following treatment paths are costly
resources (R2)	optimize resource efficiency, increase conservation of resources	increase collection ratios for separated recyclables at households, trade, and industries	transfer from mixed to separate waste streams
		doubling material recycling for plastic and wood wastes	increase material recycling
		doubling material recycling of wte bottom ashes	
		two-stage process for biogenic waste: first biogasification and second composting fermentation residue.	increase material and energy recovery
sustainability (S3)	provide clean product cycles, reduce long-term emission	residual and bulky waste from households are incinerated	to reduce dissipation of hazardous substances
		combustible recyclables (wood, plastics, paper and biogenic waste) are incinerated	
		enhanced landfill aftercare for long time periods	reduces long-term emissions from landfills

DOI: 10.1021/acs.est.6b04204
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waste input is incinerated in waste-to-energy (WTE) plants, and 7% is either mechanically biologically treated (MBT) or biotechnologically in composting or biogas plants. About 18% off the input are released to the environment, mainly as off-gas into the air through biotechnical and thermal treatment. 12% are landfilled and 4% are exported to other countries. The largest share of the deposited materials are bottom ashes from incineration processes, residues after mechanical and biological waste treatment and C&D-waste.

Figure 3 shows substance balances for C, Cd, Cr, Cu, Fe, Hg, N, Ni, P, Pb, and Zn. About one-third of carbon and half of nitrogen are released to the air by biotechnical and thermal treatment. Carbon is discharged mainly in the form of CO_2 and to a lesser extent as CH_4, and nitrogen mainly as N_2 and in small quantities as N_2O and NO_x. The overall carbon content of all landfilled material, despite prior treatment, is still over 50 g/kg—which is the legal limit for landfilling in Austria. Residues from thermal processes which are landfilled contain relevant concentrations of Cd, P, Cr, Pb, and Zn. About one-third of the phosphorus is contained in ashes and dusts, which are used either for the production of concrete or recycled within the cement industry. Separate collected metal fractions like Fe, Cu, Pb, Ni, and Zn are mainly recycled. About 50% of the Cd is deposited as residues from thermal treatment. Recycled cadmium is mainly contained in metals and plastics. Mercury is mainly landfilled; around 20% of mercury can be found in secondary resources, such as paper and plastics. A detail overview of substances in different products is provided in the Supporting Information.

In the future, if clean product cycles are aimed at as provided by the Austrian waste legislation, certain substances in products, like Cd in plastics, need to be removed to ensure that recycled materials do not present a greater risk than comparable primary materials.[1] A "clean cycle" strategy is based on the sustainability principle embedded in the Austrian waste legislation. Waste derived problems should not be exported into the future, neither by landfills requiring extensive aftercare, nor by recycling of hazardous constituents in products that entail costly future treatment. In order to establish clean cycles, ways to remove hazardous substances from modern products that often represent a mix of numerous and sometimes hazardous substances must be explored. If clean product cycles are established, the safe disposal of hazardous substances removed from these cycles is necessary, and thus a clean product cycle strategy requires final sinks.[55] A "final sink" is a sink that either destroys a substance completely, or that holds a substance for a very long time period.[55] Landfills become final sinks, if waste is transformed into inert materials and if they are situated in an area with low erosion rates.[56] The MFA on the level of substances therefore shows the necessity of landfills for metals like Cd, Hg, Pb, and Zn. If economic conditions will change in the future extraction of beneficial substances could be viable. The detailed MFA on the level of goods and substances including data uncertainties are provided in Brunner et al.[50] and in the Supporting Information.

Figure 4 shows the MFA on the level of goods for the year 2012. For investigation of long-term effects from landfill the temporal system boundary is extended to 1,000 years for the inputs (precipitation) and outputs (landfill gas and leachate).

Based on the MFA, the criteria listed in Table 2 can be calculated on the level of goods and substances (see Table 4). These results can be used for comparison of different scenarios (e.g., years, treatment options), to evaluate WM-system, to understand the functioning, and to provide a base for future impact assessment.

Scenario Analysis. Based on the MFA results, three scenarios have been defined to better understand and evaluate the Austrian WM-system. The aim of this scenario analysis is to investigate changes within the system and to gain insight about the functioning of the WM-system and associated impacts. Each scenario focuses on different key aspects to investigate effects of different measures on future WM (see Table 5).

Based on the defined scenarios the MFA was performed again on the level of goods and substances for each scenario. The detail results of the scenario analysis including the MFA on the level of goods and substances is provided in Brunner et al.[50] and in the Supporting Information. Shifts in flows for the primary waste but also the consequent change in the secondary waste streams are evident. Figure 5 shows the different treatment paths for the status quo (SQ) and each scenario. Scenario E1 and S3 show higher incineration rates compared to the SQ and biotechnical treatment is reduced accordingly. Scenario E1 is most similar to the SQ. The landfill volumes are approximately equal for all scenarios, with a slight increase in scenario S3. Scenario R2 shows the highest sorting and processing of separate collected waste with the focus on recycling.

The MFA based seven criteria (see Table 2) are calculated for every scenario. Table 6 (level of goods) and Figure 6 (level of substances) provide an overview of the percentage changes for each scenario compared to the SQ.

Table 6. Scenario Analysis: Percent Change Relative to the SQ - Level of Goods

flow		percent change relative to the status quo E1	R2	S3
input (1 year)	*∑ waste*	0%	0%	0%
	precipitation	−1%	−13%	17%
stock (1 year)	*waste II and waste III*	0%	−14%	20%
output (1 year)	*emissions I*	27%	−30%	134%
	export	−2%	10%	−72%
	resources M	−6%	14%	−30%
	resources E	−21%	−75%	−100%
	emissions II	−1%	−13%	16%
	landfill gas	*-52%*	*-24%*	*-100%*
	leachate load	*-36%*	*-17%*	*-32%*
	evaporation, surface runoff	*-1%*	*-13%*	*17%*
changes in viewing long-term effects (1000 years)	*precipitation*	−1%	−13%	17%
	stock	0%	−14%	21%
	emissions II	−1%	−13%	17%
	landfill gas	*-69%*	*-22%*	*-100%*
	leachate load	*-7%*	*-13%*	*-61%*
	evaporation, surface runoff	*-1%*	*-13%*	*17%*

Although waste prevention is the most favored option according to the EU waste hierarchy, it was not included in the scenario analysis. Waste prevention comprises using less products and/or less material per product, keeping products longer in the use phase, and using less hazardous materials. In general, waste prevention is outside of the sphere of influence of WM. Nevertheless, feedback from WM stakeholders to other sectors of the economy (e.g., designers, producers and

DOI: 10.1021/acs.est.6b04204
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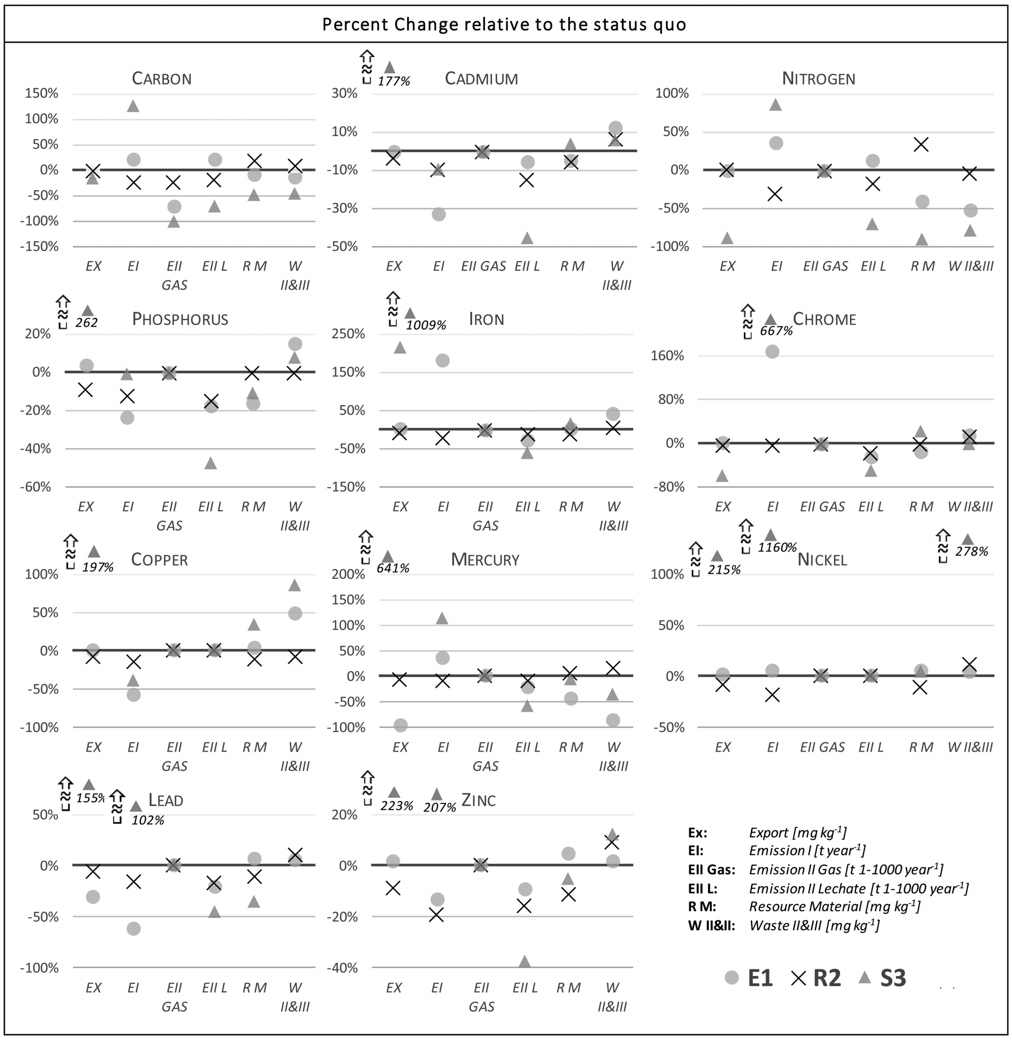

Figure 6. Scenario Analysis: Percent Change Relative to SQ - Level of Substances.

manufacturers of goods and services) is necessary. According to the Austrian WM act, treatment autarky should be sought. Hence, on the level of goods, scenario S3 is the most favored option with a reduction of waste exports of about 70%. Increased waste-to-energy reduces the export of C and N in waste products, and also concentrates many metals in bottom ash and air-pollution-control-residues (APC-residues). APC-residues are mainly exported to Germany and disposed of in underground storages. On the level of goods, releases to the air are reduced by 30% within scenario R2, and increased by about 130% within scenario S3. Increased recycling reduces discharges especially of C and N to the air by about 25%. Within scenario R2 also, metal emissions in very small quantities to the gas stream can be reduced between 3% and 19% due to reduced thermal treatment. Long-term gaseous emissions and leachate loads from landfills can be reduced within all scenarios, with scenario S3 showing the highest reduction. Landfilling of pretreated biogenic waste is much reduced within scenario E1 and S3, hence gaseous emissions are also substantially decreased. Long-term leachate emissions from landfill are about equally reduced within scenario R2 and S3. On the level of substances, leachate loads are reduced within S3 by extended landfill after-care treatment. In scenario R2, material recycling is increased by about 14%. The most significant change is the shift of wood and plastic wastes from energy recovery to material recycling

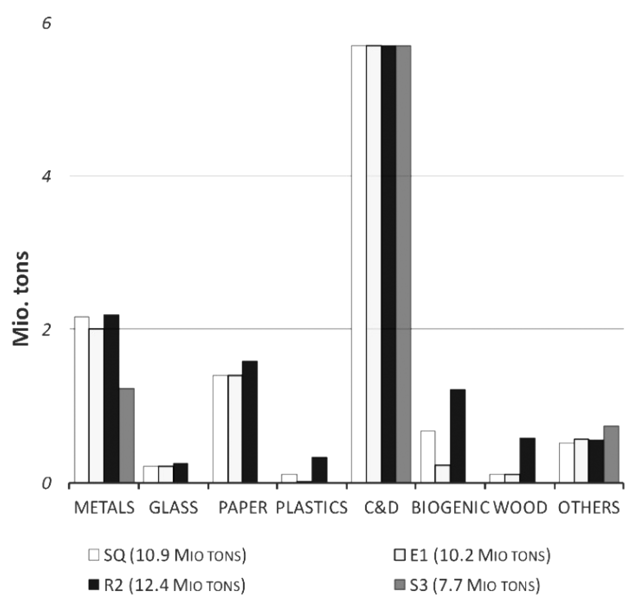

Figure 7. Scenario analysis: Products from waste treatment as secondary resources.

(see Figure 7). This also increases the amount of carbon contained in secondary resources (products of waste treatment).

DOI: 10.1021/acs.est.6b04204
Environ. Sci. Technol. 2017, 51, 540−551

Increased recycling within scenario R2 decreases the concentration of different substances, but the absolute amount of substances recycled increases. Especially, the increased flow of Hg and Cd into recycling products needs to be carefully assessed in view of the goal "protection of human health and environment". For further impact assessment of hazardous substances within product cycles the evaluation of single recycling products and especially their area of application is necessary. Scenario S3 recycles the least waste due to increased WTE, although bottom ashes are partly used as secondary products.

Scenario R2 reduces the landfilled amounts by 14% (mass) though increased recycling and reduction of secondary wastes. Although, increased WTE reduces waste volumes sent to landfills, within scenario S3 due to the decreased recycling, the waste mass sent to landfill is not reduced compared to the SQ.

Final Remarks. The system "Austrian waste management" was analyzed and evaluated in its entirety. Its structure was mapped in a coherent, transparent and verifiable way by displaying the SQ by means of the mass balance principle on the level of goods and selected substances. This MFA facilitates the understanding of how a particular WM-system is functioning, and simplifies comparison of different treatment options and their effects on emissions, secondary resources, exports and landfilled wastes (see Figures 2 and 3). The approach developed requires the selection of criteria for the evaluation of the WM-system. These criteria are based on stakeholder value choices and on predefined WM goals, which, in the case of Austria, are stated in the Federal Waste Management Act.[1] The selected criteria represent the specific WM-system in focus, and are not universal criteria, hence they might be different for different stakeholders and WM goals. Based on the MFA results for the year 2012, a scenario analysis was carried out to understand and evaluate the Austrian WM-system. On the level of goods scenario R2 (focusing on recycling) provides the best results for material recycling and reduction of emissions from waste treatment plants. Scenario S3 (focusing on clean cycles) reduces exports and long-term emissions from landfills significantly. On the level of substances, complex relations become apparent. The best scenario varies according to the substance taken into account. In summary the scenario analysis of Austrian WM reveals a potential for higher collection and recycling rates, but also shows a limitation regarding "clean" product cycles. Some hazardous substances are recycled instead of eliminated by WTE or disposed of in safe deposits. Further, short and long-term discharges to the environment can be decreased by promoting recycling and by prolonging landfill aftercare. The assessment of three scenarios compared to the status quo shows that it is not possible to improve every defined criterion with a single measure only. Therefore, because of the mass balance principle taking into account all in- and outflows, the MFA approach provides a suitable tool to point out dependencies and contradictions between given goals and criteria. For final decisions on how a WM-system should be developed further, additional social and economic issues need to be taken into account. Economic aspects have been considered in the comprehensive study[50] but are not subject of this publication. The study also discloses deficits of assessment methods that cannot be overcome by this MFA approach, such as lack of proper tools to take into account long-term effects on recycling product cycles. It will be necessary to evaluate hazardous substances within recycling products and to increase the system boundary by looking into the area of application. The combination of MFA on the level of goods and substances serves as a factual basis for future decision-making by authorities and WM stakeholders. MFA allows a complete characterization of WM-systems, and is therefore an important and necessary base for assessments like benchmarking or LCA. The results of this study reveal the following benefits of a mass balance approach if both levels of goods and substances are taken into account.

- Inputs, outputs and stocks are balanced and data consistency is ensured.
- Results are reproducible with known uncertainties.
- MFA allows a transparent and open way to inform researchers as well as external stakeholders.
- The application of different criteria enables to reveal contradictions.
- A complete, unambiguous and consistent data set can be used as a base for subsequent assessment methods (e.g., scenario analysis, benchmarking, LCA).

These benefits help understanding WM-systems. They facilitate well-founded and goal-oriented decisions. Hence, they are an essential base for planning and operating WM-systems and for developing effective and goal-oriented strategies.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b04204.

> Detailed description and data of waste generation, substance concentrations, transfer coefficients including data uncertainties and references are provided along with MFA-systems of the status quo on the level of goods and substances and the quantitative main system of the three scenarios are available (PDF)

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The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The work presented is part of the project "Benchmarking the Austrian waste management".[50] The project has been financially supported by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, Austrian federal states (Vienna, Lower-Austria, Upper-Austria, Styria, Burgenland, Carinthia, Salzburg), Altstoff-Recycling-Austria, Association of Austrian-Disposal-Companies. The project was a co-operation of Vienna University of Technology, University of Natural Resources and Life Sciences in Vienna Montanuniversität of Leoben and University of Innsbruck.

■ REFERENCES

(1) WMA, Waste Management Act (Bundesgesetz über eine nachhaltige Abfallwirtschaft). In *BGBl. I Nr. 102/2002*, 2002.

(2) BiPRO. Screening of Waste Management Performance of EU Member States. *Report submitted under the EC project "Support to Member States in improving waste management based on assessment of Member States' performance". Report prepared for the European Commission, DG ENV.* 2012.

(3) Allesch, A.; Brunner, P. H. Assessment methods for solid waste management: A literature review. *Waste Manage. Res.* **2014**, *32* (6), 461−473.
(4) Finnveden, G.; Björklund, A.; Moberg, Å.; Ekvall, T.; Moberg, Å. Environmental and economic assessment methods for waste management decision-support: possibilities and limitations. *Waste Management & Research* **2007**, *25* (3), 263−269.
(5) Karmperis, A. C.; Aravossis, K.; Tatsiopoulos, I. P.; Sotirchos, A. Decision support models for solid waste management: Review and game-theoretic approaches. *Waste Manage.* **2013**, *33* (5), 1290−1301.
(6) Pires, A.; Martinho, G.; Chang, N.-B. Solid waste management in European countries: A review of systems analysis techniques. *J. Environ. Manage.* **2011**, *92* (4), 1033−1050.
(7) Santorio, S., Medicina statica: Being the aphorisms of Sanctorius, 5th ed.; T. Longman and J. Newton: London, 1737.
(8) Fischer-Kowalski, M. Society's Metabolism. *J. Ind. Ecol.* **1998**, *2* (1), 61−78.
(9) Fischer-Kowalski, M.; Hüttler, W. Society's Metabolism. *J. Ind. Ecol.* **1998**, *2* (4), 107−136.
(10) Donahue, C. J. The Anthroposphere, Material Flow Analysis, and Chemical Education. *J. Chem. Educ.* **2015**, *92* (4), 598−600.
(11) Chen, W.-Q.; Graedel, T. E. Anthropogenic cycles of the elements: A critical review. *Environ. Sci. Technol.* **2012**, *46* (16), 8574−8586.
(12) Brunner, P. H.; Baccini, P. Regional material management and environmental protection. *Waste management & research* **1992**, *10* (2), 203−212.
(13) Asari, M.; Sakai, S.-i. Li-ion battery recycling and cobalt flow analysis in Japan. *Resources, Conservation and Recycling* **2013**, *81*, 52−59.
(14) Buchner, H.; Laner, D.; Rechberger, H.; Fellner, J. Dynamic Material Flow Modeling: An Effort to Calibrate and Validate Aluminum Stocks and Flows in Austria. *Environ. Sci. Technol.* **2015**, *49* (9), 5546−5554.
(15) Cain, A.; Disch, S.; Twaroski, C.; Reindl, J.; Case, C. R. Substance Flow Analysis of Mercury Intentionally Used in Products in the United States. *J. Ind. Ecol.* **2007**, *11* (3), 61−75.
(16) Chen, W.-Q.; Graedel, T. E. Dynamic analysis of aluminum stocks and flows in the United States: 1900−2009. *Ecological Economics* **2012**, *81*, 92−102.
(17) Graedel, T. E.; Allwood, J.; Birat, J. P.; Buchert, M.; Hagelüken, C.; Reck, B. K.; Sibley, S. F.; Sonnemann, G. What do we know about metal recycling rates? *J. Ind. Ecol.* **2011**, *15* (3), 355−366.
(18) Guo, X.; Zhong, J.; Song, Y.; Tian, Q. Substance flow analysis of zinc in China. *Resources, Conservation and Recycling* **2010**, *54* (3), 171−177.
(19) Huang, C.-L.; Vause, J.; Ma, H.-W.; Li, Y.; Yu, C.-P., Substance flow analysis for nickel in mainland China in 2009. *J. Cleaner Prod.* **2014***84*, 450−458.10.1016/j.jclepro.2013.12.079
(20) Kral, U.; Lin, C.-Y.; Kellner, K.; Ma, H.-w.; Brunner, P. H. The Copper Balance of Cities. *J. Ind. Ecol.* **2014**, *18* (3), 432−444.
(21) Lanzano, T.; Bertram, M.; De Palo, M.; Wagner, C.; Zyla, K.; Graedel, T. E. The contemporary European silver cycle. *Resources, Conservation and Recycling* **2006**, *46* (1), 27−43.
(22) Månsson, N.; Bergbäck, B.; Sörme, L. Phasing Out Cadmium, Lead, and Mercury. *J. Ind. Ecol.* **2009**, *13* (1), 94−111.
(23) Nakajima, K.; Matsubae-Yokoyama, K.; Nakamura, S.; Itoh, S.; Nagasaka, T. Substance flow analysis of zinc associated with iron and steel cycle in Japan, and environmental assessment of EAF Dust Recycling Process. *ISIJ Int.* **2008**, *48* (10), 1478−1483.
(24) Rechberger, H.; Graedel, T. E. The contemporary European copper cycle: statistical entropy analysis. *Ecological Economics* **2002**, *42* (1−2), 59−72.
(25) Saurat, M.; Bringezu, S. Platinum Group Metal Flows of Europe, Part 1. *J. Ind. Ecol.* **2008**, *12* (5−6), 754−767.
(26) Spatari, S.; Bertram, M.; Fuse, K.; Graedel, T. E.; Rechberger, H. The contemporary European copper cycle: 1 year stocks and flows. *Ecological Economics* **2002**, *42* (1−2), 27−42.
(27) Spatari, S.; Bertram, M.; Fuse, K.; Graedel, T. E.; Shelov, E. The contemporary European zinc cycle: 1-year stocks and flows. *Resources, Conservation and Recycling* **2003**, *39* (2), 137−160.
(28) Spatari, S.; Bertram, M.; Gordon, R. B.; Henderson, K.; Graedel, T. E. Twentieth century copper stocks and flows in North America: A dynamic analysis. *Ecological Economics* **2005**, *54* (1), 37−51.
(29) Tanimoto, A. H.; Gabarrell Durany, X.; Villalba, G.; Pires, A. C. Material flow accounting of the copper cycle in Brazil. *Resources, Conservation and Recycling* **2010**, *55* (1), 20−28.
(30) Themelis, N. J.; Gregory, A. F. Sources and Material Balance of Mercury in the New York-New Jersey Harbor. *Report to the New York Academy of Sciences* **2001**, 17−19.
(31) Vexler, D.; Bertram, M.; Kapur, A.; Spatari, S.; Graedel, T. E. The contemporary Latin American and Caribbean copper cycle: 1 year stocks and flows. *Resources, Conservation and Recycling* **2004**, *41* (1), 23−46.
(32) Liu, G.; Müller, D. B. Mapping the Global Journey of Anthropogenic Aluminum: A Trade-Linked Multilevel Material Flow Analysis. *Environ. Sci. Technol.* **2013**, *47* (20), 11873−11881.
(33) Peiró, L. T.; Méndez, G. V.; Ayres, R. U. Material Flow Analysis of Scarce Metals: Sources, Functions, End-Uses and Aspects for Future Supply. *Environ. Sci. Technol.* **2013**, *47* (6), 2939−2947.
(34) Scopus: Abstract and citation database - Website. https://www.scopus.com (accessed July 7, 2016).
(35) Al Sabbagh, M. K.; Velis, C. A.; Wilson, D. C.; Cheeseman, C. R. Resource management performance in Bahrain: a systematic analysis of municipal waste management, secondary material flows and organizational aspects. *Waste Manage. Res.* **2012**, *30* (8), 813−824.
(36) Arena, U.; Di Gregorio, F. A waste management planning based on substance flow analysis. *Resources, Conservation and Recycling* **2014**, *85*, 54−66.
(37) Binder, C. R. From material flow analysis to material flow management Part I: social sciences modeling approaches coupled to MFA. *J. Cleaner Prod.* **2007**, *15* (17), 1596−1604.
(38) Döberl, G.; Huber, R.; Brunner, P. H.; Eder, M.; Pierrard, R.; Schönbäck, W.; Frühwirth, W.; Hutterer, H. Long-term assessment of waste management options - a new, integrated and goal-oriented approach. *Waste Management & Research* **2002**, *20* (4), 311−327.
(39) Masood, M.; Barlow, C. Y.; Wilson, D. C. An assessment of the current municipal solid waste management system in Lahore, Pakistan. *Waste Manage. Res.* **2014**, *32* (9), 834−847.
(40) Mastellone, M. L.; Brunner, P. H.; Arena, U. Scenarios of Waste Management for a Waste Emergency Area. *J. Ind. Ecol.* **2009**, *13* (5), 735−757.
(41) Stanic-Maruna, I.; Fellner, J. Solid waste management in Croatia in response to the European Landfill Directive. *Waste Manage. Res.* **2012**, *30* (8), 825−838.
(42) Stanisavljevic, N.; Brunner, P. H. Combination of material flow analysis and substance flow analysis: A powerful approach for decision support in waste management. *Waste Manage. Res.* **2014**, *32* (8), 733−744.
(43) Tonini, D.; Dorini, G.; Astrup, T. F. Bioenergy, material, and nutrients recovery from household waste: Advanced material, substance, energy, and cost flow analysis of a waste refinery process. *Appl. Energy* **2014**, *121*, 64−78.
(44) Zhang, H.; He, P.-J.; Shao, L.-M. Implication of heavy metals distribution for a municipal solid waste management system — a case study in Shanghai. *Sci. Total Environ.* **2008**, *402* (2−3), 257−267.
(45) Bringezu, S.; Moriguchi, Y., 8. Material flow analysis. In *A Handbook of Industrial Ecology*; Ayres, R. U.; Ayres, L. W., Eds.; Edward Elgar Publishing Limited: Cheltenham, UK, 2002.
(46) Müller, E.; Hilty, L. M.; Widmer, R.; Schluep, M.; Faulstich, M. Modeling metal stocks and flows: A review of dynamic material flow analysis methods. *Environ. Sci. Technol.* **2014**, *48* (4), 2102−2113.
(47) Brunner, P. H.; Rechberger, H. *Practical Handbook of Material Flow Analysis*; CRC Press LLC: Boca Raton, 2004.
(48) Allesch, A.; Brunner, P. H. Material flow analysis as a decision support tool for waste management: A literature review. *J. Ind. Ecol.* **2015**, *19* (5), 753−764.

