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SCIENCE DIRECT
Journal of Cleaner Production 13 (2005) 1165–1173
Journal of Cleaner Production
www.elsevier.com/locate/jclepro

Environmental systems analysis tools – an overview

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Received 9 October 2001; received in revised form 16 May 2004; accepted 16 June 2004

Abstract

A large number of tools for assessing environmental impacts are available. It is of interest to characterise different tools in order to better understand their relationships and the appropriateness of different tools in different situations. The characteristics used here are whether the tools are procedural or analytical, what types of impacts are included, what the object of the study is and whether the studies are descriptive or change-orientated. For each object discussed here, there is a tool focusing on both use of natural resources and environmental impacts that seems to be the most suitable. Because different tools focus on different objects, different tools cannot in general easily replace each other.

1. Introduction

A large number of tools for assessing environmental impacts are available [1–6]. Examples include Environmental Impact Assessment (EIA), System of Economic and Environmental Accounting (SEEA), Environmental Auditing, Life-Cycle Assessment (LCA) and Material Flow Analysis (MFA). Because they all focus on environmental impacts, it is of interest to characterise the different methods in order to better understand their interrelationships and the appropriateness of different tools in different applications. In this paper, different tools are discussed in relation to some characteristics. This paper is largely based on a series of earlier reports [7–11]. This work has been done largely in parallel to the CHAINET project [6]. The aim of that book is to link demand and supply of environmental information in the field of Life-Cycle Management. Its focus is on analytical tools for business decision-making. In this paper we will include also some procedural tools and tools used at a societal level, thus broadening the scope. In this paper we start by describing a number of tools using some characteristics of the tools. In the end of the paper we are discussing the tools in relation to some aspects of the decision context, which are described in the discussion. The tools were chosen after discussions with a reference group with members from the Swedish Environmental Protection Agency (EPA) and industries. The characteristics of the tools and the decision context are based on previous studies [1,6,9,12]. It may be possible to use other aspects and characteristics to structure the tools.

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0959-6526/$ - see front matter
doi:10.1016/j.jclepro.2004.06.004

2. Characteristics

Different tools can be described in relation to a number of different characteristics [1,6,9,12]. Here we focus on four aspects:

1. Is the tool a procedural or an analytical tool?
   Procedural tools focus on the procedures and the connections to its societal and decision context,

List of acronyms

CBA	Cost–Benefit Analysis
DMC	Direct Material Consumption
DMI	Direct Material Input
EF	Ecological Footprint
EIA	Environmental Impact Assessment
EMAS	Eco Management and Audit Scheme
EMS	Environmental Management System
En	Energy Analysis
EU	European Union
GE	General Equilibrium
GDP	Gross Domestic Product
IOA	Input–Output Analysis
ISO	International Organisation for Standardisation
LCA	Life-Cycle Assessment
LCC	Life-Cycle Costing
LCM	Life-Cycle Management
MFA	Material Flow Accounting
MIPS	Material Intensity Per Unit Service
NGO	Non-Governmental Organisation
OECD	Organisation for Economic Co-operation and Development
SEA	Strategic Environmental Assessment
SEEA	System of Economic and Environmental Accounts
SFA	Substance Flow Analysis
TMR	Total Material Requirement

whereas analytical tools focus on technical aspects of the analysis [6]. Analytical tools can be used within the framework of procedural tools.

2. What types of impacts are considered?
   Here the distinctions are made between tools that focus on the resources used or the environmental impacts, or both, and if economic aspects are included as well [9].
3. What is the object of the study?
   Here the distinction is made between five groups of objects [9]:
   - Policies, plans, programmes and projects
   - Regions or nations
   - Organisations, companies
   - Products and services
   - Substances

These objects are related in different ways. For example, a policy may concern the use of a substance in a product within a region. However, if an assessment is made concerning such a policy, the policy is the object of the study, not the specific product, substance or region. So, even in cases where the objects are related, it is often one object which can be identified as the object of the study.