DOI: 10.1021/acs.est.6b04204
Environ. Sci. Technol. 2017, 51, 540−551

(49) Laner, D.; Feketitsch, J.; Rechberger, H.; Fellner, J. A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and its Application to Plastics Flows in Austria. *J. Ind. Ecol.* **2016**, *20* (5), 1050−1063.

(50) Brunner, P. H.; Allesch, A.; Getzner, M.; Huber-Humer, M.; Pomberger, R.; Müller, W.; Jandric, A.; Kanitschar, G.; Knapp, J.; Kreindl, G.; Grüblinger, G.; Mostbauer, P.; Obersteiner, G.; Pertl, A.; Plank, L.; Salhofer, S.; Schwarz, T.; Färber, B. *Benchmarking für die österreichische Abfallwirtschaft - Benchmarking for the Austrian waste management*; Technische Universität Wien, Institut für Wassergüte, Ressourcenmanagement und Abfallwirtschaft: Wien, 2015.

(51) Cencic, O.; Rechberger, H. Material flow analysis with software STAN. *J. Environ. Eng. Manage.* **2008**, *18* (1), 3.

(52) Cencic, O. Nonlinear data reconciliation in material flow analysis with software STAN. *Sustainable Environment Research* **2016**, *26*, 291−298.

(53) Tabasaran, O.; Rettenberger, G. *Grundlage zur Planung von Entgasungsanlagen - Basis for planning of degassing systems*; Erich Schmidt Verlag: Berlin, 1987.

(54) Laner, D. *Understanding and Evaluating Long-Term Environmental Risks from Landfills*; Vienna University of Technology: Vienna, 2011.

(55) Kral, U.; Kellner, K.; Brunner, P. H. Sustainable resource use requires "clean cycles" and safe "final sinks. *Sci. Total Environ.* **2013**, *461−462*, 819−822.

(56) Brunner, P. H. Materials flow analysis and the ultimate sink. *J. Ind. Ecol.* **2004**, *8* (3), 4−7.

DOI: 10.1021/acs.est.6b04204
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MATERIAL FLOW ANALYSIS AS A TOOL TO IMPROVE WASTE MANAGEMENT SYSTEMS: THE CASE OF AUSTRIA

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Summary Information

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CONTENT

1 WASTE GENERATION 2012 (BMLFUW 2013[1] AND EDM 2012[2])

Table S 1. Waste generation in tons and uncertainties.

	Waste fractions	Tons	Uncertainty
Biogenic waste	Biogenic waste from households	791,000.0	7%
	Other biogenic waste	695,000.0	31%
Bulky waste	Bulky waste	330,000.0	3%
Construction and demolition waste	Concrete demolition waste	2,410,000.0	31%
	Construction waste	2,160,000.0	31%
	Rail-gravel	227,000.0	7%
	Road surface materials	1,480,000.0	31%
Drosses, slags and metallic dusts	Drosses	10,200.0	10%
	Dust and ashes	154,000.0	10%
	Salt slags	47,900.0	10%
	Slags	49,400.0	10%
Glass waste	Glass waste from households	293,000.0	7%
	Other glass waste	4,370.0	7%
Incineration residues	Fly ashes	189,000.0	3%
	Other Ashes	16,400.0	3%
	Wood Ashes	122,000.0	3%
Lime mud	Lime mud	21,900.0	7%
Metal waste	Aluminum	112,000.0	7%
	Copper	43,300.0	7%
	Iron and steel	873,000.0	7%
	Metal packaging waste	29,500.0	7%
	Metal waste from commercial trade and industry	841,000.0	7%
	Metal waste from households	87,800.0	7%
	Nickel	23,100.0	7%

	Waste fractions	Tons	Uncertainty
	Other metal waste	93,500.0	7%
	Zinc	2,640.0	7%
Oils and oil contaminated waste	Filters and wipes	9,150.0	7%
	Oil	38,900.0	7%
	Oil contaminated soil	126,000.0	8%
	Oil-containing drilling muds and wastes	121,000.0	7%
	Other	22,500.0	7%
	Waste from de-sanding	14,500.0	7%
Other waste	Acids	56,200.0	7%
	Asbestos waste	61,800.0	7%
	Batteries	17,000.0	7%
	Lime mud	1.0	7%
	Other hazardous waste	55,700.0	7%
	Oxides and hydroxides	89,300.0	3%
	Paints and lacquers	6,680.0	7%
	Paints and lacquers from households	21,200.0	10%
	Salts	5,060.0	3%
	Solvents	47,900.0	7%
	Wash and process water	7,740.0	3%
Paper waste	Paper waste	2,050,000.0	7%
Plastic waste	Other plastic waste	172,000.0	3%
	Plastic waste from households	179,000.0	3%
Residual waste	Residual waste	1,960,000.0	3%
Textile waste	Textile fibers	2,390.0	20%
	Textile sludge	513.0	20%
	Textile waste from households	37,900.0	31%
WEEE	Lighting equipment	1,090.0	3%
	Other WEEE	1,760.0	3%
	Refrigeration appliances	12,800.0	3%

	Waste fractions	Tons	Uncertainty
	Screens	18,700.0	3%
	WEEE big	18,800.0	3%
	WEEE small	27,000.0	3%
Wood waste	Barks	116,000.0	31%
	Chip-board waste	25,900.0	31%
	Construction and demolition waste wood	312,000.0	31%
	Piles	42,200.0	31%
	Railway sleepers	31,000.0	31%
	Sawdust	147,000.0	31%
	Wood packaging	321,000.0	31%
SUM		**17,300,000.0**	

1.1 Composition of the residual and bulky waste

Table S 2. Waste composition residual waste

Waste fraction	*[%]*
Biogenic Waste	17.8
Food waste	9.8
Plastic waste	15.6
Paper waste	10.6
Textiles	5.2
Glass waste	4.2
Metals	4
Wood Waste	1.3
WEEE	0.8
Hazardous Waste from households	0.4
Composite materials	2.6
Sanitary products	15.8
Inert materials	6
Other waste	5.9

Table S 3. Waste composition bulky waste

Waste fraction	*[%]*
Hazardous Waste from households	0.02%
Packaging waste	3.5%
Wood Waste	32.73%
Metals	0.6%
Plastic waste	5.0%
WEEE	0.3%
Furniture	38.9%
Construction waste	4.3%
Sport and leisure equipment	0.4%
Inert materials	3.4%
Residual waste	1.2%
Windows with glass	6.6%
Other waste	3.2%

2 Substance concentration

Table S 4. Substance concentration (Cd, C, Fe, N, and P) in mg/kg and uncertainties (Uncer.).

Waste fraction	Cd		C		Fe		N		P	
	mg/kg	Uncer. [%]	mg/kg	Uncer. [%]	mg/kg	Uncer. [%]	mg/kg	Uncer. [%]	mg/kg	Uncer. [%]
Biogenic waste from households	0.3	11%	184,000.0	11%	3,140.0	11%	10,800.0	11%	1,840.0	11%
Other biogenic waste	0.3	24%	182,000.0	24%	3,160.0	24%	8,300.0	25%	1,620.0	24%
Bulky waste	35.4	4%	164,000.0	4%	608.0	4%	1,210.0	4%	80.6	4%
Concrete demolition waste	0.2	32%	89,000.0	32%	7,000.0	32%	200.0	32%		
Construction waste	0.2	32%	60,000.0	32%	11,000.0	32%	200.0	32%		
Rail-gravel	3.8	32%								
Road surface materials	0.2	32%	89,000.0	32%	7,000.0	32%	200.0	32%		
Drosses	61.0	32%	150,000.0	32%	2,280.0	32%			1.0	32%
Dust and ashes	5.0	32%	500,000.0	32%	21,900.0	32%			38,300.0	32%
Salt slags	3.0	32%	1,000.0	32%	15,300.0	32%				
Slags	108.0	32%			144,000.0	32%			1,540.0	32%
Glass waste from households	0.2	32%	3,000.0	32%	11,800.0	32%	0.0	32%	0.0	32%
Other glass waste	0.2	96%	3,000.0	96%	11,800.0	96%	0.0	96%	0.0	96%
Fly ashes	187.0	4%	20,200.0	4%	15,400.0	4%	830.0	4%	6,280.0	4%
Other Ashes	53.7	4%	15,600.0	4%	38,300.0	4%	207.0	4%	5,230.0	4%
Wood Ashes	1.0	4%			10,600.0	4%			7,800.0	4%
Lime mud	0.2	96%								
Aluminum										
Copper										
Iron and steal	10.0	11%	500.0	11%	715,000.0	11%			300.0	11%
Metal packaging waste	2.0	32%	110,000.0	32%	767,000.0	32%	489.0	32%	49.0	32%
Metal waste from commercial trade and industry	10.0	12%	500.0	12%	669,000.0	11%			300.0	12%
Metal waste from households	4.0	32%	210,000.0	32%	661,000.0	32%	903.0	32%	90.0	32%
Nickel					500.0	32%			500.0	32%
Other metal waste	9.5	32%	476.0	32%	653,000.0	32%			285.0	32%
Zinc										
Filters and wipes	0.1	32%	50,000.0	32%	400.0	32%	12,000.0	32%	10,000.0	32%

Waste fraction	Cd		C		Fe		N		P	
	mg/kg	Uncer. [%]	mg/kg	Uncer. [%]	mg/kg	Uncer. [%]	mg/kg	Uncer. [%]	mg/kg	Uncer. [%]
Oil	0.1	32%	700,000.0	32%	400.0	32%	12,000.0	32%	10,000.0	32%
Oil contaminated soil	0.9	32%	113,000.0	32%	12,700.0	32%	993.0	32%	613.0	32%
Oil-containing drilling muds and wastes	2.8	32%	278,000.0	32%	44,100.0	32%			1,500.0	32%
Other	3.9	32%	750,000.0	32%	29,600.0	32%	1,000.0	32%	30.0	32%
Waste from de-sanding	5.5	32%	120,000.0	32%					1,500.0	32%
Acids	0.0	96%			0.0	96%	9,870.0	96%	0.4	96%
Asbestos waste					39,000.0	32%				
Batteries	305.0	32%	87,000.0	32%	64,000.0	32%	1,000.0	32%	10.0	32%
Lime mud	0.2	96%								
Other hazardous waste	0.5	89%	802.0	89%	5,560.0	89%	11,000.0	89%	70.0	89%
Oxides and hydroxides	33.8	45%	7,000.0	45%	183,000.0	45%			355.0	45%
Paints and lacquers	0.7	70%								
Paints and lacquers from households	20.8	96%			52.8	96%	3,770.0	96%		
Salts	1.2	96%			1,000.0	96%			21,000.0	96%
Solvents	1.1	96%			317.0	96%				
Wash and process water	0.5	32%					7,380.0	32%	391.0	32%
Paper waste	2.0	32%	350,000.0	32%	2,020.0	32%	3,650.0	32%	105.0	32%
Other plastic waste	47.2	33%	593,000.0	34%	15,200.0	96%	7,850.0	33%	956.0	32%
Plastic waste from households	11.0	32%	574,000.0	32%	4,080.0	32%	3,540.0	32%	391.0	32%
Residual waste	6.1	4%	203,000.0	4%	21,200.0	4%	7,270.0	4%	1,000.0	4%
Textile fibers	0.3	32%	683,000.0	32%	2,170.0	32%	23,500.0	32%	764.0	32%
Textile sludge	2.5	32%	357,000.0	32%	2,170.0	32%	23,500.0	32%	764.0	32%
Textile waste from households	2.5	32%	357,000.0	32%	2,170.0	32%	23,500.0	32%	764.0	32%
Lighting equipment	0.1	32%	10,700.0	32%	5,860.0	32%	128.0	32%	5.5	32%
Other WEEE	13.1	96%	154,000.0	96%	149,000.0	96%	2,030.0	96%	275.0	96%
Refrigeration appliances	12.9	96%	159,000.0	96%	164,000.0	96%	2,140.0	96%	264.0	96%
Screens			117,000.0	96%	3,620.0	96%	1,580.0	96%	195.0	96%
WEEE big	15.7	96%	167,000.0	96%	244,000.0	96%	2,060.0	96%	352.0	96%
WEEE small	14.1	96%	174,000.0	96%	185,000.0	96%	2,340.0	96%	288.0	96%
Barks	0.3	11%	514,000.0	11%	150.0	11%	5,500.0	11%	60.0	11%
Chip-board waste	0.4	32%	450,000.0	32%	566.0	32%	4,000.0	32%	119.0	32%
Construction and demolition waste wood	0.4	32%	450,000.0	32%	355.0	32%	4,000.0	32%	219.0	32%

Waste fraction	Cd		C		Fe		N		P	
	mg/kg	Uncer. [%]	mg/kg	Uncer. [%]	mg/kg	Uncer. [%]	mg/kg	Uncer. [%]	mg/kg	Uncer. [%]
Piles	0.4	32%	461,000.0	32%	618.0	32%	3,910.0	32%	94.4	32%
Railway sleepers	0.5	32%	450,000.0	32%	3,700.0	32%	4,000.0	32%	153.0	32%
Sawdust	0.4	22%	465,000.0	22%	453.0	27%	3,400.0	23%	93.8	22%
Wood packaging	0.3	32%	450,000.0	32%	283.0	32%	4,000.0	32%	60.2	32%

Table S 5. Substance concentration (Cr, Cu, Hg, Ni, Pb and Zn) in mg/kg and uncertainties (Uncer.).

Waste fraction	Cr		Cu		Hg		Ni		Pb		Zn	
	mg/kg	US [-]	mg/kg	US [-]	mg/kg	US [-]	mg/kg	US [-]	mg/kg	US [-]	mg/kg	US [-]
Biogenic waste from households	7.5	11%	2.4	909%	0.1	11%	6.9	11%	19.1	11%	74.3	11%
Other biogenic waste	6.9	24%	4.9	409%	0.1	24%	6.3	32%	19.1	24%	70.2	24%
Bulky waste	353.0	4%	8.4	2500%	0.2	4%	4.4	4%	1,280.0	4%	767.0	4%
Concrete demolition waste	15.0	32%	3.8	313%	0.0	32%	22.0	32%	27.0	32%	25.0	32%
Construction waste	40.0	32%	4.8	313%	0.2	32%			40.0	32%	50.0	32%
Rail-gravel	108.0	32%	97.6	313%	0.4	32%	114.0	32%	176.0	32%	420.0	32%
Road surface materials	15.0	32%	3.8	313%	0.0	32%	22.0	32%	27.0	32%	25.0	32%
Drosses	16.5	32%	1,850.0	313%	1.0	32%	607.0	32%	1,000.0	32%	190,000.0	32%
Dust and ashes	143.0	32%	73.3	313%	6.0	32%	72.0	32%	441.0	32%	1,870.0	32%
Salt slags	602.0	32%	1,510.0	313%	2.6	32%	213.0	32%	724.0	32%	2,490.0	32%
Slags	531.0	32%	1,610.0	313%	44.0	32%	209.0	32%	65,800.0	32%	14,200.0	32%
Glass waste from households	3,370.0	32%	0.3	313%	0.0	32%	1.0	32%	0.9	32%	6.0	32%
Other glass waste	3,370.0	96%	1.0	104%	0.0	96%	1.0	96%	0.9	96%	6.0	96%
Fly ashes	390.0	4%	64.0	2500%	14.8	4%	6,180.0	4%	5,110.0	4%	15,200.0	4%
Other Ashes	369.0	4%	153.0	2500%	2.0	4%	198.0	4%	1,970.0	4%	5,710.0	4%
Wood Ashes	69.8	4%	8.1	2500%	0.4	4%	30.7	4%	910.0	4%	1,360.0	4%
Lime mud	8.9	96%	8.8	104%	0.1	96%	3.9	96%	6.0	96%	19.0	96%
Aluminum		0%										
Copper		0%	320,000.0	313%								
Iron and steal	1,300.0	11%	330.0	909%			81,000.0	11%	20.0	11%	500.0	11%
Metal packaging waste	12,400.0	32%	1,920.0	313%			6,900.0	32%		0%		
Metal waste from commercial trade and industry	1,300.0	12%	375.0	801%			81,000.0	12%	20.0	12%	500.0	12%
Metal waste from households	12,400.0	32%	1,920.0	313%			6,900.0	32%		0%		0%

Waste fraction	Cr		Cu		Hg		Ni		Pb		Zn	
	mg/kg	US [-]	mg/kg	US [-]	mg/kg	US [-]	mg/kg	US [-]	mg/kg	US [-]	mg/kg	US [-]
Nickel	500.0	32%	160.0	313%			500,000.0	32%	500.0	32%		0%
Other metal waste	1,250.0	32%	919.0	313%			77,100.0	32%	12,400.0	32%	476.0	32%
Zinc											1,000,000.0	32%
Filters and wipes	2.0	32%	1.0	313%	0.0	32%				0%	10.0	32%
Oil	2.0	32%	1.0	313%	0.0	32%	0.4	32%		0%	10.0	32%
Oil contaminated soil	64.1	32%	41.0	313%	5.7	32%	48.3	32%	56.9	32%	688.0	32%
Oil-containing drilling muds and wastes	304.0	32%	28.1	313%	1.6	32%	68.5	32%	1.0	32%	28.3	32%
Other	318.0	32%	84.5	313%	4.0	32%	40.8	32%	63.3	32%	1,060.0	32%
Waste from de-sanding	204.0	32%	216.0	313%	1.3	32%	234.0	32%			2,540.0	32%
Acids	0.0	96%	12.4	105%	0.3	96%	4.1	96%	1.9	96%	186.0	96%
Asbestos waste												
Batteries	33.4	32%	1,590.0	313%			4.0	32%	484,000.0	32%	262,000.0	32%
Lime mud	8.9	96%	8.8	104%	0.1	96%	3.9	96%	6.0	96%	19.0	96%
Other hazardous waste	20.0	89%	15.2	112%	1.0	89%	5.0	89%	86.0	89%	226.0	89%
Oxides and hydroxides	58,500.0	45%	2,890.0	223%	33.4	45%	92,500.0	45%	9,900.0	45%	23,600.0	45%
Paints and lacquers	6.5	70%	6.0	142%	0.4	70%	9.7	70%	45.8	70%	302.0	70%
Paints and lacquers from households	23.7	96%	261.0	104%	55.2	96%	8.2	96%	288.0	96%	315.0	96%
Salts	10.2	96%	11.9	104%	38.3	96%			46.5	96%	106.0	96%
Solvents	132.0	96%	82.9	104%	3.0	96%	6.9	96%	273.0	96%	120.0	96%
Wash and process water	38.3	32%	47.0	311%	0.2	32%	27.2	32%			255.0	32%
Paper waste	19.0	32%	15.0	313%	0.2	32%	95.8	32%	16.9	32%	22.0	32%
Other plastic waste	101.0	32%	16.7	313%	4.3	32%	14.9	32%	420.0	32%	406.0	32%
Plastic waste from households	62.2	32%	17.7	313%	0.1	32%	21.4	32%	91.7	32%	0.0	32%
Residual waste	180.0	4%	29.2	2490%	0.4	4%	53.5	4%	296.0	4%	713.0	4%
Textile fibers	19.6	32%	28.8	313%	0.2	32%	6.5	32%	14.5	32%	137.0	32%
Textile sludge	180.0	32%	84.3	313%	0.3	32%	7.2	32%	156.0	32%	478.0	32%
Textile waste from households	182.0	32%	84.5	313%	0.3	32%	7.0	32%	155.0	32%	482.0	32%
Lighting equipment	3.6	32%	221.0	313%	1.8	32%	143.0	32%	23.1	32%	24,000.0	32%
Other WEEE	15,300.0	96%	10,900.0	104%	1.1	96%	7,310.0	96%	3,660.0	96%	759.0	96%
Refrigeration appliances	3,460.0	96%	17,500.0	104%	1.2	96%	1,530.0	96%	0.9	96%	113.0	96%
Screens	33.0	96%	3,160.0	104%	0.9	96%	40.8	96%	21,100.0	96%	2,100.0	96%
WEEE big	57,800.0	96%	2,310.0	104%	1.1	96%	27,600.0	96%	120.0	96%	297.0	96%

Waste fraction	Cr		Cu		Hg		Ni		Pb		Zn	
	mg/kg	US [-]	mg/kg	US [-]	mg/kg	US [-]	mg/kg	US [-]	mg/kg	US [-]	mg/kg	US [-]
WEEE small	30.8	96%	20,800.0	104%	1.3	96%	104.0	96%	127.0	96%	522.0	96%
Barks	5.0	11%	0.5	909%	0.0	11%	1.4	11%	3.0	11%	90.0	11%
Chip-board waste	3.7	32%	8.9	313%	0.1	32%	4.1	32%	11.9	32%	22.1	32%
Construction and demolition waste wood	8.9	32%	170.0	313%	0.2	32%	39.1	32%	31.9	32%	124.0	32%
Piles	10.9	32%	79.5	313%	0.1	32%	6.2	32%	14.4	32%	109.0	32%
Railway sleepers	18.8	32%	6.8	313%	0.1	32%	3.0	32%	10.3	32%	69.7	32%
Sawdust	10.0	22%	33.9	363%	0.1	22%	4.6	26%	15.2	21%	88.6	23%
Wood packaging	6.9	32%	1.3	313%	0.2	32%	0.9	32%	12.8	32%	47.4	32%

Table S 6. References for substance concentration.

Waste fraction	References: Estimated from -
Asbestos waste	[3] and general molecular composition of asbestos cement
Construction waste	[4-7]
Concrete demolition waste	[4, 6, 8]
Rail-gravel	[9]
road surface materials	[4, 8, 10]
Batteries	[11, 12]
Biogenic waste	[13-15]
Other WEEE	Mean value of all WEEE
Lighting equipment	[16-18]
Screens	[19, 20]
WEEE small	[20, 21]
WEEE big	[22]
Refrigeration appliances	[20, 23]
Paints and lacquers	[9]
Oils and oil containing waste, filter, wipes,	[9, 24]
Glass waste	[25-28]
Construction and demolition waste wood	[9, 29, 30]
Railway sleepers	[30]
Wood packaging	[29, 30]
Piles	[30]
Barks	[9, 31]
Sawdust	[9, 30]
Wood or slabs / splinters,	[29, 30]
Chip-board waste	[30]
Lime mud	[9]
Plastic waste	[32, 33]
Plastic waste from households	[34, 35]
Lyes	[9]
Solvents	[9]
Metal waste from households	[34, 36, 37]
Metal packaging waste	[27, 35, 38]

Waste fraction	References: Estimated from -
Metal waste from commercial trade and industry,	[9, 39]
Aluminium	Estimated 100% Aluminium
Lead	Estimated 100% Lead
Iron and steal	[9, 39]
Copper	Estimated 100% Copper
Non-iron metals	[39], [9]
Nickel	Estimated 100% Nickel
Other metal waste	[39], [9]
Zinc	Estimated 100% Zinc
Salt slags, slags, metallic dust and ashes, metallic drosses	[9]
Oxides and hydroxides	[9]
Residual waste	[34, 40-45]
Salts	[9]
Acids	[9]
Bulky waste	Composition from [1]; substance concentration from different waste fractions
Textile waste from households	[34, 46]
Textile fibres and sludge	[9]
Fly, wood and other ashes	[30, 47-61]
Contaminated soil	estimated
Washing- and process water,	[9]
Other hazardous waste	[9]
Paper waste from households	[34, 38, 62]
Paper packaging waste and other paper waste	[9]

3 TRANSFER COEFFICIENT

Table S 7. Transfer coefficient (TC) for waste treatment plants (goods, Cd, C, Fe, N, P, Cr, Cu, Hg, Ni, Pb, Zn) and uncertainties (UC).

Processes	Output	Goods		Cd		C		Fe		N		P		Cr		Cu		Hg		Ni		Pb		Zn	
		TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC
Composting plant	Emissions to air	0.52	11%		32%	0.55	32%		32%	0.48	32%		32%							0.52	96%				
	compost	0.36	11%	0.50	32%	0.27	32%		32%	0.46	32%	0.97	32%	0.96	32%	0.67	32%	0.86	32%	0.36	96%	0.59	32%	0.75	32%
	screen overflow to incineration	0.09	11%	0.15	32%	0.18	32%		32%	0.06	32%	0.03	32%	0.04	32%	0.01	32%	0.02	32%	0.09	96%	0.17	32%	0.03	32%
	Waste to incineration (GF)	0.01	11%	0.12	32%		32%		32%		32%		32%			0.10	32%	0.04	32%	0.01	96%	0.08	32%	0.07	32%
	Waste to incineration (FBC)	0.01	11%	0.12	32%		32%		32%		32%		32%			0.10	32%	0.04	32%	0.01	96%	0.08	32%	0.07	32%
	Scrap to shredder	0.01	11%	0.12	32%		32%	1.00	32%		32%		32%			0.10	32%	0.04	32%	0.01	96%	0.08	32%	0.07	32%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
Biogas plant	Emissions to air	0.02	11%		32%	0.01	32%		32%	0.04	32%		32%					0.02	96%	0.02	96%				
	Biogas	0.12	11%		32%	0.54	32%		32%		32%		32%					0.12	96%	0.12	96%				
	Liquid digestate	0.79	11%	0.32	32%	0.40	32%		32%	0.95	32%	0.96	32%	0.95	32%	0.65	32%	0.79	96%	0.79	96%	0.52	32%	0.72	32%
	Digestate compost	0.02	11%	0.07	32%	0.04	32%		32%	0.01	32%	0.04	32%	0.05	32%	0.06	32%	0.02	96%	0.02	96%	0.04	32%	0.05	32%
	Waste to incineration (GF)	0.02	11%	0.23	32%		32%		32%		32%		32%			0.11	32%	0.02	96%	0.02	96%	0.16	32%	0.09	32%
	Waste to incineration (FBC)	0.02	11%	0.23	32%		32%		32%		32%		32%			0.11	32%	0.02	96%	0.02	96%	0.16	32%	0.09	32%
	Scrap to shredder	0.01	11%	0.15	32%		32%	1.00	32%		32%		32%			0.07	32%	0.01	96%	0.01	96%	0.11	32%	0.06	32%
	screen overflow to incineration	0.00	11%	0.01	32%	0.00	32%		32%	0.00	32%	0.00	32%	0.00	32%	0.00	32%	0.00	96%	0.00	96%	0.01	32%	0.00	32%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
Mechanical biological treatment	Emissions to water	0.04	4%	0.00	11%		11%		11%		11%		11%												
	Emissions to air	0.16	4%		11%	0.13	11%		11%	0.16	11%		11%												
	Waste export	0.00	4%		11%		11%		11%		11%		11%												
	Scrap to shredder	0.04	4%	0.68	11%	0.01	11%	0.75	11%	0.01	11%	0.02	11%	0.20	11%	0.10	11%	0.01	11%	0.26	11%	0.04	11%	0.14	11%
	Waste to incineration (GF)	0.27	4%	0.14	11%	0.38	11%	0.07	11%	0.35	11%	0.14	11%	0.30	11%	0.40	11%	0.45	11%	0.17	11%	0.41	11%	0.35	11%
	Waste to incineration (FBC)	0.27	4%	0.14	11%	0.38	11%	0.07	11%	0.35	11%	0.14	11%	0.30	11%	0.40	11%	0.45	11%	0.17	11%	0.41	11%	0.35	11%
	Waste to landfill	0.24	4%	0.04	11%	0.09	11%	0.10	11%	0.13	11%	0.71	11%	0.21	11%	0.11	11%	0.09	11%	0.40	11%	0.14	11%	0.15	11%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
Organic – chemical-physical treatment	Emissions to water	0.01	32%	0.01	96%	0.05	96%		96%	0.10	96%	0.05	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%	0.05	96%
	Waste to incineration (FBC)	0.16	32%	0.16	96%	0.16	96%		96%	0.15	96%	0.16	96%	0.16	96%	0.16	96%	0.16	96%	0.16	96%	0.16	96%	0.16	96%
	Waste to incineration (RK)	0.16	32%	0.16	96%	0.16	96%		96%	0.15	96%	0.16	96%	0.16	96%	0.16	96%	0.16	96%	0.16	96%	0.16	96%	0.16	96%
	Waste to landfill	0.66	32%	0.66	96%	0.64	96%	1.00	96%	0.60	96%	0.64	96%	0.66	96%	0.66	96%	0.66	96%	0.66	96%	0.66	96%	0.64	96%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
Inorganic – chemical-	Emissions to water	0.01	32%	0.01	96%	0.01	96%		96%	0.01	96%	0.05	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%
	Emissions to soil	0.01	32%	0.01	96%	0.01	96%		96%	0.01	96%	0.00	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%

Processes	Output	Goods		Cd		C		Fe		N		P		Cr		Cu		Hg		Ni		Pb		Zn	
		TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC
physical treatment	emissions to air	0.01	32%	0.01	96%	0.01	96%		96%	0.01	96%	0.00	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%
	Waste to landfill	0.97	32%	0.97	96%	0.97	96%	1.00	96%	0.97	96%	0.95	96%	0.97	96%	0.97	96%	0.97	96%	0.97	96%	0.97	96%	0.97	96%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
Organic and Inorganic – chemical-physical treatment	Emissions to water	0.01	32%	0.01	96%	0.05	96%		96%	0.10	96%	0.05	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%	0.01	96%	0.05	96%
	Waste to landfill	0.99	32%	0.99	96%	0.95	96%	1.00	96%	0.90	96%	0.95	96%	0.99	96%	0.99	96%	0.99	96%	0.99	96%	0.99	96%	0.95	96%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
MSW Incineration grate furnace	Iron scrap to shredder	0.02	4%	0.25	11%	0.00	11%	0.69	11%	0.00	11%	0.00	11%	0.13	11%	0.03	11%	0.00	11%	0.15	11%	0.00	11%	0.00	11%
	Slags recovery	0.07	4%	0.04	11%	0.00	11%	0.09	11%	0.00	11%	0.25	11%	0.25	11%	0.28	11%	0.05	11%	0.25	11%	0.20	11%	0.19	11%
	Slags to landfill	0.10	4%	0.05	11%	0.01	11%	0.12	11%	0.01	11%	0.35	11%	0.35	11%	0.39	11%	0.06	11%	0.35	11%	0.29	11%	0.27	11%
	Slags to CPT	0.07	4%	0.03	11%	0.00	11%	0.08	11%	0.00	11%	0.23	11%	0.23	11%	0.26	11%	0.04	11%	0.23	11%	0.19	11%	0.18	11%
	Ashes recovery	0.01	4%	0.19	11%	0.00	11%	0.00	11%	0.00	11%	0.05	11%	0.01	11%	0.01	11%	0.09	11%	0.01	11%	0.09	11%	0.10	11%
	Ashes to landfill	0.01	4%	0.26	11%	0.00	11%	0.00	11%	0.00	11%	0.07	11%	0.02	11%	0.01	11%	0.13	11%	0.01	11%	0.13	11%	0.15	11%
	Ashes to CPT	0.01	4%	0.17	11%	0.00	11%	0.00	11%	0.00	11%	0.05	11%	0.01	11%	0.01	11%	0.08	11%	0.01	11%	0.09	11%	0.10	11%
	Filter cake - export	0.00	4%	0.01	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.49	11%	0.00	11%	0.00	11%	0.00	11%
	Emissions to water	0.00	4%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%
	Emissions to air	0.70	4%	0.00	11%	0.98	11%	0.01	11%	0.98	11%	0.00	11%	0.00	11%	0.00	11%	0.05	11%	0.00	11%	0.00	11%	0.00	11%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
MSW Incineration fluidised bed combustion	Ashes recovery	0.06	4%	0.30	11%	0.00	11%	0.30	11%	0.00	11%	0.25	11%	0.30	11%	0.30	11%	0.09	11%	0.30	11%	0.30	11%	0.30	11%
	Ashes to landfill	0.08	4%	0.42	11%	0.00	11%	0.42	11%	0.00	11%	0.35	11%	0.42	11%	0.42	11%	0.13	11%	0.41	11%	0.42	11%	0.42	11%
	Ashes to CPT	0.06	4%	0.28	11%	0.00	11%	0.28	11%	0.00	11%	0.23	11%	0.28	11%	0.28	11%	0.09	11%	0.28	11%	0.28	11%	0.28	11%
	Filter cake - export	0.02	4%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.17	11%	0.00	11%	0.01	11%	0.66	11%	0.01	11%	0.00	11%	0.00	11%
	Emissions to water	0.00	4%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%	0.00	11%
	Emissions to air	0.79	4%	0.00	11%	0.99	11%	0.00	11%	0.99	11%	0.00	11%	0.00	11%	0.00	11%	0.03	11%	0.00	11%	0.00	11%	0.00	11%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
Cement rotary kilns	cement	0.29	32%	0.99	32%	0.01	32%	1.00	32%	0.01	32%	1.00	32%	1.00	32%	1.00	32%	0.66	32%	1.00	32%	1.00	32%	1.00	32%
	Emissions to air	0.71	32%	0.01	32%	0.99	32%		32%	0.99	32%	0.00	32%	0.00	32%	0.00	32%	0.34	32%	0.00	32%	0.00	32%	0.00	32%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
Co-incineration wood industry	Ashes recovery	0.01	32%	0.01	96%	0.00	96%	1.00	96%	0.00	96%	0.15	96%	0.16	96%	0.01	96%	0.00	96%	0.16	96%	0.02	96%	0.03	96%
	Ashes to landfill	0.02	32%	0.01	96%	0.00	96%		96%	0.00	96%	0.21	96%	0.23	96%	0.02	96%	0.00	96%	0.22	96%	0.03	96%	0.04	96%
	Ashes to CPT	0.01	32%	0.01	96%	0.00	96%		96%	0.00	96%	0.14	96%	0.15	96%	0.01	96%	0.00	96%	0.15	96%	0.02	96%	0.02	96%
	Zyklon Ashes recovery	0.00	32%	0.12	96%	0.00	96%		96%	0.00	96%	0.12	96%	0.10	96%	0.00	96%	0.02	96%	0.12	96%	0.07	96%	0.11	96%
	Zyklon Ashes to landfill	0.01	32%	0.17	96%	0.00	96%		96%	0.00	96%	0.17	96%	0.15	96%	0.01	96%	0.02	96%	0.17	96%	0.10	96%	0.15	96%
	Zyklon Ashes to CPT	0.00	32%	0.11	96%	0.00	96%		96%	0.00	96%	0.12	96%	0.10	96%	0.00	96%	0.02	96%	0.11	96%	0.07	96%	0.10	96%
	Fly Ashes recovery	0.00	32%	0.00	96%	0.00	96%		96%	0.00	96%	0.00	96%	0.00	96%	0.00	96%	0.00	96%	0.00	96%	0.00	96%	0.00	96%
	Fly Ashes to landfill	0.00	32%	0.16	96%	0.00	96%		96%	0.00	96%	0.05	96%	0.06	96%	0.00	96%	0.19	96%	0.03	96%	0.19	96%	0.18	96%
	Fly Ashes to CPT	0.00	32%	0.16	96%	0.00	96%		96%	0.00	96%	0.05	96%	0.06	96%	0.00	96%	0.19	96%	0.03	96%	0.19	96%	0.18	96%
	Emissions to air	0.94	32%	0.25	96%	0.99	96%		96%	0.99	96%	0.00	96%	0.00	96%	0.94	96%	0.55	96%	0.00	96%	0.30	96%	0.20	96%

Processes	Output	Goods		Cd		C		Fe		N		P		Cr		Cu		Hg		Ni		Pb		Zn	
		TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
Co-incineration paper industry	Fly Ashes recovery	0.10	32%	0.29	96%	0.00	96%	1.00	96%	0.00	96%	0.10	96%	0.27	96%	0.10	96%	0.23	96%	0.27	96%	0.28	96%	0.27	96%
	Fly Ashes to landfill	0.14	32%	0.40	96%	0.00	96%		96%	0.00	96%	0.14	96%	0.38	96%	0.14	96%	0.32	96%	0.38	96%	0.40	96%	0.38	96%
	Fly Ashes to CPT	0.09	32%	0.27	96%	0.00	96%		96%	0.00	96%	0.09	96%	0.25	96%	0.09	96%	0.21	96%	0.25	96%	0.26	96%	0.25	96%
	Ashes recovery		32%	0.00	96%	0.00	96%		96%	0.00	96%		96%	0.03	96%			0.02	96%	0.03	96%	0.02	96%	0.03	96%
	Ashes to landfill		32%	0.01	96%	0.00	96%		96%	0.00	96%		96%	0.04	96%			0.02	96%	0.04	96%	0.02	96%	0.04	96%
	Ashes to CPT		32%	0.00	96%	0.00	96%		96%	0.00	96%		96%	0.03	96%			0.01	96%	0.03	96%	0.01	96%	0.02	96%
	Emissions to air	0.68	32%	0.02	96%	0.99	96%		96%	0.98	96%	0.68	96%	0.00	96%	0.68	96%	0.20	96%	0.00	96%	0.00	96%	0.01	96%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
Other incineration fluidized bed combustion	Ashes recovery	0.05	11%	0.20	32%	0.00	32%	0.30	32%	0.00	32%	0.25	32%	0.30	32%	0.30	32%	0.01	32%	0.30	32%	0.29	32%	0.30	32%
	Ashes to landfill	0.07	11%	0.28	32%	0.00	32%	0.42	32%	0.00	32%	0.35	32%	0.42	32%	0.42	32%	0.01	32%	0.41	32%	0.41	32%	0.41	32%
	Ashes to CPT	0.05	11%	0.19	32%	0.00	32%	0.28	32%	0.00	32%	0.23	32%	0.28	32%	0.28	32%	0.01	32%	0.28	32%	0.27	32%	0.28	32%
	Filter cake - export	0.00	11%	0.33	32%	0.00	32%	0.00	32%	0.00	32%	0.17	32%	0.00	32%	0.01	32%	0.97	32%	0.01	32%	0.02	32%	0.01	32%
	Emissions to water	0.00	11%	0.00	32%	0.00	32%	0.00	32%	0.00	32%	0.00	32%	0.00	32%	0.00	32%	0.00	32%	0.00	32%	0.00	32%	0.00	32%
	Emissions to air	0.82	11%	0.00	32%	0.99	32%	0.00	32%	0.99	32%	0.00	32%	0.00	32%	0.00	32%	0.01	32%	0.00	32%	0.00	32%	0.00	32%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
Other incineration rotary kiln	Slags recovery	0.06	11%	0.02	32%	0.00	32%	0.21	32%	0.00	32%	0.25	32%	0.28	32%	0.23	32%	0.01	32%	0.25	32%	0.16	32%	0.12	32%
	Slags to landfill	0.09	11%	0.02	32%	0.01	32%	0.30	32%	0.01	32%	0.35	32%	0.39	32%	0.32	32%	0.01	32%	0.34	32%	0.22	32%	0.16	32%
	Slags to CPT	0.06	11%	0.01	32%	0.00	32%	0.20	32%	0.00	32%	0.23	32%	0.26	32%	0.21	32%	0.01	32%	0.23	32%	0.15	32%	0.11	32%
	Ashes recovery	0.01	11%	0.25	32%	0.00	32%	0.01	32%	0.00	32%		32%	0.02	32%	0.05	32%	0.03	32%	0.04	32%	0.14	32%	0.18	32%
	Ashes to landfill	0.01	11%	0.35	32%	0.00	32%	0.01	32%	0.00	32%		32%	0.03	32%	0.07	32%	0.05	32%	0.05	32%	0.20	32%	0.25	32%
	Ashes to CPT	0.01	11%	0.23	32%	0.00	32%	0.01	32%	0.00	32%		32%	0.02	32%	0.04	32%	0.03	32%	0.04	32%	0.13	32%	0.17	32%
	Filter cake - export	0.01	11%	0.12	32%	0.00	32%	0.00	32%	0.00	32%	0.17	32%	0.00	32%	0.00	32%	0.86	32%	0.00	32%	0.00	32%	0.01	32%
	Iron scrap to shredder	0.02	11%	0.00	32%	0.00	32%	0.27	32%	0.00	32%	0.00	32%	0.01	32%	0.08	32%	0.00	32%	0.05	32%	0.00	32%	0.00	32%
	Emissions to water	0.00	11%	0.00	32%	0.00	32%	0.00	32%	0.00	32%	0.00	32%	0.00	32%		32%	0.00	32%	0.00	32%	0.00	32%	0.00	32%
	Emissions to air	0.73	11%	0.00	32%	0.98	32%	0.00	32%	0.98	32%	0.00	32%	0.00	32%		32%	0.00	32%		32%	0.00	32%		32%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
MSW Sorting (mechanical treatment to produce secondary fuels)	Scrap to shredder	0.05	0.32	0.70	0.32	0.00	0.32	0.57	0.32	0.00	0.32	0.06	0.32	0.05	0.96	0.05	0.96	0.05	0.05	0.05	0.96	0.05	0.96	0.05	0.96
	Waste to incineration	0.70	0.32	0.12	0.32	0.60	0.32	0.27	0.32	0.51	0.32	0.41	0.32	0.65	0.96	0.65	0.96	0.65	0.65	0.65	0.96	0.65	0.96	0.65	0.96
	Waste to landfill	0.10	0.32	0.04	0.32	0.01	0.32	0.03	0.32	0.10	0.32	0.11	0.32	0.10	0.96	0.10	0.96	0.10	0.10	0.10	0.96	0.10	0.96	0.10	0.96
	Waste to MBT	0.15	0.32	0.15	0.32	0.40	0.32	0.13	0.32	0.39	0.32	0.43	0.32	0.20	0.96	0.20	0.96	0.20	0.20	0.20	0.96	0.20	0.96	0.20	0.96
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	1.00	1.00		1.00		1.00	
C&D processing facilities	Product	0.91	32%	0.92	32%	0.91	32%	0.91	32%	0.91	32%	0.90	32%	0.89	32%	0.92	32%	0.91	96%	0.93	32%	0.91	96%	0.91	96%
	Waste to incineration (GF)	0.02	32%	0.00	32%	0.02	32%	0.00	32%	0.02	32%	0.05	32%					0.02	96%			0.02	96%	0.02	96%
	Waste to landfill	0.04	32%	0.04	32%	0.04	32%	0.05	32%	0.04	32%	0.03	32%	0.06	32%	0.04	32%	0.04	96%	0.04	32%	0.04	96%	0.04	96%
	Waste to landfill	0.04	32%	0.04	32%	0.04	32%	0.05	32%	0.04	32%	0.03	32%	0.06	32%	0.04	32%	0.04	96%	0.04	32%	0.04	96%	0.04	96%
	SUMS	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	

Processes	Output	Goods		Cd		C		Fe		N		P		Cr		Cu		Hg		Ni		Pb		Zn	
		TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC
Shredder	*Product*	*0.95*	*32%*	0.70	*32%*	0.10	*32%*	0.98	*32%*	0.90	*32%*	0.90	*32%*	*0.95*	*32%*	*0.95*	*32%*	*0.95*	*32%*	*0.95*	*32%*	*0.95*	*32%*	*0.95*	*32%*
	Waste to incineration (GF)	*0.01*	*32%*	*0.08*	*32%*	*0.23*	*32%*	*0.01*	*32%*	*0.03*	*32%*	*0.03*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*
	Waste to incineration (FBC)	*0.01*	*32%*	*0.08*	*32%*	*0.23*	*32%*	*0.01*	*32%*	*0.03*	*32%*	*0.03*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*
	Waste to incineration (P)	*0.01*	*32%*	*0.05*	*32%*	*0.16*	*32%*	*0.00*	*32%*	*0.02*	*32%*	*0.02*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*
	Waste to incineration (W)	*0.01*	*32%*	*0.04*	*32%*	*0.12*		*0.00*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*
	Waste to incineration (C)	*0.01*	*32%*	*0.06*	*32%*	*0.17*	*32%*	*0.00*	*32%*	*0.02*	*32%*	*0.02*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*
	SUMS	***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***	
Paper processing facilities	*Product*	*0.74*	*11%*	*0.74*	*32%*	0.74	*32%*	0.74	*32%*	0.74	*32%*	0.74	*32%*	*0.74*	*96%*	*0.74*	*96%*	*0.74*	*96%*	*0.74*	*96%*	*0.74*	*96%*	*0.74*	*96%*
	Waste export	*0.24*	*11%*	*0.24*	*32%*	0.24	*32%*	0.24	*32%*	0.24	*32%*	0.24	*32%*	*0.24*	*96%*	*0.24*	*96%*	*0.24*	*96%*	*0.24*	*96%*	*0.24*	*96%*	*0.24*	*96%*
	Waste to incineration (GF)	*0.01*	*11%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Waste to incineration (FBC)	*0.01*	*11%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Waste to incineration (P)	*0.00*	*11%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*
	Waste to incineration (W)	*0.00*	*11%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*
	Waste to incineration (C)	*0.00*	*11%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*
	SUMS	***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***	
Glass processing facilities	*Product*	*0.74*	*11%*	*0.74*	*32%*	*0.00*	*32%*	*0.66*	*32%*	*0.74*	*32%*	*0.74*	*32%*	*0.76*	*32%*	*0.74*	*96%*	*0.74*	*96%*	*0.74*	*96%*	*0.74*	*96%*	*0.74*	*96%*
	Waste export	*0.20*	*11%*	*0.20*	*32%*	*0.20*	*32%*	*0.20*	*32%*	*0.20*	*32%*	*0.20*	*32%*	*0.20*	*32%*	*0.20*	*96%*	*0.20*	*96%*	*0.20*	*96%*	*0.20*	*96%*	*0.20*	*96%*
	Waste to incineration (GF)	*0.01*	*11%*	*0.01*	*32%*	*0.20*	*32%*	*0.04*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Waste to incineration (FBC)	*0.01*	*11%*	*0.01*	*32%*	*0.20*	*32%*	*0.04*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Waste to incineration (P)	*0.01*	*11%*	*0.01*	*32%*	*0.14*	*32%*	*0.02*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Waste to incineration (W)	*0.01*	*11%*	*0.01*	*32%*	*0.11*	*32%*	*0.02*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Waste to incineration (C)	*0.01*	*11%*	*0.01*	*32%*	*0.15*	*32%*	*0.03*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	SUMS	***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***	
Metal packaging processing facilities	*Product*	*0.85*	*11%*		*32%*	*0.02*	*32%*	*1.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.85*	*96%*	*0.85*	*96%*	*0.85*	*96%*	*0.85*	*96%*	*0.85*	*96%*	*0.85*	*96%*
	Scrap to shredder	*0.15*	*11%*	1.00	*32%*	*0.98*	*32%*	*0.00*	*32%*	*1.00*	*32%*	*1.00*	*32%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*
	SUMS	***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***	
Scrap metal processing facilities	*Product*	*0.00*	*11%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*	*0.00*	*32%*
	Scrap to shredder	*1.00*	*11%*	*1.00*	*32%*	*1.00*	*32%*	*1.00*	*32%*	*1.00*	*32%*	*1.00*	*32%*	*1.00*	*32%*	*1.00*	*32%*	*1.00*	*32%*	*1.00*	*32%*	*1.00*	*32%*	*1.00*	*32%*
	SUMS	***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***	
Metal processing facilities	*Product*	*0.68*	*11%*	*0.68*	*32%*	*0.68*	*32%*	*0.68*	*32%*	*0.68*	*32%*	*0.68*	*32%*	*0.68*	*32%*	*0.68*	*32%*	*0.68*	*32%*	*0.68*	*32%*	*0.68*	*32%*	*0.68*	*32%*
	Scrap to shredder	*0.32*	*11%*	*0.32*	*32%*	*0.32*	*32%*	*0.32*	*32%*	*0.32*	*32%*	*0.32*	*32%*	*0.32*	*32%*	*0.32*	*32%*	*0.32*	*32%*	*0.32*	*32%*	*0.32*	*32%*	*0.32*	*32%*
	SUMS	***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***	
Wood processing facilities	*Product*	*0.55*	*11%*	*0.56*	*32%*	*0.55*	*32%*	*0.53*	*32%*	*0.55*	*32%*	*0.55*	*32%*	*0.55*	*32%*	*0.54*	*32%*	*0.54*	*32%*	*0.55*	*32%*	*0.56*	*32%*	*0.55*	*32%*
	Waste to incineration (GF)	*0.11*	*11%*	*0.11*	*32%*	*0.11*	*32%*	*0.12*	*32%*	*0.11*	*32%*	*0.11*	*32%*	*0.11*	*32%*	*0.11*	*32%*	*0.11*	*32%*	*0.11*	*32%*	*0.11*	*32%*	*0.11*	*32%*
	Waste to incineration (FBC)	*0.11*	*11%*	*0.11*	*32%*	*0.11*	*32%*	*0.12*	*32%*	*0.11*	*32%*	*0.11*	*32%*	*0.11*	*32%*	*0.11*	*32%*	*0.11*	*32%*	*0.11*	*32%*	*0.11*	*32%*	*0.11*	*32%*
	Waste to incineration (P)	*0.08*	*11%*	*0.08*	*32%*	*0.08*	*32%*	*0.08*	*32%*	*0.08*	*32%*	*0.08*	*32%*	*0.08*	*32%*	*0.08*	*32%*	*0.08*	*32%*	*0.08*		*0.08*	*32%*	*0.08*	*32%*
	Waste to incineration (W)	*0.06*	*11%*	*0.06*	*32%*	*0.06*	*32%*	*0.06*	*32%*	*0.06*	*32%*	*0.06*	*32%*	*0.06*	*32%*	*0.06*	*32%*	*0.06*	*32%*	*0.06*		*0.06*	*32%*	*0.06*	*32%*

Processes	Output	Goods		Cd		C		Fe		N		P		Cr		Cu		Hg		Ni		Pb		Zn	
		TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC
	Waste to incineration (C)	*0.08*	*11%*	*0.08*	*32%*	*0.08*	*32%*	*0.09*	*32%*	*0.09*	*32%*	*0.09*	*32%*	*0.08*	*32%*	*0.09*	*32%*	*0.09*	*32%*	*0.09*	*32%*	*0.08*	*32%*	*0.08*	*32%*
	SUMS	*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*	
Plastic waste (HH)processing facilities	*Product*	*0.75*	*11%*	*0.82*	*32%*	*0.83*	*32%*	*0.34*	*32%*	*0.63*	*32%*	*0.57*	*32%*	*0.75*	*96%*	*0.75*	*96%*	*0.75*	*96%*	*0.75*	*96%*	*0.75*	*96%*	*0.75*	*96%*
	Waste export	*0.05*	*11%*	*0.05*	*32%*	*0.06*	*32%*	*0.02*	*32%*	*0.05*	*32%*	*0.04*	*32%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*
	Waste to incineration (GF)	*0.05*	*11%*	*0.03*	*32%*	*0.03*	*32%*	*0.16*	*32%*	*0.08*	*32%*	*0.10*	*32%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*
	Waste to incineration (FBC)	*0.05*	*11%*	*0.03*	*32%*	*0.03*	*32%*	*0.16*	*32%*	*0.08*	*32%*	*0.10*	*32%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*
	Waste to incineration (P)	*0.04*	*11%*	*0.02*	*32%*	*0.02*	*32%*	*0.11*	*32%*	*0.06*	*32%*	*0.07*		*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*
	Waste to incineration (W)	*0.03*	*11%*	*0.02*	*32%*	*0.01*	*32%*	*0.09*	*32%*	*0.04*	*32%*	*0.05*		*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*
	Waste to incineration (C)	*0.04*	*11%*	*0.02*	*32%*	*0.02*	*32%*	*0.12*	*32%*	*0.06*	*32%*	*0.07*	*32%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*
	SUMS	*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*	
Plastic waste processing facilities	*Product*	*0.60*	*32%*	*0.60*	*96%*	*0.60*	*96%*	*0.60*	*96%*	*0.60*	*96%*	*0.60*	*96%*	*0.60*	*96%*	*0.60*	*96%*	*0.60*	*96%*	*0.60*	*96%*	*0.60*	*96%*	*0.60*	*96%*
	Waste to incineration (GF)	*0.10*	*32%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*
	Waste to incineration (FBC)	*0.10*	*32%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*	*0.10*	*96%*
	Waste to incineration (P)	*0.07*	*32%*	*0.07*	*96%*	*0.07*	*96%*	*0.07*	*96%*	*0.07*	*96%*	*0.07*	*96%*	*0.07*	*96%*	*0.07*	*96%*	*0.07*	*96%*	*0.07*	*96%*	*0.07*	*96%*	*0.07*	*96%*
	Waste to incineration (W)	*0.05*	*32%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*
	Waste to incineration (C)	*0.08*	*32%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*
	SUMS	*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*	
Textile waste processing facilities	*Product*	*0.40*	*96%*	*0.40*	*96%*	*0.40*	*96%*	*0.40*	*96%*	*0.40*	*96%*	*0.40*	*96%*	*0.40*	*96%*	*0.40*	*96%*	*0.40*	*96%*	*0.40*	*96%*	*0.40*	*96%*	*0.40*	*96%*
	Waste to incineration (GF)	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*
	Waste to incineration (FBC)	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*	*0.15*	*96%*
	Waste to incineration (P)	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*
	Waste to incineration (W)	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*	*0.08*	*96%*
	Waste to incineration (C)	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*	*0.11*	*96%*
	SUMS	*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*	
WEEE Screens processing facilities	*Product*	*0.12*	*32%*	*0.12*	*96%*	*0.12*	*96%*	*0.12*	*96%*	*0.12*	*96%*	*0.12*	*96%*	*0.12*	*96%*	*0.95*	*96%*	*0.12*	*96%*	*0.12*	*96%*	*0.12*	*96%*	*0.95*	*96%*
	Waste to incineration (GF)	*0.04*	*32%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.01*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.01*	*96%*
	Waste to incineration (FBC)	*0.04*	*32%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.01*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.04*	*96%*	*0.01*	*96%*
	Waste to incineration (P)	*0.02*	*32%*	*0.02*	*96%*	*0.02*	*96%*	*0.02*	*96%*	*0.02*	*96%*	*0.02*	*96%*	*0.02*	*96%*	*0.01*	*96%*	*0.02*	*96%*	*0.02*	*96%*	*0.02*	*96%*	*0.01*	*96%*
	Waste to incineration (W)	*0.02*	*32%*	*0.02*	*96%*	*0.02*	*96%*	*0.02*	*96%*	*0.02*	*96%*	*0.02*	*96%*	*0.02*	*96%*	*0.01*	*96%*	*0.02*	*96%*	*0.02*	*96%*	*0.02*	*96%*	*0.01*	*96%*
	Waste to incineration (C)	*0.03*	*32%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.01*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.01*	*96%*
	Waste export	*0.71*	*32%*	*0.71*	*96%*	*0.71*	*96%*	*0.71*	*96%*	*0.71*	*96%*	*0.71*	*96%*	*0.71*	*96%*	*0.00*	*96%*	*0.71*	*96%*	*0.71*	*96%*	*0.71*	*96%*	*0.00*	*96%*
	Unknown	*0.03*	*32%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.00*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.03*	*96%*	*0.00*	*96%*
	SUMS	*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*	
WEEE Refrigerators processing facilities	*Emission to air*	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*		*0.00*		*0.00*	*96%*	*0.00*		*0.00*	*96%*	*0.00*	*96%*
	Product	*0.68*	*32%*	*0.68*	*96%*	*0.68*	*96%*	*0.68*	*96%*	*0.68*	*96%*	*0.68*	*96%*	*0.95*	*96%*	*0.95*	*96%*	*0.68*	*96%*	*0.68*	*96%*	*0.68*	*96%*	*0.68*	*96%*
	Waste export	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.00*		*0.00*		*0.01*	*96%*	*0.01*		*0.01*	*96%*	*0.01*	*96%*
	Waste to incineration (GF)	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*

Processes	Output	Goods		Cd		C		Fe		N		P		Cr		Cu		Hg		Ni		Pb		Zn	
		TC	*UC*	*TC*	*UC*	*TC*	*UC*	*TC*	*UC*	*TC*	*UC*	*TC*	*UC*	*TC*	*UC*	*TC*	*UC*	*TC*	*UC*	*TC*	*UC*	*TC*	*UC*	*TC*	*UC*
	Waste to incineration (FBC)	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Waste to incineration (P)	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Waste to incineration (W)	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Waste to incineration (C)	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Unknown	*0.27*	*32%*	*0.27*	*96%*	*0.27*	*96%*	*0.27*	*96%*	*0.27*	*96%*	*0.27*	*96%*					*0.27*	*96%*	*0.27*		*0.27*	*96%*	*0.27*	*96%*
	SUMS	***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***	
	Emission to air	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*			*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*
	Product	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*			*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Waste export	*0.93*	*32%*	*0.93*	*96%*	*0.93*	*96%*	*0.93*	*96%*	*0.93*	*96%*	*0.93*	*96%*	*0.93*	*96%*	*0.93*	*96%*	*0.83*	*96%*	*0.93*	*96%*	*0.93*	*96%*	*0.93*	*96%*
	Waste to incineration (GF)	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.04*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*
WEEE lighting processing facilities	*Waste to incineration (FBC)*	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.04*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*
	Waste to incineration (P)	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.03*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*
	Waste to incineration (W)	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.02*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*
	Waste to incineration (C)	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.03*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*
	Unknown	*0.06*	*32%*	*0.06*	*96%*	*0.06*	*96%*	*0.06*	*96%*	*0.06*	*96%*	*0.06*	*96%*	*0.06*	*96%*	*0.06*	*96%*	*0.00*		*0.06*	*96%*	*0.06*	*96%*	*0.06*	*96%*
	SUMS	***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***	
	Product	*0.45*	*32%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.95*	*96%*
	Waste to incineration (GF)	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Waste to incineration (FBC)	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
WEEE big processing facilities	*Waste to incineration (P)*	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.01*	*96%*
	Waste to incineration (W)	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.01*	*96%*
	Waste to incineration (C)	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.01*	*96%*
	Unknown	*0.53*	*32%*	*0.53*	*96%*	*0.53*	*96%*	*0.53*	*96%*	*0.53*	*96%*	*0.53*	*96%*	*0.53*	*96%*	*0.53*		*0.53*	*96%*	*0.53*	*96%*	*0.53*	*96%*		
	SUMS	***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***	
	Product	*0.45*	*32%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.95*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.95*	*96%*
	Waste to incineration (GF)	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
	Waste to incineration (FBC)	*0.01*	*32%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*	*0.01*	*96%*
WEEE small processing facilities	*Waste to incineration (P)*	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.01*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.01*	*96%*
	Waste to incineration (W)	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.01*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.01*	*96%*
	Waste to incineration (C)	*0.00*	*32%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.01*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.00*	*96%*	*0.01*	*96%*
	Unknown	*0.53*	*32%*	*0.53*	*96%*	*0.53*	*96%*	*0.53*	*96%*	*0.53*	*96%*	*0.53*	*96%*	*0.53*	*96%*			*0.53*	*96%*	*0.53*	*96%*	*0.53*	*96%*		
	SUMS	***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***	
	Product	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*
microbiological treatment of soil	*Emissions to air*	*0.05*	*96%*	*0.05*	*96%*	*0.90*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*	*0.05*	*96%*
	Waste to landfill	*0.45*	*96%*	*0.45*	*96%*	*0.03*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*
	Waste to landfill	*0.45*	*96%*	*0.45*	*96%*	*0.03*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*	*0.45*	*96%*
	SUMS	*1.00*		***1.00***		***1.00***		***1.00***		***1.00***		***1.00***		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*	

Processes	Output	Goods		Cd		C		Fe		N		P		Cr		Cu		Hg		Ni		Pb		Zn	
		TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC	TC	UC
Packaging asbestos waste	*Waste to landfill*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*
	Waste to landfill	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*	*0.50*	*32%*
	SUMS	*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*		*1.00*	

GF: grate furnace, FBC: fluidised bed combustion, RK: rotary kiln, P: paper industry, H: wood industry, C: cement rotary kilns

Table S 8. References for Transfer coefficients.

Processes	References
Composting plant	[13, 14, 63, 64]
Biogas plant	[13, 14, 63, 64]
Mechanical biological treatment	Personnel interviews, [65-80]
Organic – chemical-physical treatment	Personnel interviews and expert estimation
Inorganic – chemical-physical treatment	
Organic and Inorganic – chemical-physical treatment	
MSW Incineration grate furnace	[81, 38, 82, 54, 56]
MSW Incineration fluidised bed combustion	[81, 38 83, 82]
Cement rotary kilns	[38 84 85 83]
Co-incineration wood industry	[86 87 83]
Co-incineration paper industry	[86 88 83]
Other incineration fluidized bed combustion	[38, 81, 82]
Other incineration rotary kiln	[81-83]
MSW Sorting	[75, 89]
C&D processing facilities	[6]
Shredder	Personnel interviews and expert estimation
Paper processing facilities	[38, 62, 90]
Glass processing facilities	[25, 28]
Metal packaging processing facilities	[35]
Scrap metal processing facilities	expert estimation
Metal processing facilities	expert estimation
Wood processing facilities	Personnel interviews and expert estimation
Plastic waste (HH)processing facilities	[35]
Plastic waste processing facilities	[91]

Processes	References
Textile waste processing facilities	38
WEEE Screens processing facilities	92, 93
WEEE Refrigerators processing facilities	
WEEE lighting processing facilities	
WEEE big processing facilities	
WEEE small processing facilities	
microbiological treatment of soil	expert estimation
Packaging asbestos waste	expert estimation

4 LONG-TERM EMISSIONS FROM LANDFILL

Long term gaseous emissions were only calculated for mass waste landfills with significant organic compounds based on Tabasaran and Rettenberger.[94] To evaluate long-term leachate emissions a model based on Laner[95] is used to calculate the concentration of TOC and NH_4-N in the leachate after t years. For metals and phosphorus, a constant substance concentration over time in the leachate is assumed. The leachate is collected and treated.

$$G_p = 1{,}868 * TOC_{deg} * (0{,}014 * T + 0{,}28)$$

G_p	Gas generation potential [$m^3 t^{-1}$]
TOC_{deg}	Degradable organic carbon [kg C t^{-1}]t]
T	Temperature [°C]

$$Gt = Gp * (1 + 10^{-(t*k_i)})$$

G_t	Cumulative amount of generated landfill gas after t years [$m^3 t^{-1}$]
G_p	Gas generation potential [$m^3 t^{-1}$]
t	Time after deposition [years]
k_i	velocity constant [$years^{-1}$]

The velocity constant (k_i) can be calculated estimating the half-time ($t_{1/2}$) of different organic combinations.

$$k_i = (-\frac{\ln 0{,}5}{t_{\frac{1}{2}}})$$

Table S 9. Half-time ($t_{1/2}$) of the different organic combinations

Waste fractions	Half -time [$years^{-1}$]
Easily degradable	4.1
Medium poorly degradable	8.7
poorly degradable	23
Very poorly degradable	5,000
non-degradable	-

Although methane oxidation rates in landfill covers are influenced by many factors a conservative factor of 10% for the average annual fraction of oxidized methane for cohesive soils is assumed.[95] Further, 50% of the generated landfill gas is used for energetic utilization. For inorganic landfills, leachate emissions are in the focus and CO_2- and CH_4-emissions can be neglected. To evaluate long-term leachate emissions a model based on Laner[95] is used to calculate the concentration of TOC and NH_4-N in the leachate after t years.

$$c(t) = c_0 * e^{-\left(\frac{c_0}{m_v} * \Delta\frac{L}{S} * h\right) * t}$$

c	substance concentration in the leachate after t years [mg l^{-1}]
c_0	substance concentration in the leachate directly after the intensive reactor phase [mg l^{-1}]
m_v	mobilizable waste fraction in mg/kg of dry matter [mg kg^{-1}]
ΔL/S	change of the deposited waste's liquid-to-solid ratio per year [l kg^{-1} a^{-1}]
h	heterogeneity factor; total volume of the waste body divided by the volume taking part in water flow and contributing to leachate emissions

For metals and phosphorus, a constant substance concentration over time in the leachate is assumed. The leachate is collected and treated. The retention capacity is estimated according to following table.

Table S 10. Retention capacity.

Substances	Retention capacity [%]	References
TOC	95	[96]
NH_4	80	
P	90	
Cd	63	[97]
Cr	54	
Fe	60	assumption
Hg	92	[97]
Pb	89	
Zn	84	

5 MATERIAL FLOW ANALYSIS – SYSTEM

5.1 Qualitative System and Subsystems

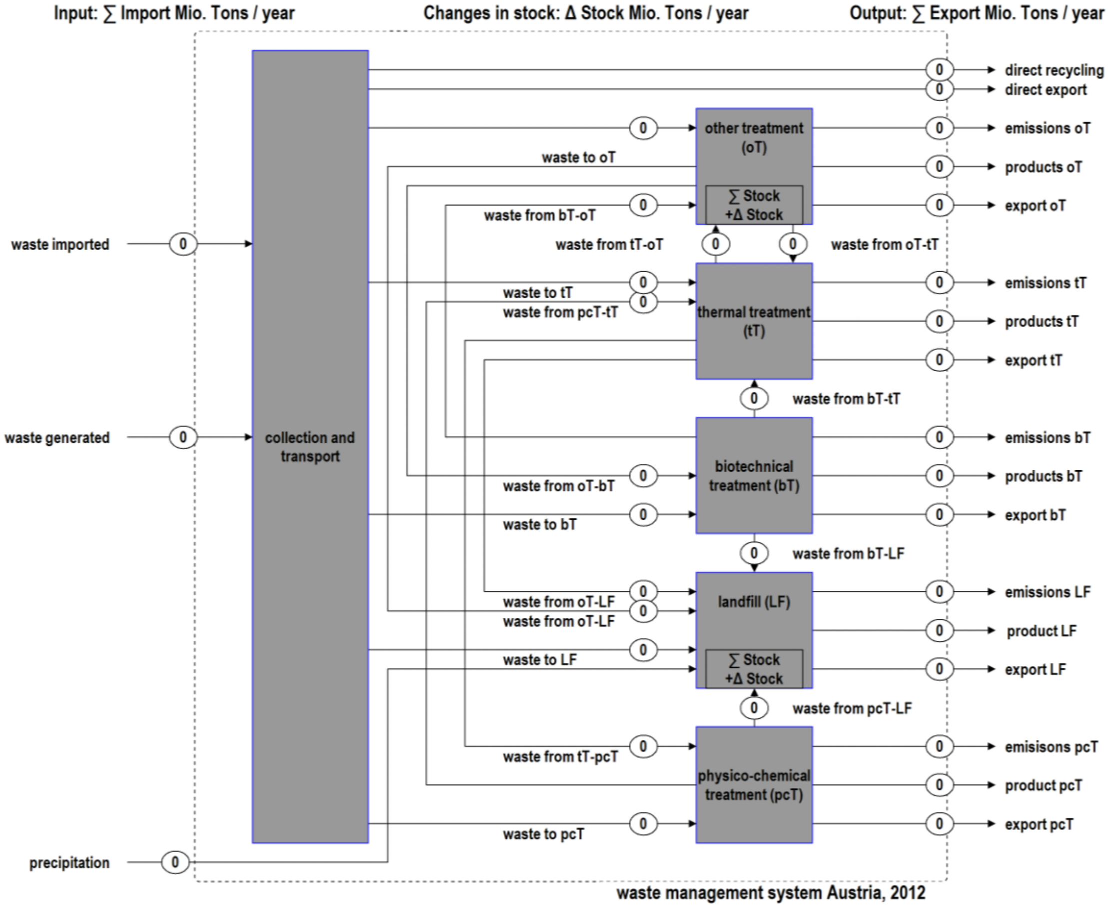

Figure S 1. Main System.

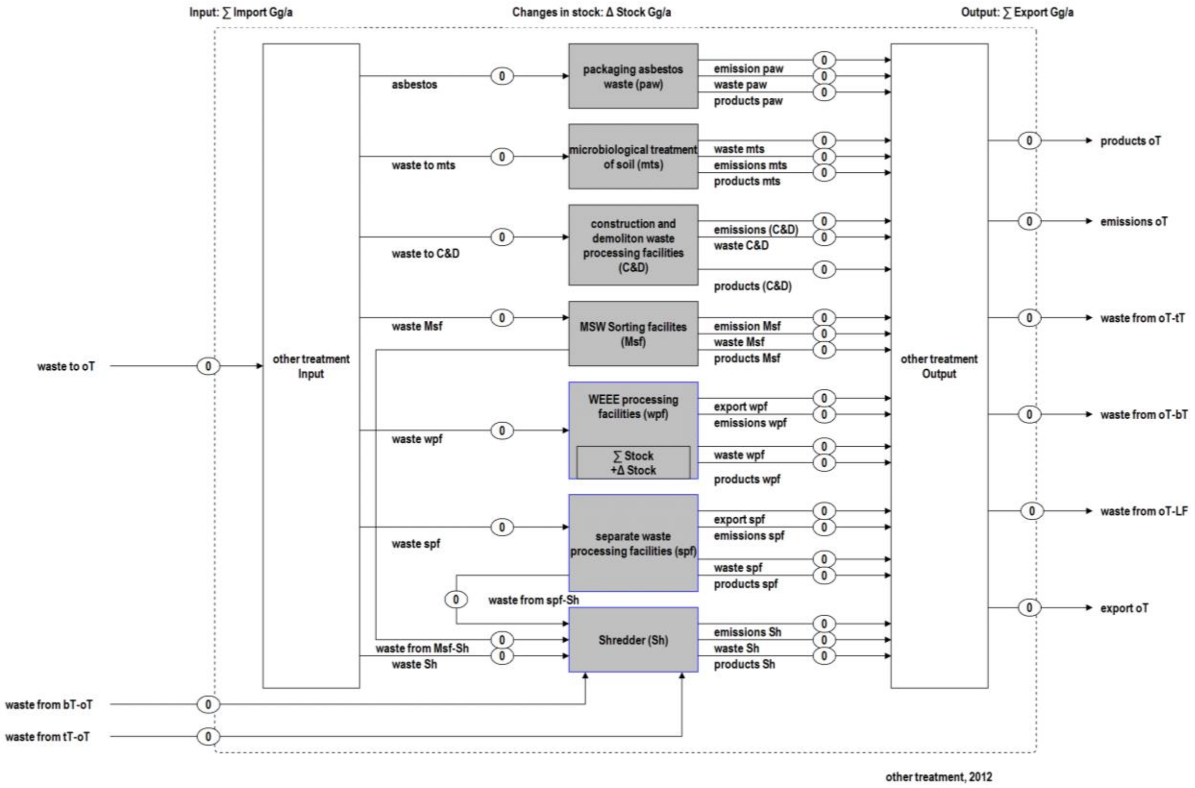

Figure S 2. Subsystem other treatment.

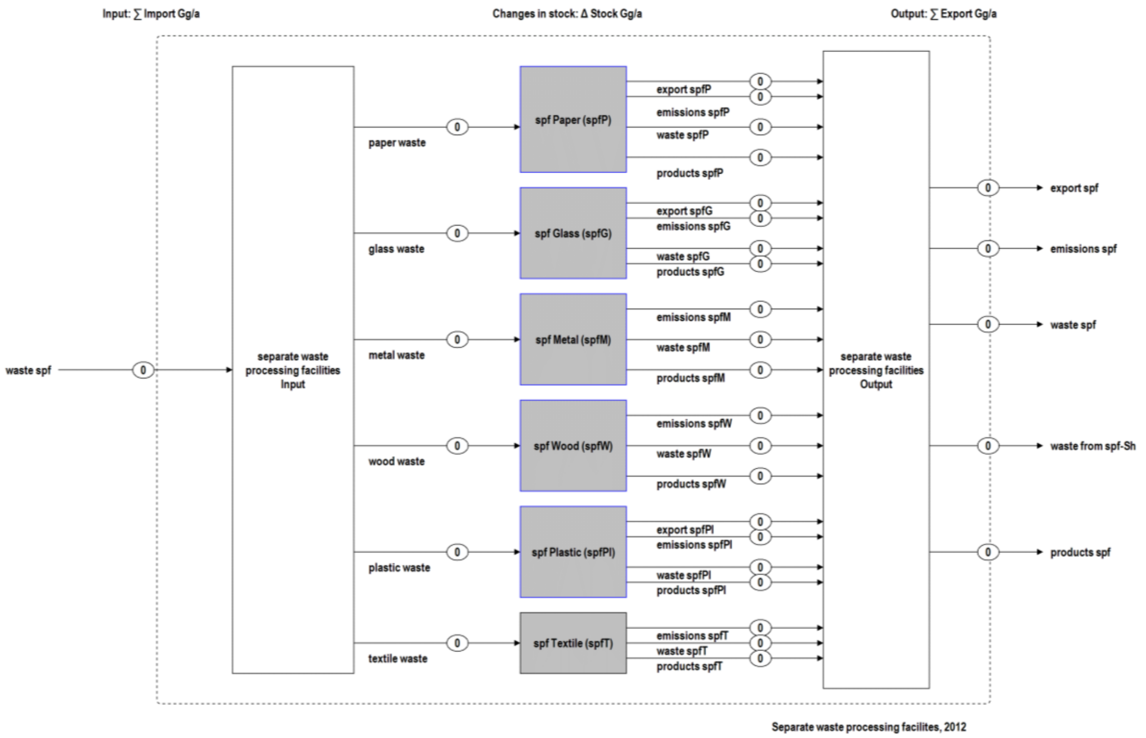

Figure S 3. Sub-Subsystem Separate waste processing facility.

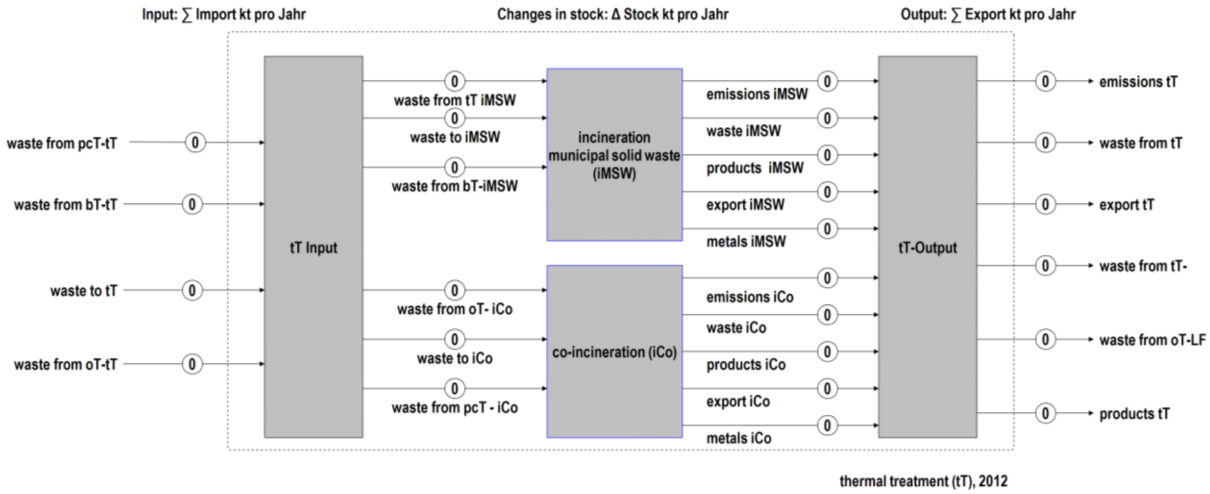

Figure S 4. Subsystem thermal treatment.

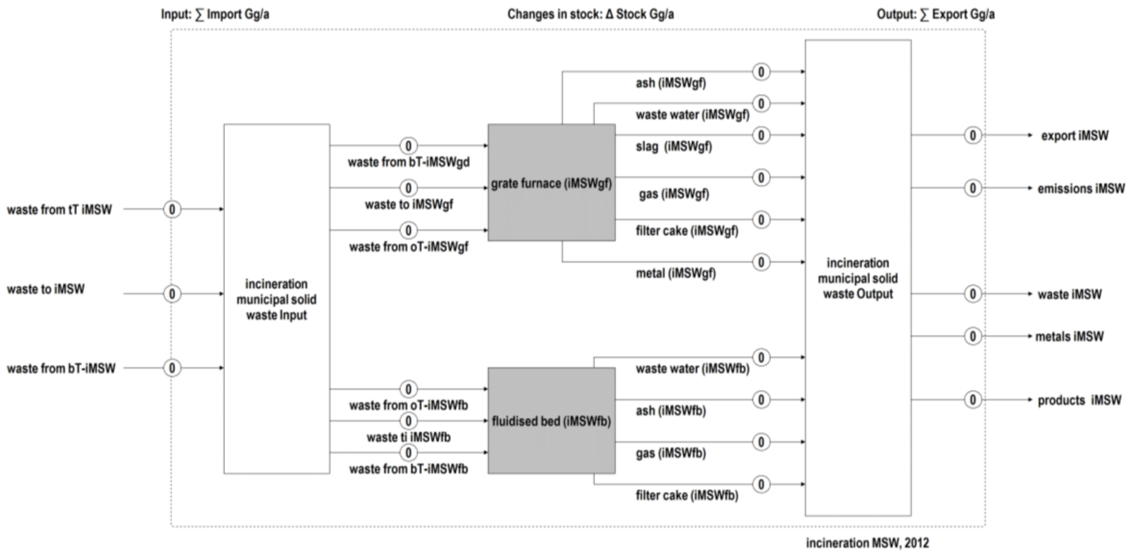

Figure S 5. Sub-Subsystem Incineration MSW.

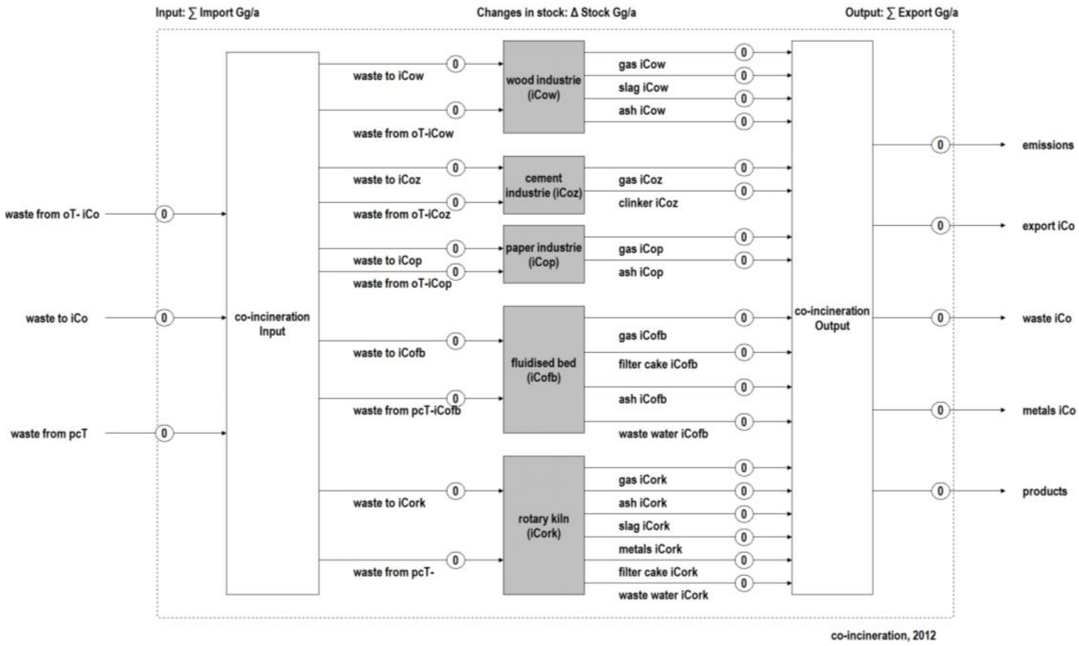

Figure S 6: Sub-Subsystem Co-Incineration

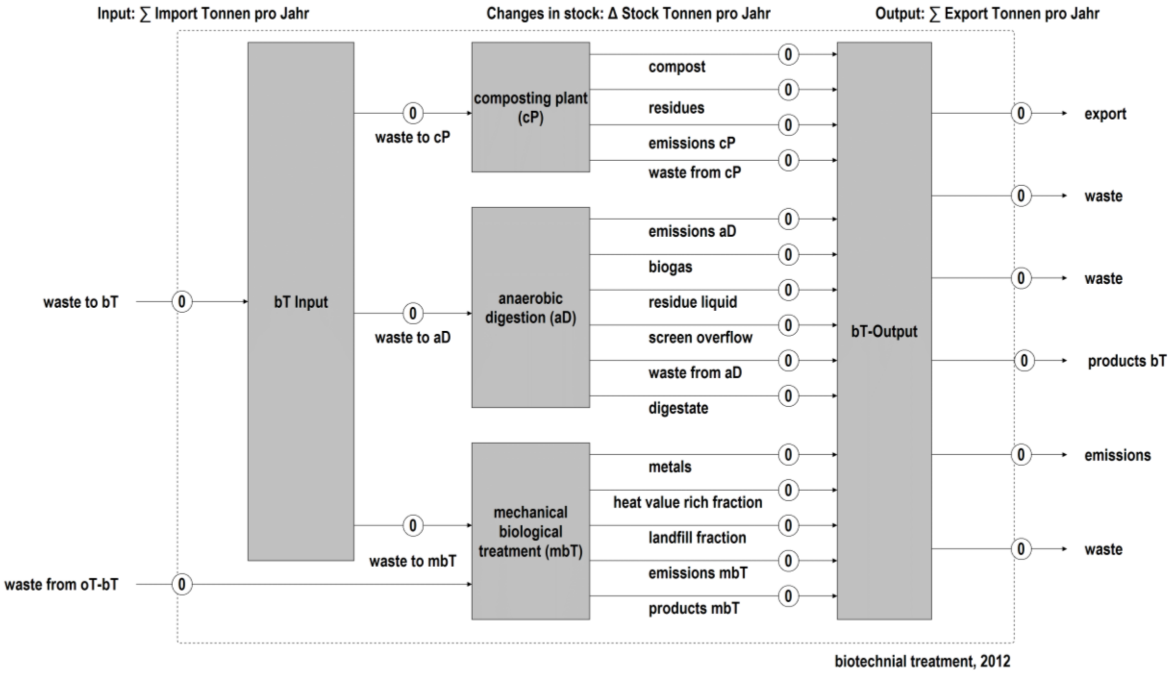

Figure S 7. Subsystem biotechnical treatment.

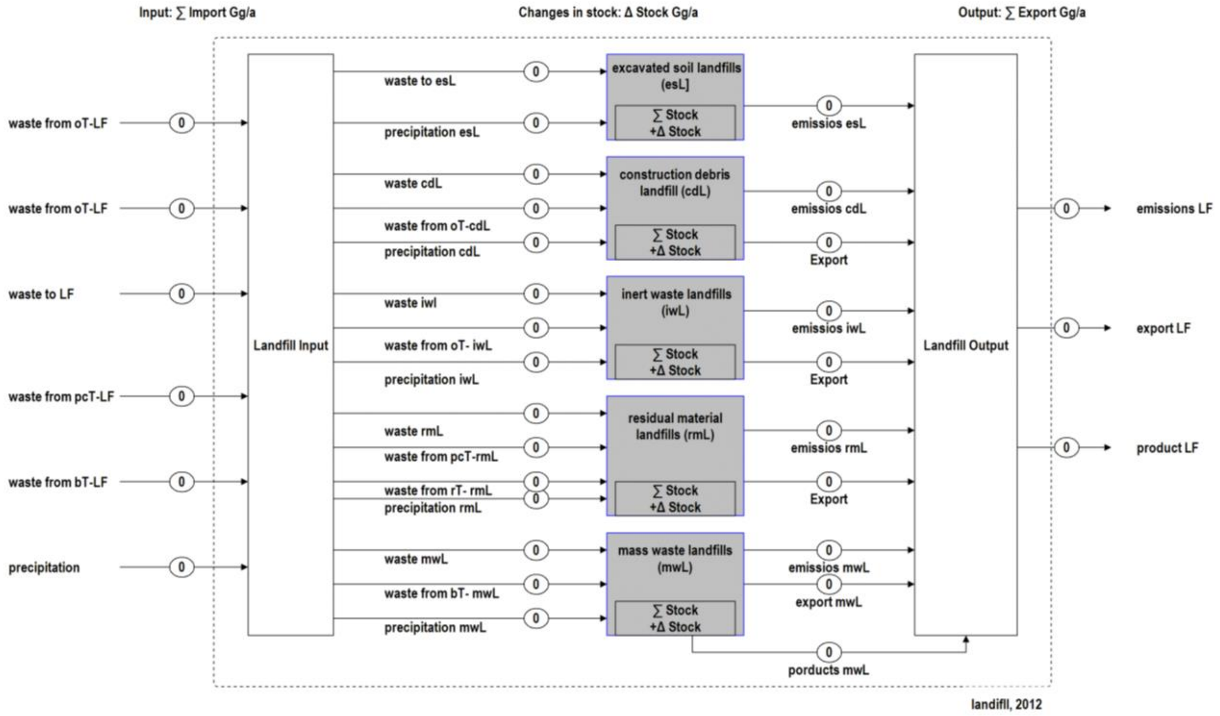

Figure S 8: Subsystem Landfill

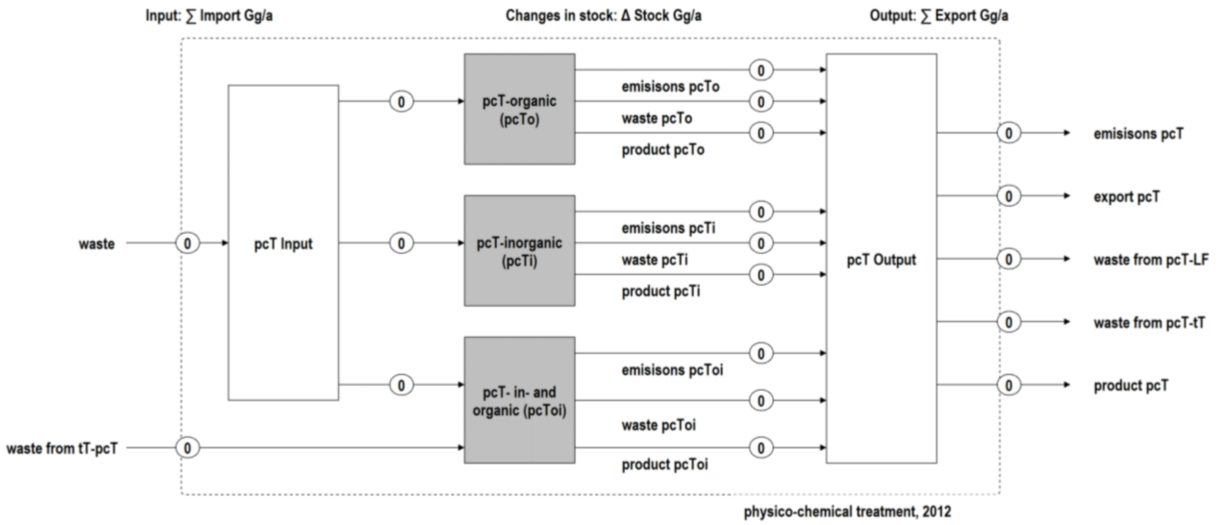

Figure S 9. Subsystem physico-chemical treatment.

5.2 Quantitative Main System

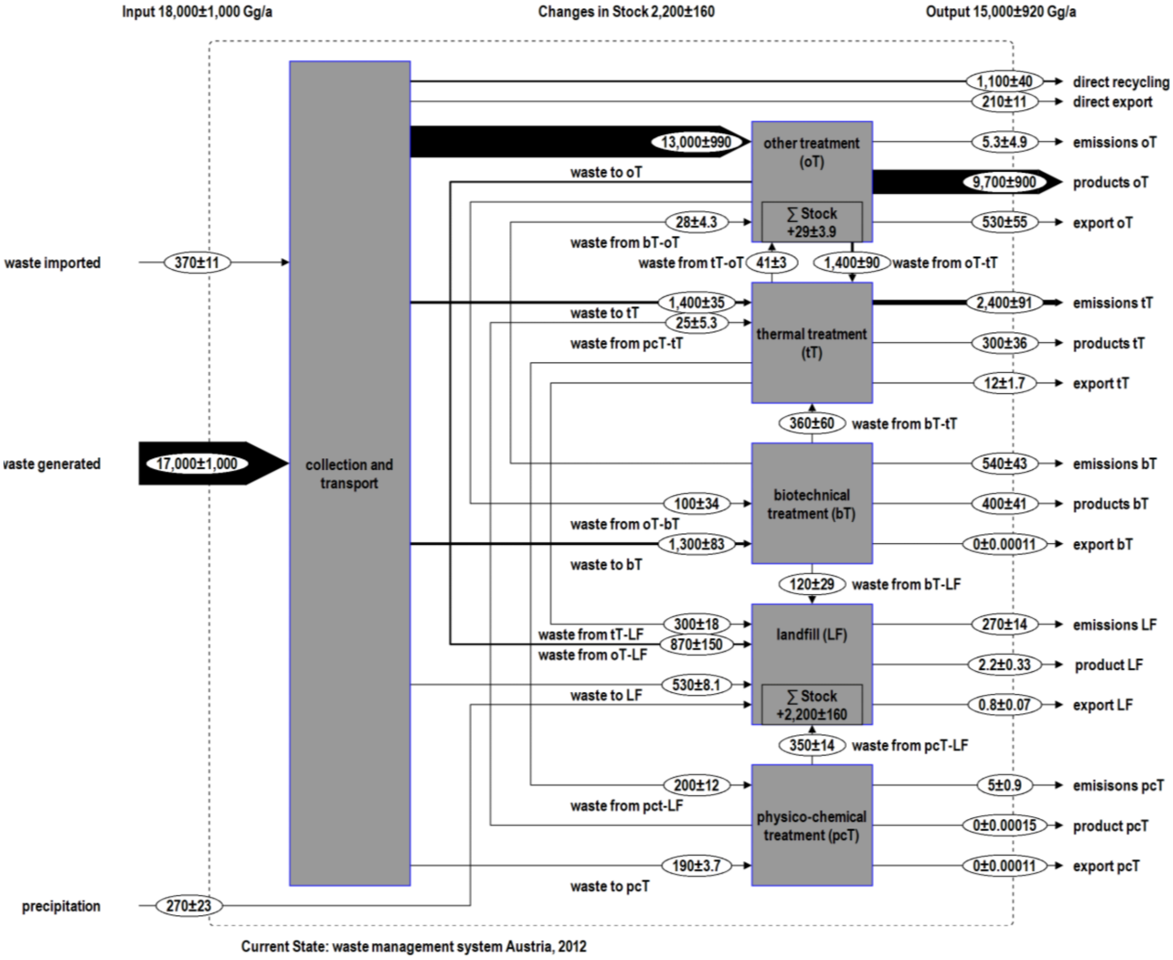

Figure S 10. Main System Goods.

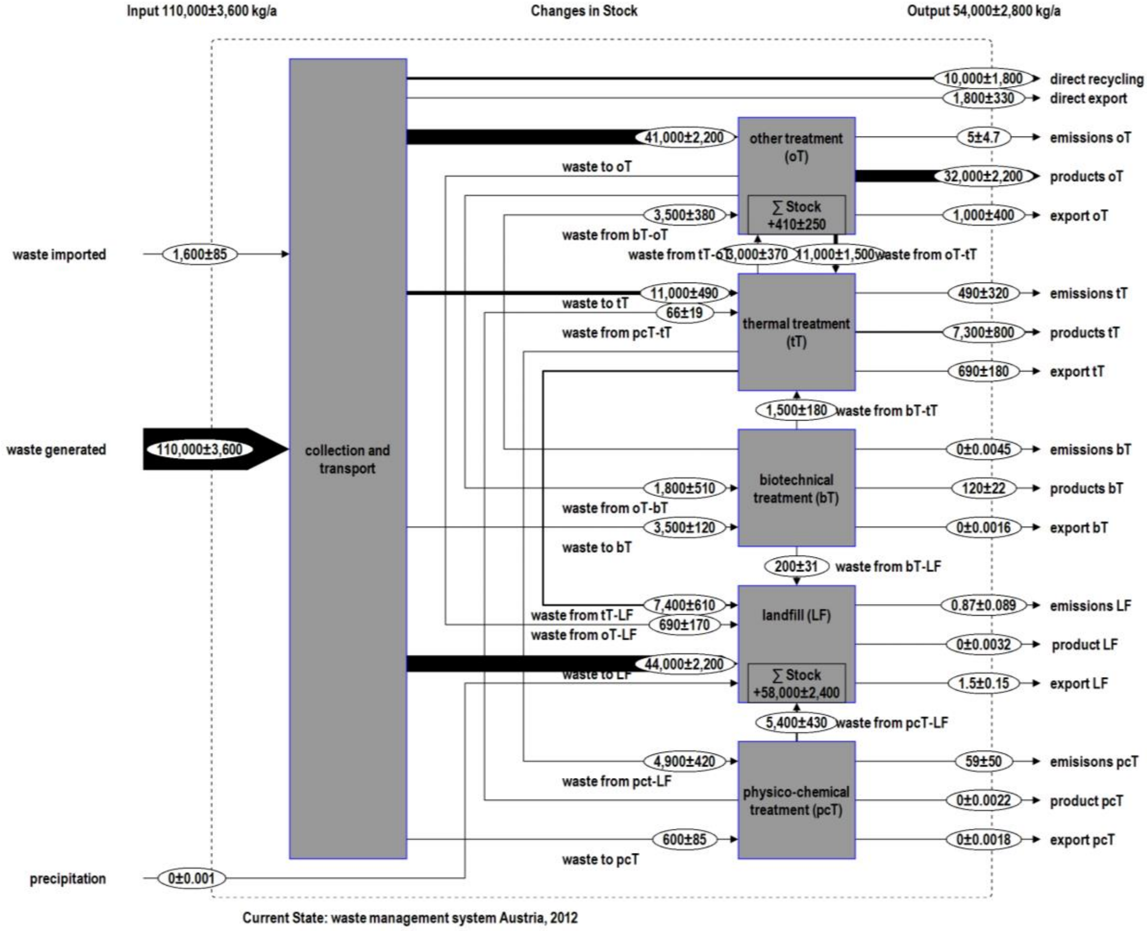

Figure S 11. Main System Cadmium.

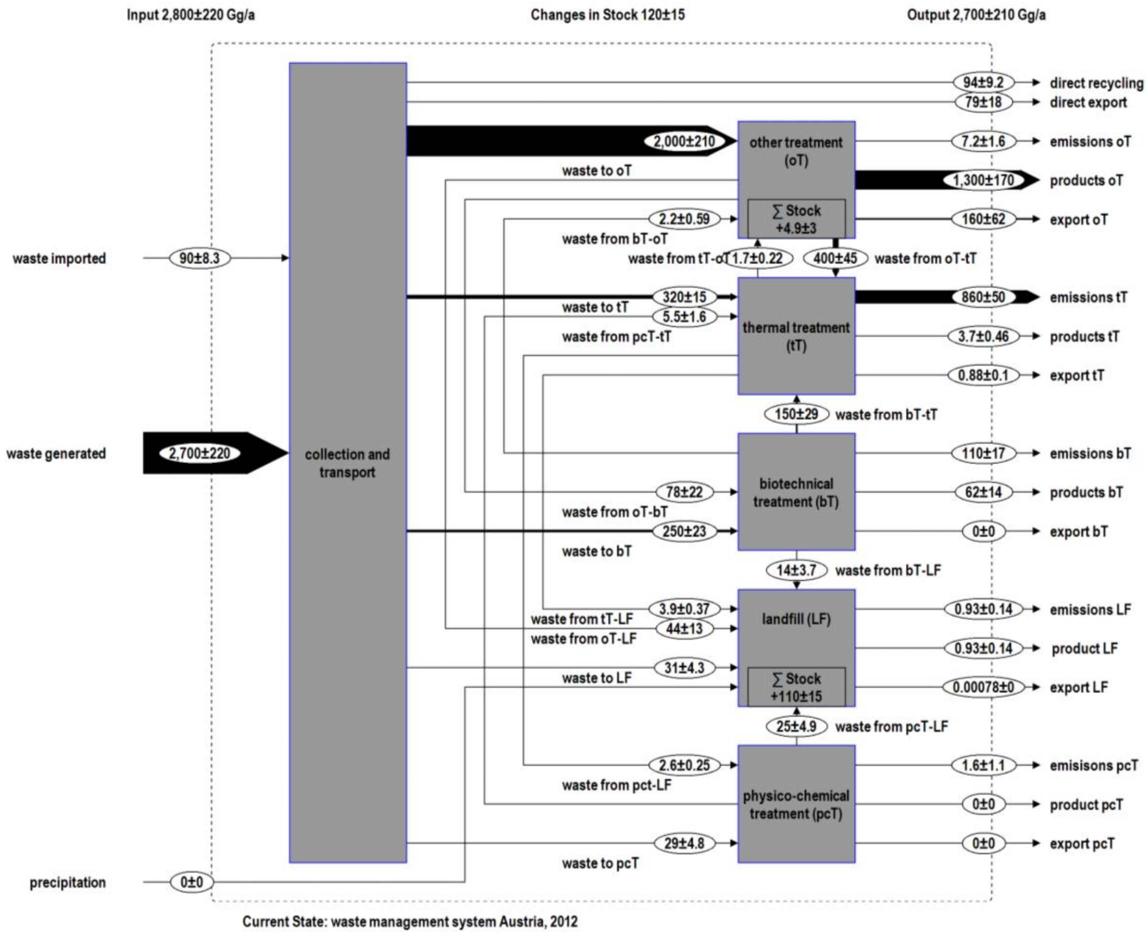

Figure S 12. Main System Carbon.

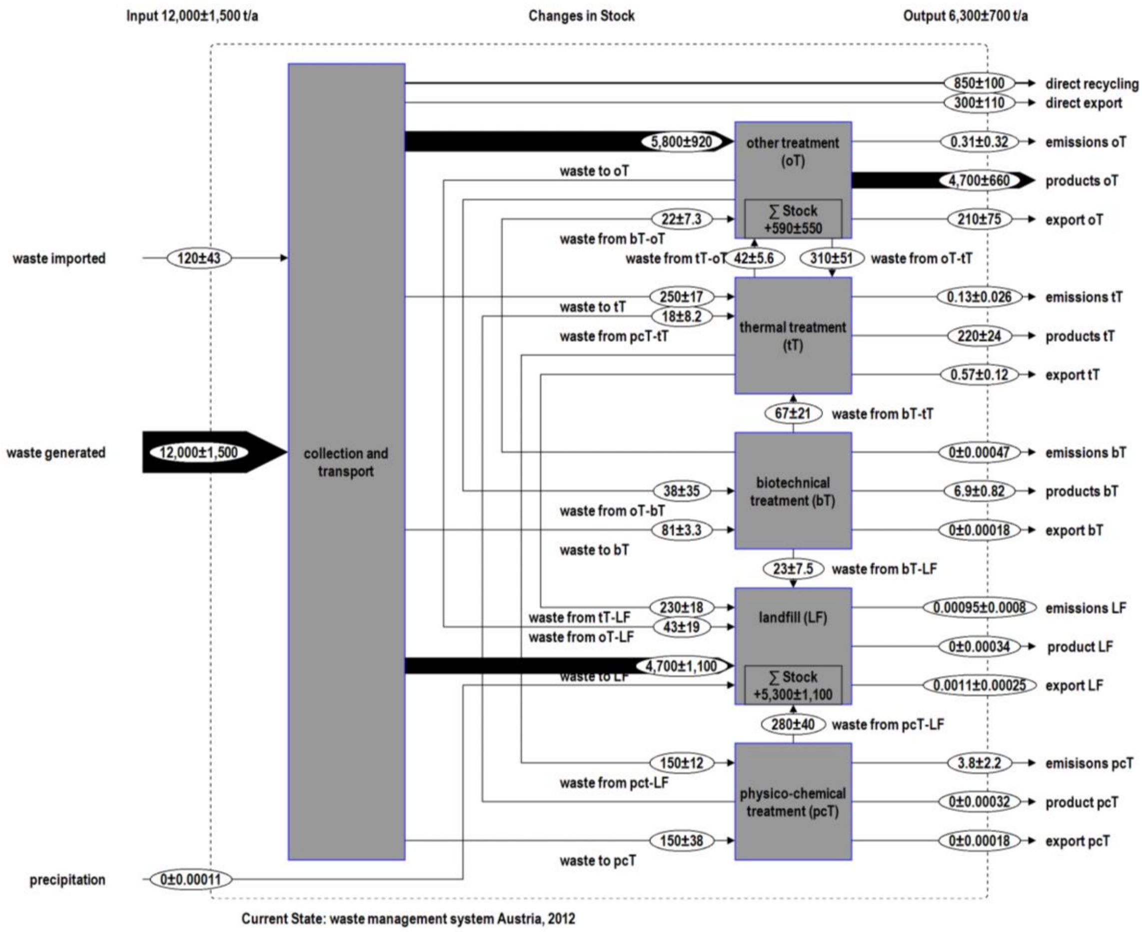

Figure S 13. Main System Chrome.

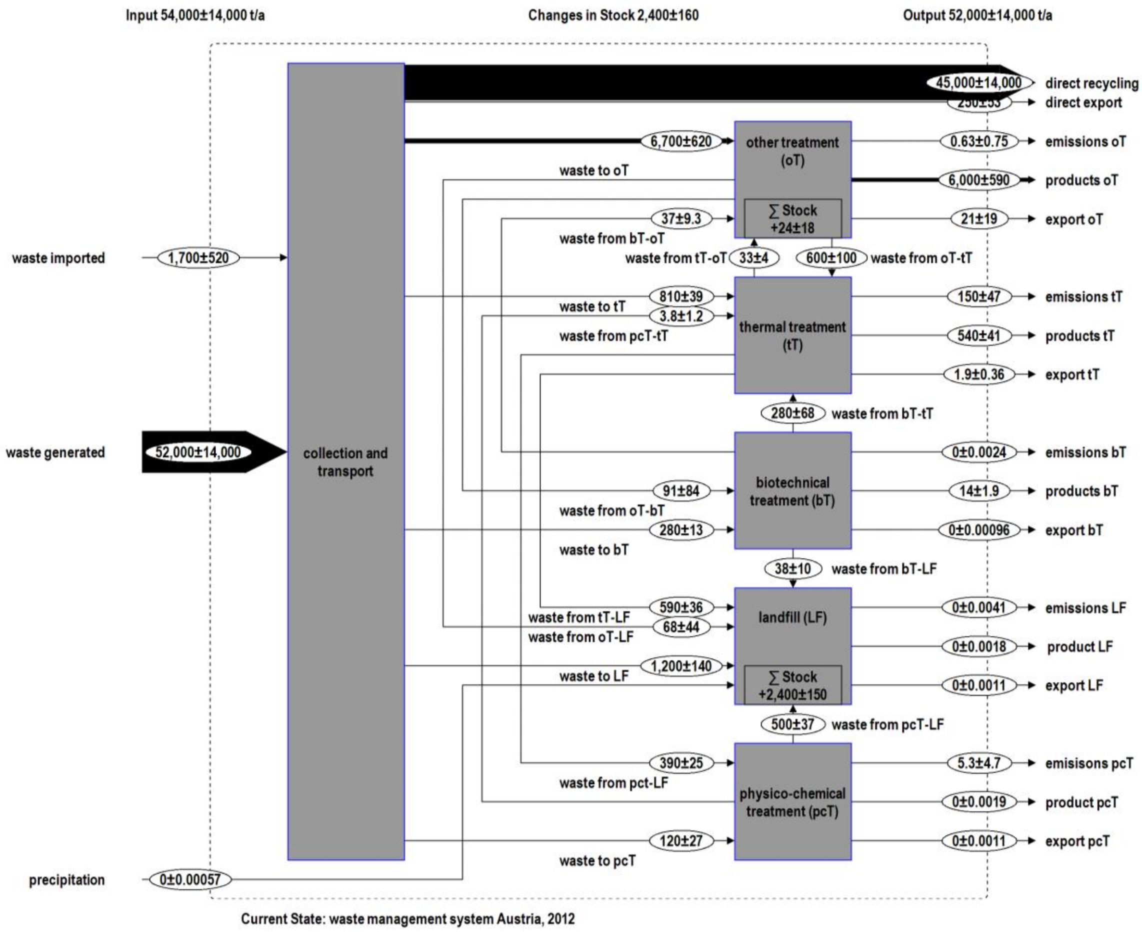

Figure S 14. Main System Copper

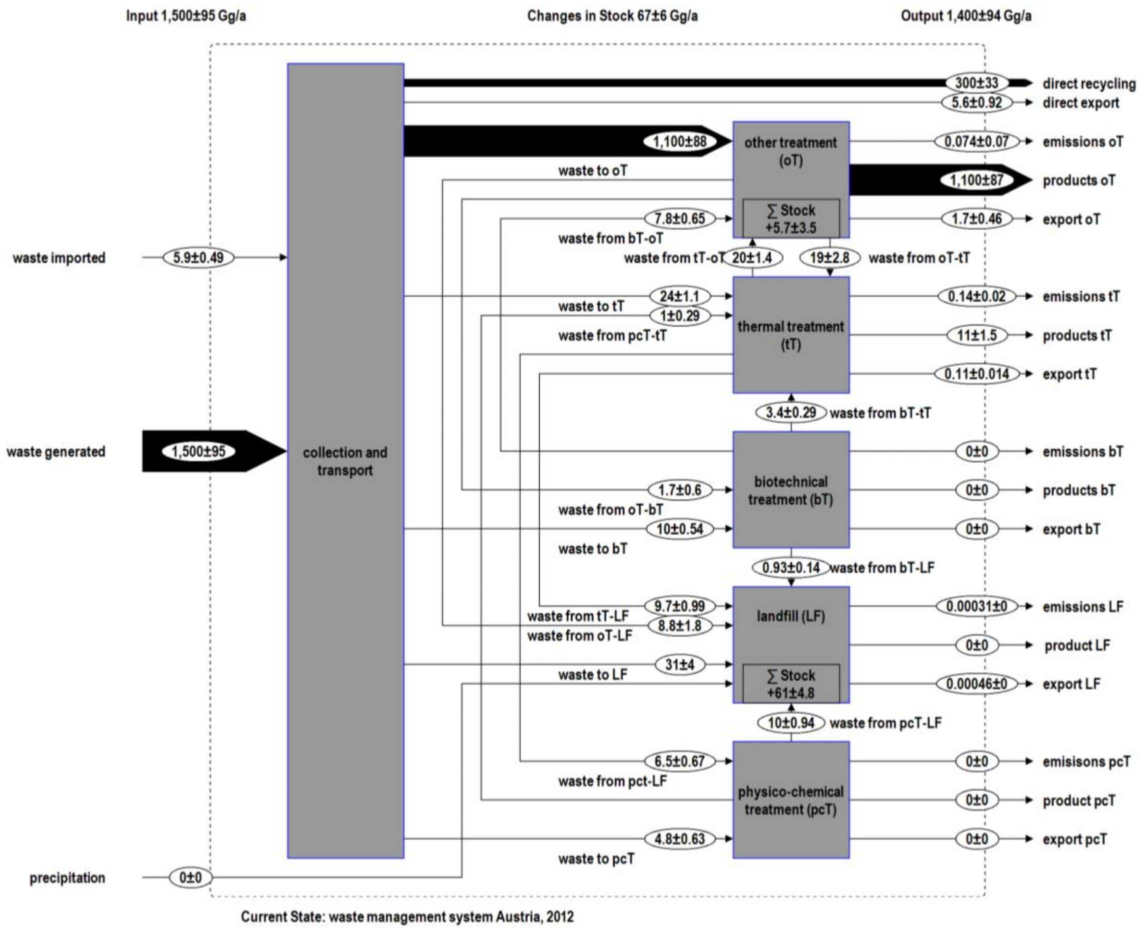

Figure S 15. Main System Iron

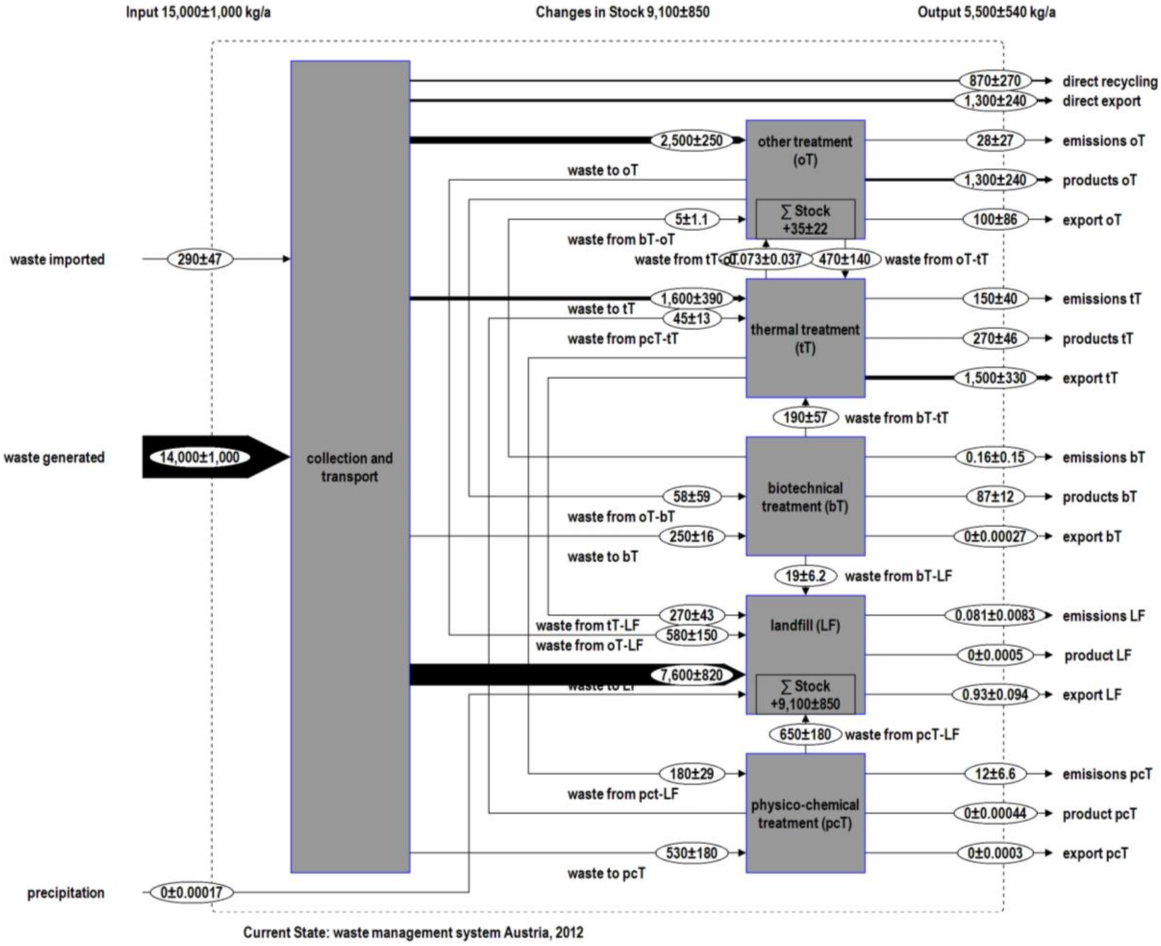

Figure S 16. Main System Mercury

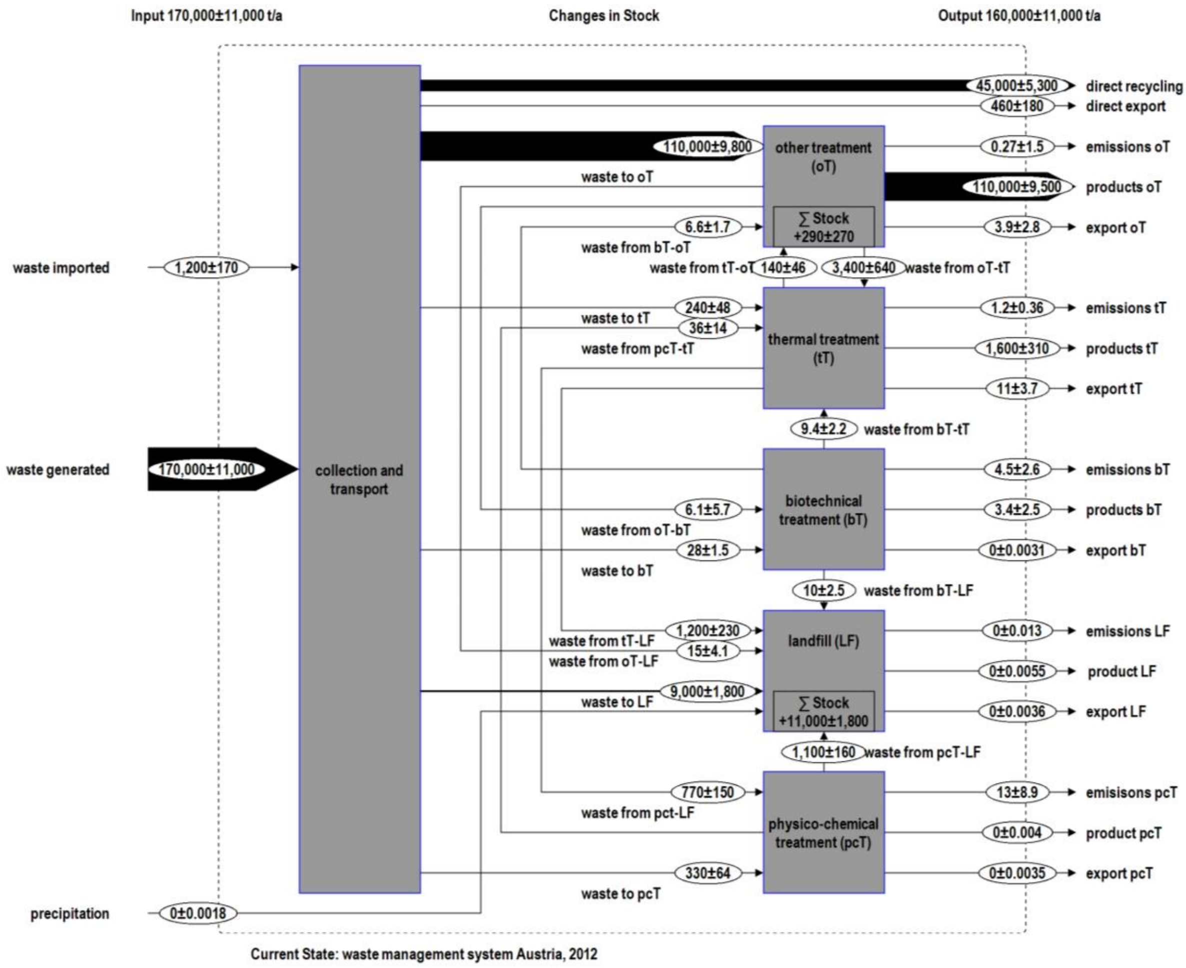

Figure S 17. Main System Nickel

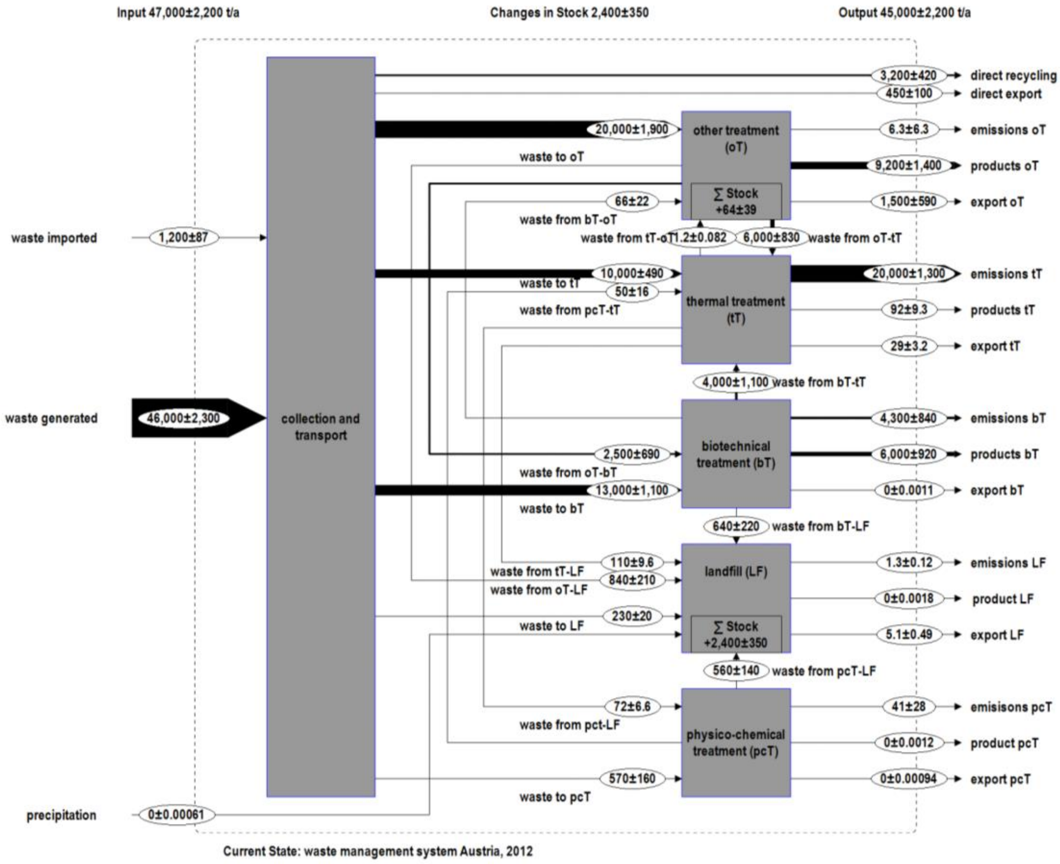

Figure S 18. Main System Nitrogen

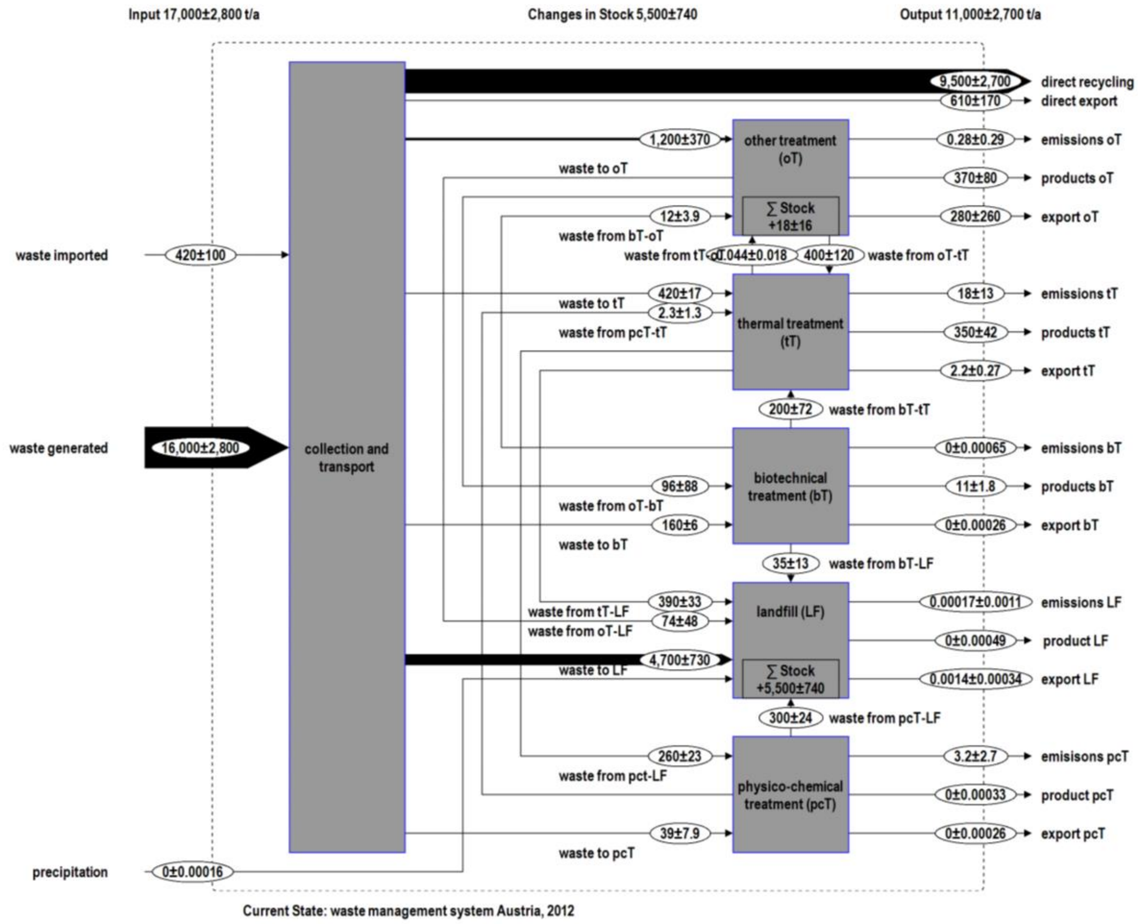

Figure S 19. Main System Lead

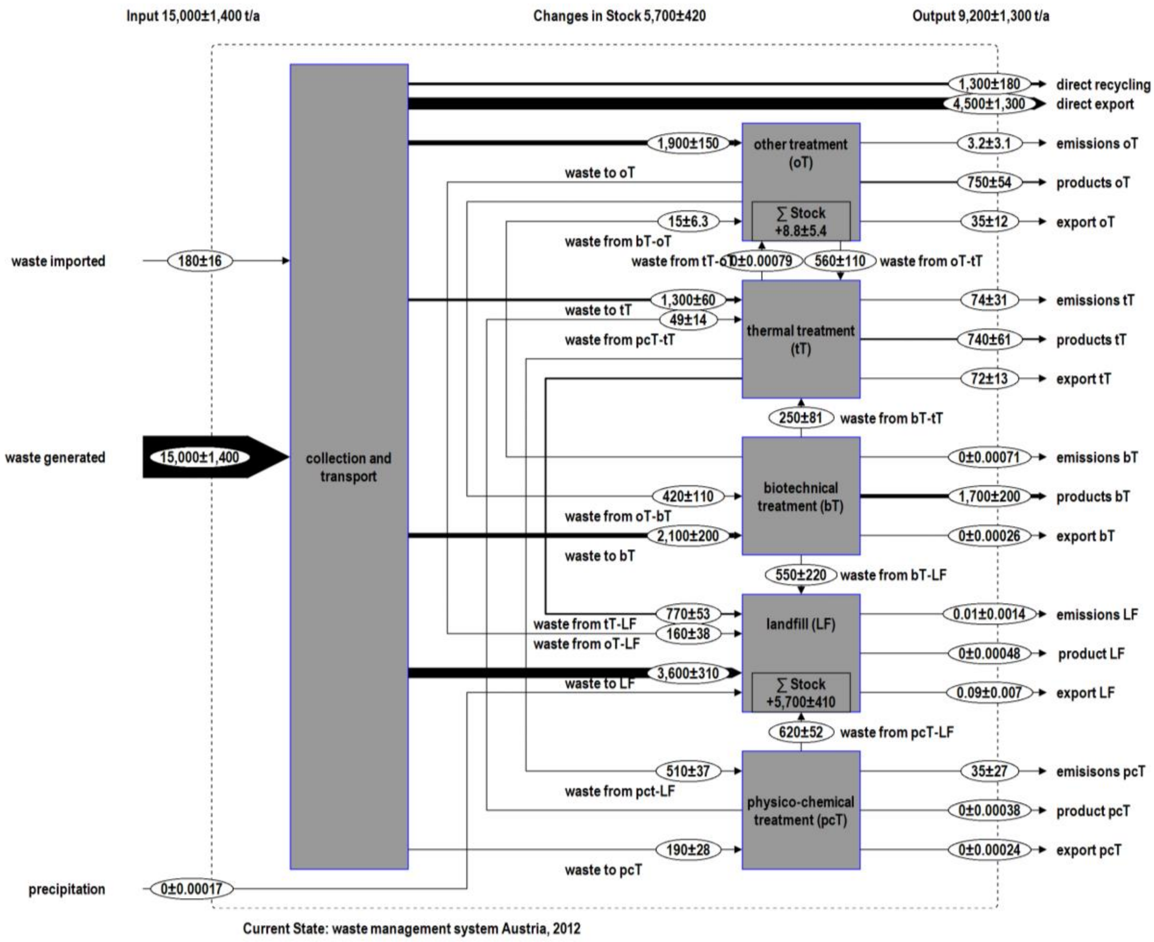

Figure S 20. Main System Phosphorus

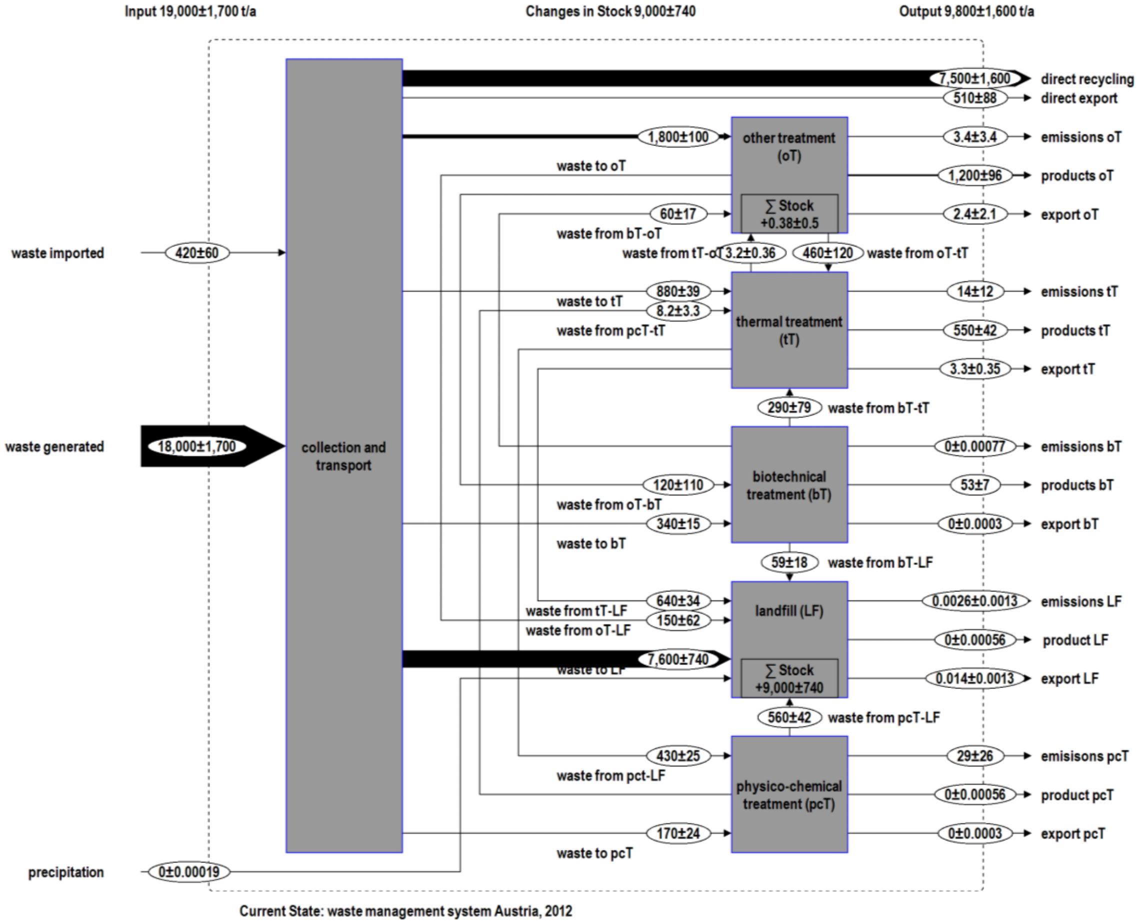

Figure S 21. Main System Zinc

5.3 Products: Goods and Substances

Table S 11. Mass flows in tons and kg for goods and substances

Products	goods [t]	Cd [kg]	C [kg]	Fe [kg]	N [kg]	P [kg]	Cr [kg]	Cu [kg]	Hg [kg]	Ni [kg]	Pb [kg]	Zn [kg]
Biogenic materials	368,000	89	60,600,000	917,000	5,160,000	798,000	3,380	8,780	38	1,360	6,880	28,800
C&D	5,710,000	1,880	432,000,000	46,200,000	1,100,000		150,000	137,000	514	103,000	210,000	274,000
Compost	305,000	108	42,200,000		3,200,000	1,330,000	5,670	11,700	80	3,050	9,670	45,000
Glass	218,000	33		2,290,000			749,000	218		218	196	1,310
Metal	2,170,000	26,200	3,140,000	1,340,000,000	145,000	596,000	3,760,000	49,300,000	19	154,000,000	1,240,000	3,600,000
Paper	1,400,000	2,880	490,000,000	2,900,000	4,700,000	103,000	27,000	63,000	283	17,300	1,370	9,970
Plastic	214,000	5,330	132,000,000	1,820,000	1,020,000	115,000	16,300	11,500	348	4,040	45,200	31,800
Slags and ashes	303,000	7,260	3,700,000	10,600,000	92,000	741,000	221,000	535,000	267	1,570,000	351,000	546,000
Wood	550,000	193	253,000,000	231,000	2,210,000	66,400	4,540	107,000	73	7,560	4,780	24,700
Other Products	222,000	6,120	50,300,000	10,300,000	855,000	693,000	843,000	993,000	868	705,000	8,340,000	4,690,000
Sum	11,500,000	50,100	1,470,000,000	1,420,000,000	18,500,000	4,450,000	5,780,000	51,200,000	2,490	157,000,000	10,200,000	9,250,000

6 SCENARIO ANALYSIS

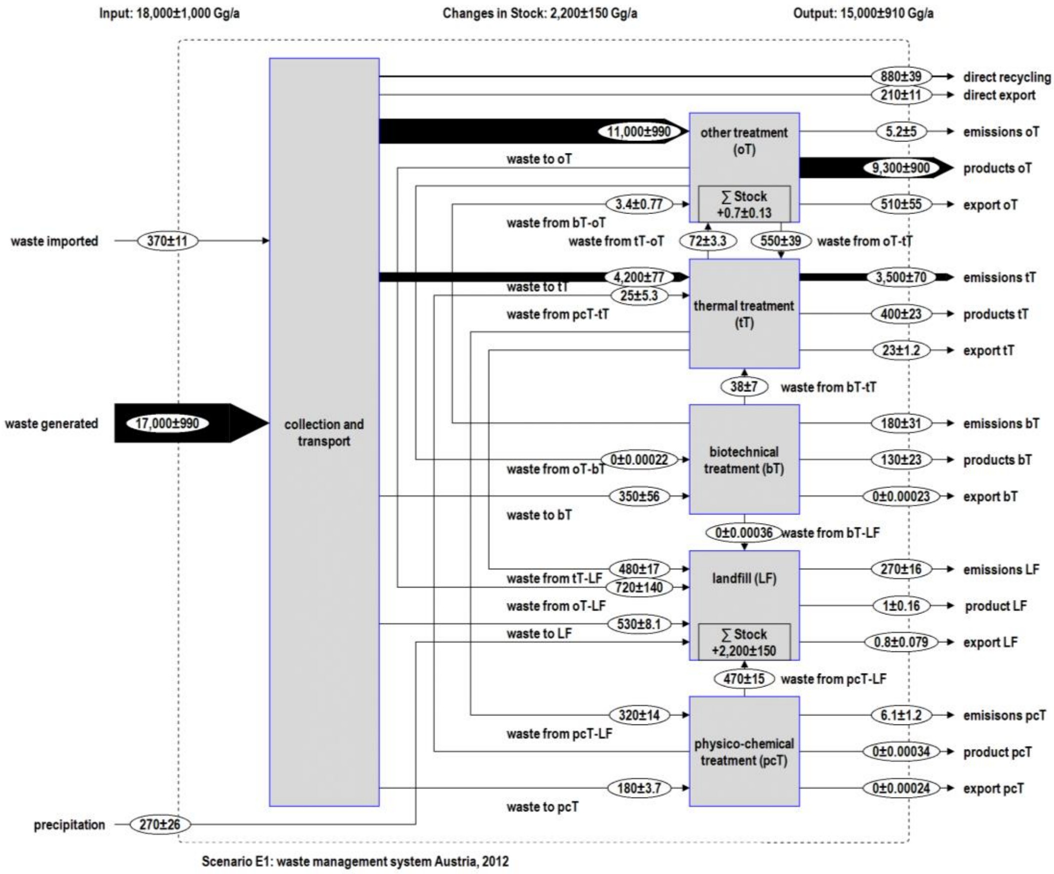

Figure S 22. Main System: Scenario E1

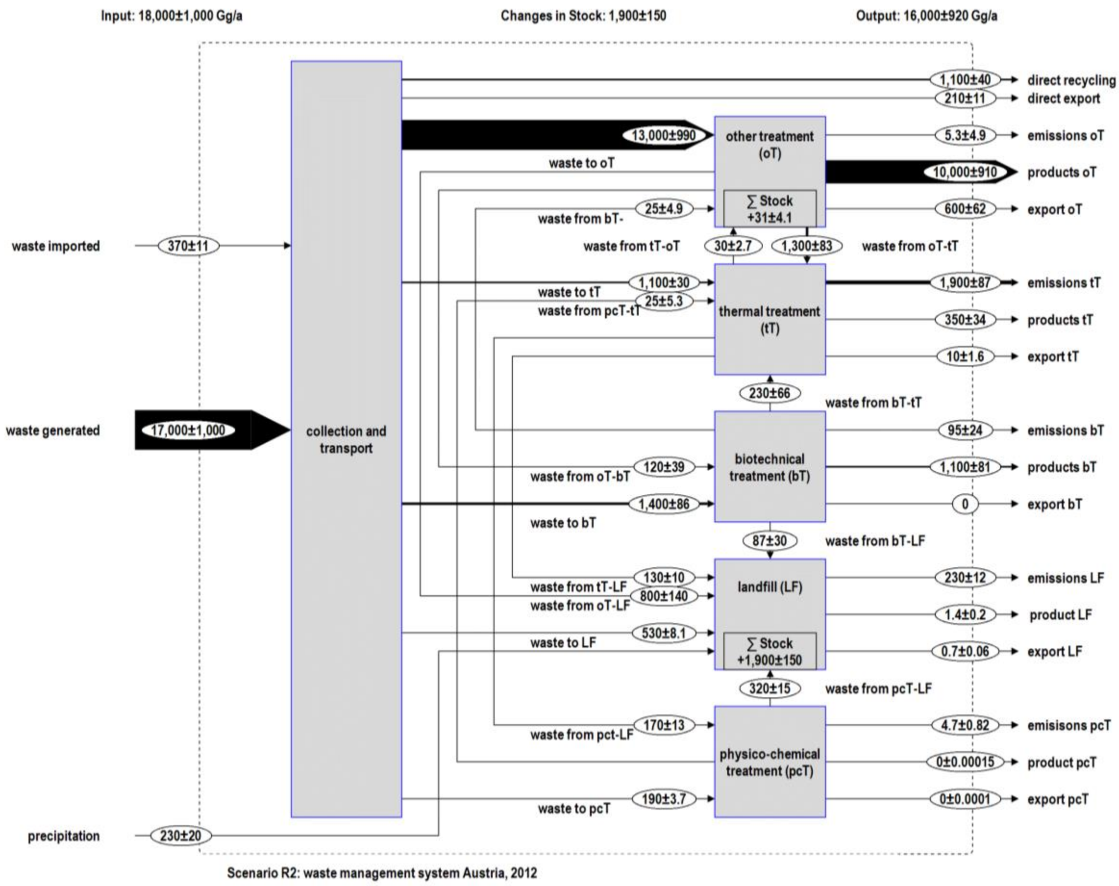

Figure S 23. Main System: Scenario R2

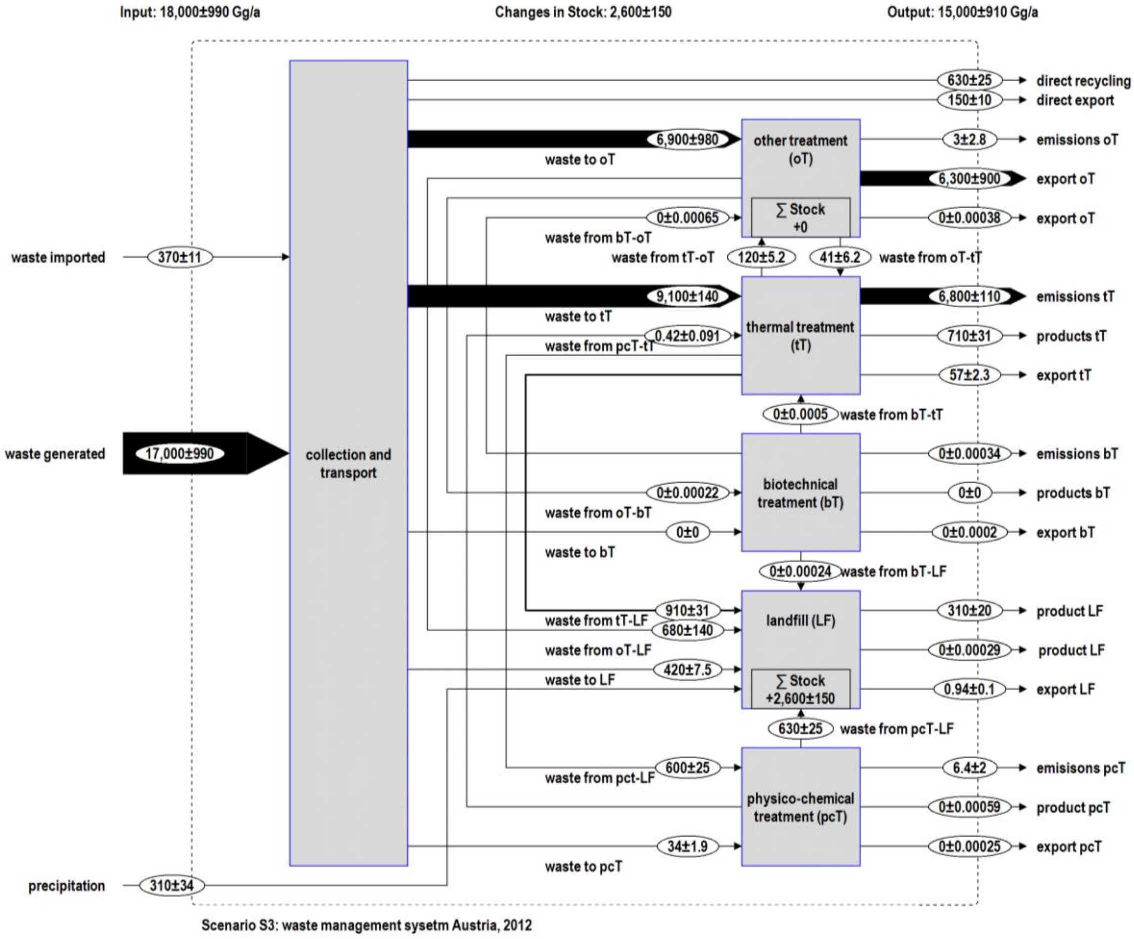

Figure S 24. Main System: Scenario S3

7 REFERENCES

1. BMLFUW *Die Bestandsaufnahme der Abfallwirtschaft in Österreich (Statusbericht 2013) - The inventory of waste management in Austria (Status Report 2013)*; Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft - Federal Ministry of Agriculture, Forestry , Environment and Water Management: Wien, **2014**.

2. EDM Daten des elektronischen Datenmanagements für das Jahr 2012 vom Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft - Data of the electronic data management for the year 2012 from the Ministry of Agriculture, Forestry , Environment and Water Management. (accessed

3. Reisinger, H.; Domenig, M.; Doujak, K. *Asbest: Materialien zur Abfallwirtschaft - Asbestos : Materials for Waste Management*; Umweltbundesamt GmbH: Klagenfurt, **2008**.

4. Glenck, E.; Lahner, T.; Arendt, M.; Brunner, P. H. *Baurestmassen in Oberösterreich, Stoffbilanzen der Bauwirtschaft - Construction waste in Upper Austria , material balances of construction*; Technische Universität Wien: Wien, **1997**.

5. Brunner, P. H.; Stämpfli, D. M., Material balance of a construction waste sorting plant. *Waste Management & Research* **1993,** *11*, (1), 27-48.

6. Schachermayer, E.; Lahner, T.; Brunner, P. H. *Stoffflussanalyse und Vergleich zweier Aufbereitungstechniken für Baurestmassen - Material flow analysis and comparison of two treatment techniques for construction waste*; Technische Universität Wien: Wien, **1998**.

7. Walker, I.; Dohmann, M. *Grundlagenuntersuchungen zur Beurteilung der Umweltverträglichkeit von Bauschutt und Baustellenabfällen - Basic research to assess environmental impacts of construction waste*; Rheinisch-Westfälische Technische Hochschule Aachen: Aachen, **1998**.

8. Grech, H.; Oliva, J.; Scheibengraf, M.; Angerer, T. *Recyclingbaustoffe: Regelung der Umweltverträglichkeit - Recycling Materials: regulation of environmental compatibility*; Umweltbundesamt: Wien, **2002**.

9. ABANDA Abfallanalysendatenbank des Landesumweltamtes (Nordrhein-Westfalen) - Waste analysis database of the Environmental Agency (North Rhine-Westphalia). http://www.nrw-luawebapps.de/abanda/auswert.htm (accessed 05.09.2014-01.06.2015)

10. Grech, H.; Oliva, J.; Scheibengraf, M.; Angerer, T. *Recyclingbaustoffe: Regelung der Umweltverträglichkeit - Recycling Materials: regulation of environmental compatibility*; Umweltbundesamt: Wien, **2003**.

11. Reisinger, H.; Schöller, G.; Müller, B.; Obersteiner, E. *Ressourcenpotenzial und Umweltbelastung der Schwermetalle Cadmium, Blei und Quecksilber in Österreich - Resource potential and environmental impacts of heavy metals cadmium , lead and mercury in Austria*; Umweltbundesamt GmbH & Technische Universität Wien: Klagenfurt/Wien, **2009**.

12. Riber, C.; Petersen, C.; Christensen, T. H., Chemical composition of material fractions in Danish household waste. *Waste Management* **2009,** *29*, (4), 1251-1257.

13. Kehres, B. *Zusammenstellung von Daten der Bundesgütegemeinschaft Kompost (Deutschland) zu Nährstoffen und Schwermetallen von Komposten und Gärprodukten - Compilation of data from the Federal compost association (Germany) to nutrients and heavy metals from compost and fermentation products*; **2014**.

14. Kern, M.; Raussen, T.; Funda, K.; Lootsma, A.; Hofmann, H. *Aufwand und Nutzen einer optimierten Bioabfallverwertung hinsichtlich Energieeffizienz, Klima-und Ressourcenschutz - Costs and benefits of an optimized bio-waste recycling in terms of energy efficiency , climate protection and resource conservation*; Witzenhausen-Institut für Abfall, Umwelt und Energie GmbH: Dessau, **2010**.

15. Kirchmeyer, F. *schriftliche Auskunft - written information*; **2014**.

16. Rabah, M. A., Recyclables recovery of europium and yttrium metals and some salts from spent fluorescent lamps. *Waste management* **2008,** *28*, (2), 318-325.

17. Grafenstein, E., Säckeweise Rohstoffe - Bags full of resources. *Recycling Magazin 01/2013* **2013**.

18. Wojtalewicz-Kasprzak, D.-I. A. *Erzeugung von synthetischen Selten-Erd-Konzentraten aus Leuchtstoffabfällen - Production of synthetic rare earth concentrates from fluorescent waste*; Clausthal, **2007**.

19. Tesar, M.; Öhlinger, A. *Flachbildschirmgeräte Behandlung - Flat screen television treatment*; Umweltbundesamt GmbH: Wien, **2012**.

20. Huisman, J.; Magalini, F.; Kuehr, R.; Maurer, C.; Ogilvie, S.; Poll, J.; Delgado, C.; Artim, E.; Szlezak, J.; Stevels, A. *review of directive 2002/96 on waste electrical and electronic equipment (WEEE)*; United Nations University: Bonn, **2008**.

21. Salhofer, S.; Tesar, M., Assessment of removal of components containing hazardous substances from small WEEE in Austria. *Journal of hazardous materials* **2011,** *186*, (2), 1481-1488.

22. Rüdenauer, I.; Gensch, C.-O.; Quack, D. *Eco-Efficiency analysis of washing machines - Life-cycle assessment and determination of optimal life span*; Öko-Institut e.V: Freiburg, **2005**.

23. Classen, M.; Althaus, H.-J.; Blaser, S.; Scharnhorst, W.; Tuchschmid, M.; Jungbluth, N.; Emmenegger, M. F. *Life cycle inventories of metals*; Swiss Centre for Life Cycle Inventories: Dübendorf, **2007**; p 1945.

24. Wagner, M.; Menapace, H.; Frate, R. *Stand der Technik bei der chemisch-physikalischen Behandlung von flüssigen Abfällen - State of the art in chemical- physical treatment of liquid waste*; Montanuniversität Leoben: Leoben, **2010**.

25. AGR *Umwelterklärung und Nachhaltigkeitsbericht 2010 - Environmental Statement and Sustainability Report 2010*; Austria Glas Recycling GmbH: **2010**.

26. BVGlas Kalknatrongläser. http://www.bvglas.de/der-werkstoff/glasarten/kalknatronglaeser (accessed 30.8.2014)

27. Arge Abfallvermeidung *Fehlwürfe in der kommunalen Abfallwirtschaft: Tolerierbar oder unzumutbar? Tagungsdokumentation nach dem Stand der ExpertInnenmeinungen - Misses in the municipal waste management: Tolerable or unreasonable? Meeting documentation prior expert opinions*; **2005**.

28. AGR *Umwelterklärung und Nachhaltigkeitsbericht 2013 - Environmental Statement and Sustainability Report 2013*; Austria Glas Recycling GmbH: **2013**.

29. Gras, B. *Schadstoffe in Altholz - Pollutants in waste wood*; Behörde für Umwelt und Gesundheit: **2002**.

30. Vock, W. *Umwelt-Materialien Nr. 178: Schadstoffgehalte in Holzabfällen (Analyseresultate der Holzkampagne 98) - Environmental Materials No. 178: contaminant levels in wood waste (Analysis results of Wood campaign 98th)*; Ingenieurbüro Abfall und Recycling: Bern, **2004**.

31. Scheffknecht, C. *Umweltanalytik: Chemisch analytische Untersuchungen von Altholz - Environmental Analysis: Chemical analytical investigations of waste wood*; Amt der Vorarlberger Landesregierung: Bregenz, **1999**.

32. Fehringer, R.; Brunner, P. H.; Baumann, H. *Kunststoffflüsse und Möglichkeiten der Kunststoffverwertung in Österreich - Plastic flows and possibilities of plastics recycling in Austria*; 3854573316; Technische Universität Wien & Österreichisches Kunststoffinstitut: Wien, **1997**.

33. Westerdahl, J.; Andersson, P.; Fuhrman, F.; Haglund, P.; Hallberg, E.; Holmgren, T.; Molander, S.; Rydberg, T.; Tivander, J.; Öman, A. *National inventory of emissions of additives from plastic materials*; Chalmers University of Technology: **2010**.

34. LfU Bayern *Restmüllzusammensetzung in Phasing-Out Gebieten: Abschöpfbares Wertstoffpotenzial als Funktion abfallwirtschaftlicher Rahmenbedingungen - Residual waste composition in phasing out regions : Possible useable recyclables potential as a function of waste management framework*; Bayerische Landesamt für Umwel: Augsburg, **2007**.

35. ARA *Nachhaltigkeitsbericht: Leistungsreport 2012 - Sustainability Report: Performance Report 2012*; Altstoff Recycling Austria AG: **2013**.

36. Frischenlager, H.; Karigl, B.; Lampert, C.; Pölz, W.; Schindler, I.; Tesar, M.; Wiesenberger, H.; Winter, B. *Klimarelevanz ausgewählter Recycling-Prozesse in Österreich - Climate relevance of selected recycling processes in Austria*; Umweltbundesamt GmbH: Wien, **2010**.

37. BDSV *Europäische Stahlschrottsortenliste*; Bundesvereinigung Deutscher Stahlrecycling- und Entsorgungsunternehmen e.V.: **1995**.

38. Brunner, P. H.; Döberl, G.; Eder, M.; Frühwirth, W.; Huber, R.; Hutterer, H.; Pierrard, R.; Wilfried, S.; Wöginger, H. *Bewertung abfallwirtschaftlicher Maßnahmen mit dem Ziel der nachsorgefreien Deponie - Assessment of waste management measures aiming at aftercare-free landfill* 3854576102; Technische Universität Wien & Gesellschaft für umfassende Analysen GmbH: **2001**.

39. Mauss, R. *Marktanalyse von Sekundärrohstoffen (Edelstahlschrott) - Market analysis of secondary raw materials (stainless steel scrap)*; KMR Stainless AG: BGR/DERA Rohstoffkonferenz 2013, **2013**.

40. Maystre, L.; Viret, F., A goal-oriented characterization of urban waste. *Waste management & research* **1995,** *13*, (3), 207-218.

41. Morf, L.; Ritter, E.; Brunner, P. H. *Online-Messung der Stoffbilanz auf der MVA Spittelau*; GEO Partner AG Umweltmanagement & Technische Universität Wien: Wien, Zürich, **2005**.

42. Morf, L. S.; Gloor, R.; Haag, O.; Haupt, M.; Skutan, S.; Lorenzo, F. D.; Böni, D., Precious metals and rare earth elements in municipal solid waste – Sources and fate in a Swiss incineration plant. *Waste Management* **2013,** *33*, (3), 634-644.

43. Schachermayer, E.; Bauer, G.; Ritter, E.; Brunner, P. *Messung der Güter-und Stoffbilanz einer Müllverbrennungsanlage*; Technische Universität Wien: Wien, **1995**.

44. Watanabe, N.; Inoue, S.; Ito, H., Antimony in municipal waste. *Chemosphere* **1999,** *39*, (10), 1689-1698.

45. Weigand, H.; Müller, S.; Marb, C. In *Seepage water emission of inorganic contaminants from MSWI bottom ash: results from lab-, pilot-, and field-scale experiments*, Sardinia Waste Management and Landfill Symposium 2003, S. Margarita di Pula, Cafgliari, Italy, 2003; Christensen T, C., R., Stegmann, R., Ed. CISA: S. Margarita di Pula, Cafgliari, Italy, 2003.

46. Lechtenböhmer, S.; Nanning, S.; Hillebrand, B.; Buttermann, H.-G. *Einsatz von Sekundärbrennstoffen - Use of alternative fuels*; Wuppertal Institut, EEFA GmbH: Dessau, **2006**.

47. Bosshard, P. P.; Bachofen, R.; Brandl, H., Metal leaching of fly ash from municipal waste incineration by Aspergillus niger. *Environmental science & technology* **1996,** *30*, (10), 3066-3070.

48. Chan, C. C.; Kirk, D. W., Behaviour of metals under the conditions of roasting MSW incinerator fly ash with chlorinating agents. *Journal of hazardous materials* **1999,** *64*, (1), 75-89.

49. Krebs, W.; Brombacher, C.; Bosshard, P. P.; Bachofen, R.; Brandl, H., Microbial recovery of metals from solids. *FEMS Microbiology Reviews* **1997,** *20*, (3-4), 605-617.

50. Mangialardi, T., Disposal of MSWI fly ash through a combined washing-immobilisation process. *Journal of hazardous materials* **2003,** *98*, (1), 225-240.

51. Ferreira, C.; Jensen, P.; Ottosen, L.; Ribeiro, A., Removal of selected heavy metals from MSW fly ash by the electrodialytic process. *Engineering Geology* **2005,** *77*, (3), 339-347.

52. Ishigaki, T.; Nakanishi, A.; Tateda, M.; Ike, M.; Fujita, M., Bioleaching of metal from municipal waste incineration fly ash using a mixed culture of sulfur-oxidizing and iron-oxidizing bacteria. *Chemosphere* **2005,** *60*, (8), 1087-1094.

53. Marrero, J.; Polla, G.; Jiménez Rebagliati, R.; Plá, R.; Gómez, D.; Smichowski, P., Characterization and determination of 28 elements in fly ashes collected in a thermal power plant in Argentina using different instrumental techniques. *Spectrochimica Acta Part B: Atomic Spectroscopy* **2007,** *62*, (2), 101-108.

54. Skutan, S.; Rechberger, H., Bestimmung von Stoffbilanzen und Transferkoeffizienten für die Linie II der MVA Wels - Determination of material flows and transfer coefficients for the line II of the MVA Wels. In Technische Universität Wien: Wien, 2007.

55. Sushil, S.; Batra, V. S., Analysis of fly ash heavy metal content and disposal in three thermal power plants in India. *Fuel* **2006,** *85*, (17), 2676-2679.

56. Winter, B.; Szednyj, I.; Reisinger, H.; Böhmer, S.; Janhsen, T. *Abfallvermeidung und Verwertung: Aschen, Schlacken und Stäube in Österreich - Waste reduction and recycling: ashes, slags and dusts in Austria*; Umweltbundesamt GmbH: Wien, **2005**.

57. Aguiar del Toro, M.; Calmano, W.; Ecke, H., Wet extraction of heavy metals and chloride from MSWI and straw combustion fly ashes. *Waste management* **2009,** *29*, (9), 2494-2499.

58. Karlfeldt Fedje, K.; Ekberg, C.; Skarnemark, G.; Steenari, B.-M., Removal of hazardous metals from MSW fly ash—an evaluation of ash leaching methods. *Journal of hazardous materials* **2010,** *173*, (1), 310-317.

59. Meinfelder, T.; Richers, U. *Entsorgung der Schlacke aus der thermischen Restabfallbehandlung - Disposal of slag from thermal treatment of residual waste*; Forschungszentrum Karlsruhe GmbH: Karlsruhe, **2008**.

60. Nowak, B.; Pessl, A.; Aschenbrenner, P.; Szentannai, P.; Mattenberger, H.; Rechberger, H.; Hermann, L.; Winter, F., Heavy metal removal from municipal solid waste fly ash by chlorination and thermal treatment. *Journal of hazardous materials* **2010,** *179*, (1), 323-331.

61. Wilewska-Bien, M.; Lundberg, M.; Steenari, B.-M.; Theliander, H., Treatment process for MSW combustion fly ash laboratory and pilot plant experiments. *Waste management* **2007,** *27*, (9), 1213-1224.

62. JRC-IPTS *End-of-waste criteria for waste paper: Technical proposals. Final report*; European Commission - Joint Research Centre - Institute for Prospective Technological Studies: Sevilla, **2011**.

63. Cuhls, C.; Mähl, B.; Berkau, S.; Clemens, J. *Ermittlung der Emissionssituation bei der Verwertung von Bioabfällen - Determination of the emissions situation in the use of biowaste*; Umwewltbundesamt: Dessau, **2008**.

64. Lampert, C.; Reisinger, H.; Zethner, G. *Bioabfallstrategie - Biowaste strategy*; Umweltbundesamt: Wien, **2014**.

65. Neubauer, C.; Öhlinger, A. *Ist-Stand der mechanisch-biologischen Abfallbehandlung (MBA) in Österreich: Zustandsbericht 2006 - Actual state of the mechanical-biological treatment (MBT) in Austria: Condition Report 2006*; Umweltbundesamt GmbH: Wien, **2006**.

66. Harant, M.; Nelles, M.; Hofer, M.; E, L. K.; B, R. *Stoffflussanalyse bei der mechanisch-biologischen Restabfallbehandlung - Material flow analysis for mechanical-biological treatment of residual waste*; 3902017058; Montanuniversität Leoben: **1999**.

67. Zeschmar-Lahl, B.; Jager, J.; Ketelsen, K.; Lahl, U.; Scheidel, K.; Steiner, M.; Heckmann, A. *Mechanisch-Biologische Abfallbehandlung in Europa - Mechanical-biological waste treatment in Europe*; 382633261X; Parey Buchverlag: Berlin, **2000**.

68. Binner, E.; Zach, A.; Lechner, P. *Stabilitätskriterien zur Charakterisierung der Endprodukte aus MBA Anlagen - Stability criteria for characterization of final products from MBT plants*; Universität für Bodenkultur: Wien, **1999**.

69. Denner, M.; Binner, E. *Evaluierung des Abfallannahmeverfahrens für MBA-Abfälle zur Deponierung - Evaluation of the waste acceptance procedure for MBA waste going to landfills*; Umweltbundesamt GmbH: Wien, **2007**.

70. Baumgartinger, H. J. *Einfluss der Rottedauer auf die Reaktivität von Restabfall: Laborversuche - Influence of rotting duration of the reactivity of residual waste: laboratory tests*; Universität für Bodenkultur: Wien, **1998**.

71. Egle, L.; Rechberger, H.; Zessner, M. *Phosphorbilanz Österreich: Grundlage für ein nachhaltiges Phosphormanagement (gegenwärtige Situation) und zukünftige Entwicklung - Phosphorus balance Austria: basis for sustainable management of phosphorus (current situation and future development)*; Technische Universität Wien: Wien, **2014**.

72. Fricke, K.; Santen, H.; Wallmann, R., Comparison of selected aerobic and anaerobic procedures for MSW treatment. *Waste management* **2005,** *25*, (8), 799-810.

73. Fricke, K.; Wallmann, R.; Doedens, H.; Cuhls, C. *Abluftemissionen bei der mechanisch-biologischen Restabfallbehandlung. In: Bio- und Restabfallbehandlung, Biologisch, Mechanisch, Thermisch - Exhaust emissions from mechanical-biological treatment of residual waste. In: Bio and residual waste treatment. Biologically. Mechanically. Thermal*; 0934-6422; Witzenhausen, **1996**; pp 25-34.

74. Neubauer, C.; Buxbaum, I. *Luftgetragene Emissionen an MBA-Standorten - Airborne emissions of MBA locations*; Umweltbundesamt GmbH: Wien, **2014**.

75. Skutan, S.; Brunner, P. H. *Stoffbilanzen mechanisch-biologischer Anlagen zur Behandlung von Restmüll - Material flow analysis of mechanical biological treatment plants for residual waste*; Technische Universität Wien: Wien, **2006**.

76. Angerer, T. *Abluftreinigung bei der mechanisch-biologischen Abfallbehandlung (MBA) - Air cleaning in mechanical-biological treatment (MBT)*; 3854575114; Umweltbundesamt GmbH: **1999**.

77. BZL *Mechanisch-biologische Abfallbehandlung: Trockenstabilat – Abfallwirtschaftliche Einordnung. Gutachten im Auftrag des Thüringer Ministeriums für Landwirtschaft, Naturschutz und Umwelt - Mechanical-biological waste treatment: Dry stabilat - Waste management arrangement. Report commissioned by the Thuringian Ministry of Agriculture , Conservation and Environment*; BZL Kommunikation und Projektsteuerung GmbH: **1998**.

78. Cuhls, C.; Doendens, H. *Abluftemissionen aus der MBA und deren Minderung nach dem Stand der Technik. In: Abluft und Abluftreinigung bei der mechanisch-biologischen Abfallbehandlung- Gasous emissions from MBA and their reduction to the state of the art . In: Exhaust air purification in the mechanical-biological waste treatment*; Wien, **2000**.

79. Cuhls, C.; Doendens, H.; Truppa, J.; Kock, H.; Levsen, K. *Bilanzierung von Umweltchemikalien bei der mechanisch-biologischen Abfallbehandlung - Accounting for environmental chemicals in the mechanical-biological waste treatment*; Verbundvorhaben–Mechanisch-biologische Behandlung von zu deponierenden Abfällen, Beiträge zur Ergebnispräsentation: Potsdam, **1999**.

80. Soyez, K.; Thrän, D.; Hermann, T.; Koller, M.; Plickert, S. *Ergebnisse des BMBF-Verbundsvorhabens mechanisch-biologische Abfallbehandlung*; Erich Schmidt Verlag Berlin: **2001**.

81. Böhmer, S.; Kügler, I.; Stoiber, H.; Walter, B., *Abfallverbrennung in Österreich (Statusbericht 2006) - Waste incineration in Austria (Status Report 2006)*. Umweltbundesamt GmbH: 2007.

82. Löschau, M., *Input-Output-Analyse als Methode zur stofflichen Bilanzierung komplexer Entsorgungssysteme - Input-Output analysis as a method for material accounting of complex disposal systems*. na: 2006.

83. Fehringer, R.; Rechberger, H.; Pesonen, H.-L.; Brunner, P. H. *Auswirkungen unterschiedlicher Szenarien der thermischen Verwertung von Abfällen in Österreich - Effects of different scenarios of thermal recycling facilities in Austria* Technische Universität Wien: Wien, **1997**.

84. Zeschmar-Lahl, B. *Schadstoffanreicherung im Erzeugnis aufgrund des Einsatzes von Ersatzbrennstoffen in Zementwerken und Feuerungsanlagen - Accumulation of pollutants in the product due to the use of substitute fuels in cement kilns and furnaces*; Technische Universität Berlin: Berlin, **2003**.

85. Mauschitz, G. *Emissionen aus Anlagen der österreichischen Zementindustrie (Berichtsjahr 2012) - Emissions from plants of the Austrian Cement Industry (Report 2012)*; Technische Universität Wien: Wien, **2013**.

86. Tarnawski, W., Emission factors for combustion of biomass fuels in the pulp and paper mills. *Fibres and Textiles in Eastern Europe* **2004,** *12*, (3), 91-95.

87. Kossina, I.; Grech, H. *Mitverbrennung von Abfällen und Reststoffen in industriellen Feuerungsanlagen - Co-incineration of waste and residues in industrial furnaces*; Umweltbundesamt GmbH: Wien, **2000**.

88. Boubela, G.; Wurst, F.; Prey, T.; Boos, R. *Materialien zur thermischen Behandlung und Verwertung von Abfällen und Reststoffen in der Zellstoff-, Papier-, Span und Faserplattenindustrie - Materials for thermal treatment and recycling of waste and residues in the pulp, paper, particleboard and fibreboard industry*; Umweltbundesamt GmbH: Wien, **2004**.

89. Neubauer, C.; Öhlinger, A. *mechanische Abfallbehandlung (MA) von gemischten Siedlungs- und Gewerbeabfälle in Österreich - mechanical waste treatment (MA) of mixed municipal and commercial wastes in Austria*; Umweltbundesamt GmbH: Wien, **2008**.

90. Austropapier *Jahresbericht der Papierindustrie 2013 - Annual Report of the paper industry in 2013*; Austropapier - Vereinigung der österreichischen Papierindustrie **2013**.

91. Bauer, M.; Lehner, M. *Post- consumer plastics in Austria and their potential for chemical recycling*; Montanuniversität Leoben: **2013**.

92. EAK *Tätigkeitsbericht 2012 - Activity Report 2012*; Elektroaltgeräte Koordinierungsstelle Austria GmbH: **2012**.

93. Tesar, M.; Öhlinger, A. *Elektroaltgerätbehandlung in Österreich: Zustandsbericht 2008 - WEEE treatment in Austria - Condition Report 2008*; Wien, **2008**.

94. Tabasaran, O.; Rettenberger, G., *Grundlage zur Planung von Entgasungsanlagen - Basis for planning of degassing systems*. Erich Schmidt Verlag: Berlin, 1987.

95. Laner, D. *Understanding and evaluating long-term environmental risks from landfills*; Vienna University of Technology: Vienna, **2011**.

96. Keppler, B. K.; Stojanovic, A.; Kogelnig, D.; Morgenbesser, C.; Galanski, M.; Krachler, R.; Fischer, L.; Falter, T.; Köllensberger, G.; Hann, S. *Elimination prioritärer Metalle aus kommunalen Abwässern*; Universität Wien & Universität für Bodenkultur: Wien, **2010**.

97. BMLFUW *Kommunales Abwasser: österreichischer Bericht 2014 - Municipal wastewater: Austrian Report 2014*; Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft: Wien, **2014**.