4. Is the tool used in descriptive or change-orientated studies?
   This is an aspect which has been much discussed, especially within the LCA world where it is recognised that choices concerning data and methodology may depend on the intended goal of the study. A distinction is often made between descriptive (attributional or accounting studies) and change-orientated (consequential or effect-orientated) studies [13–16]. If the study is change-orientated, it analyses the consequences of a choice; ideally the data and system boundaries used should then reflect the actual changes taking place, and may depend on the scale of the change and the time over which it occurs. Studies, which are not change-orientated, may be called environmental reports or accounting studies. Such studies are describing a system as it actually was (or would be) at a specific time. In such studies, the appropriate data and system boundaries should reflect what was actually happening in the system.

While recognising the importance of characterising different tools, it is also important to note that most tools are flexible and not always well defined. The characteristics that are discussed here may be seen as endpoints on scales where many tools can take several positions.

3. Overview of tools

Material Flow Accounting (MFA) is a family of different methods [17]. A common feature is the focus on material flows, especially on the input side. Different MFA methods have different objects in focus. Three types are briefly mentioned here: Total Material Requirement (TMR), Material Intensity Per Unit Service (MIPS) and Substance Flow Analysis (SFA). TMR and MIPS can also be described as bulk-MFA methods.

Total Material Requirement and related concepts such as DMI (Direct Material Input) and DMC (Direct Material Consumption) have a nation as their principal object of study. While TMR aims at calculating all material inputs to the society, including both direct and hidden inputs [18], DMI and DMC focus on the direct inputs, excluding hidden flows such as mining wastes. Recently, the total outputs and the changes of stocks of nations have also been considered [19]. The approach has developed during the 1990s and has mainly been used in accounting studies.

The MIPS is similar to TMR by focusing on the material inputs of the system, but in this case the object is a product or a service. This makes MIPS similar also to LCA (see below). The MIPS method was also developed during the 1990s. Aggregation is made in five categories: abiotic materials, biotic materials, water, air and soil [20].

An SFA focuses on specific substances, either within a region or from "cradle-to-grave" [21]. Typical examples can include studies of nitrogen flows in a county or flows of a specific metal in a country [22]. Like other MFA methods, SFA focuses on inputs, but in addition it also follows substances within the economic system to trace the outputs.

In principle, MFA methods can be used in both descriptive and change-orientated studies. In practice, the bulk-MFA methods (TMR and MIPS) have typically been applied in accounting studies using accounting methodology and data. Substance Flow Analyses have been applied in both accounting and change-orientated studies (e.g. [23]).

Input–Output Analysis (IOA) is a well-established analytical tool within economics and systems of national accounts [24] using a nation or a region as the object of the study. The input–output matrixes describe trade between industries. An IOA can be applied to include environmental impacts either by adding emissions coefficients to the monetary IOAs or by replacing the monetary input–output matrixes with matrixes based on physical flows. The former is the type most often used and discussed [25,26]. By applying such environmental IOA, results can be presented for sectors and also for broad product groups. The IOA is typically applied using descriptive data and methodology for accounting purposes. A recent exception is, however, the approach to a dynamic environmental life-cycle assessment based on input–output modelling [27].

Systems for economic and environmental accounts (SEEA) are established and developed within many countries [28]. The SEEA is a system of satellite accounts to the system of national accounts. It has the economic activities within a nation as the primary object. It includes both systems for physical accounts, i.e. measures of inputs and outputs (resources used and emissions) and monetary accounts. In some countries the system includes monetary valuation of different types of environmental impacts, which are monetised using different types of valuation techniques [29], which may be similar to techniques used for LCC and CBA (described below). Calculations of Green GDP (Gross Domestic Product) or similar measures have also been made. In SEEA, environmental IOA are used for assessing environmental impacts from different sectors [30] and TMR and similar MFA measures may be used as indicators [31]. As the name suggests, SEEA is a system for accounting studies. Data from the system can, however, also be used in different types of economic policy models, such as General Equilibrium (GE) models or econometric models, which have been applied to study the effects of different policy measures, for example concerning environmental taxes [28].

Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA) are both change-orientated procedural tools. The first of these, EIA, is an established tool mainly for assessing environmental impacts of projects (e.g. [32]). In contrast to many of the other tools discussed here, it is generally a site-specific tool. The locations of the planned project and associated emissions are often known and an EIA is often used to evaluate alternative locations. It is required in different regulations in many countries. The SEA is a more recent tool intended to be used at an earlier stage in the decision-making process, on a more strategic level (e.g. [33]). It is intended to be used for policies, plans and programmes. Its use is still limited but different types of guidelines are being developed as well as an EU-directive (Dir. 2001/42/EC). Since SEA is used on a strategic level, the exact location of different emissions sources may not be known, a feature which may require different assessment methods compared to a more traditional EIA. Since EIA and SEA are procedural tools, different analytical tools may be used as parts of the process. For example, MFA and LCA could be used as parts of an SEA (cf. [34]). Both EIA and SEA typically include environmental impacts as well as the use of natural resources. It is sometimes suggested to include economic and social aspects as well in a broader sustainability assessment, but this is typically not regarded as general practice.

Environmental Management System (EMS) with Environmental Auditing is mainly a procedural tool (cf. [6]). Two standards for EMS are EMAS (Eco Management and Audit Scheme) and ISO 14001 (International Organisation for Standardisation). Both include Environmental Auditing [35,36]. The EMS and Environmental Auditing are applied on an organisation, e.g. a company or a governmental agency. Environmental Auditing is a descriptive assessment typically including environmental aspects as well as resource use.

Life-Cycle Assessment (LCA) is a tool to assess the environmental impacts and resources used throughout a product's life from raw material acquisition through production use and disposal. The term 'product' can include not only product systems but also service systems. An ISO standard has been developed for LCA providing a framework, terminology and some methodological choices [37–39]. Initiatives have also been taken to develop best available practice [40,41]. The LCA is mainly an analytical tool. It can be used both as a descriptive tool as well as a change-orientated tool with different choices of data and methodology (e.g. [15]).

Life-Cycle Costing (LCC) can be used to assess the costs of a product or a service from a life-cycle perspective. It can also include social and environmental costs (e.g. [42]). It is an analytical tool that can be applied both in descriptive and change-orientated studies.

Cost–Benefit Analysis (CBA) is an analytical tool for assessing the total costs and benefits from a planned project. It is a well-established tool described in textbooks on environmental economics e.g. [43], sometimes required by regulations. In principle, all costs and benefits, including environmental costs, should be included and monetised. In the evaluation the costs are compared to the benefits. Although it is typically applied on projects, it can be used more broadly especially as a valuation method. If applied on products, a CBA can be similar to an LCC, although an LCC typically does not include benefits.

Energy Analysis (En) has many similarities with bulk-MFA methods. They focus on the inputs in physical measures and they may be used as evaluation techniques for different types of objects. There are several different types of energy measures. One example is exergy, which can be defined as a measure of available energy. It has been applied on many different types of systems, e.g. process engineering systems [44], nations [45] and products [46]. In emergy analysis the total inputs of energy, materials, information and labour are added using emergy-equivalents which describe the accumulated energy associated with the different types of inputs [47].

Ecological footprint (EF) is also an evaluation method which in principle can be applied on different types of objects, although it has mainly been used on regions, nations and projects such as aquaculture. The results are presented in terms of area used. The focus is on the area necessary for different types of activities, but the indirect area which could be used for assimilating different types of emissions is also included [48].

Risk assessment is a broad term covering many different types of assessments. Here, a distinction is made between risk assessment of chemical substances and risk assessment of accidents. The latter may include environmental aspects. Risk assessment of accidents concerns unplanned incidents, e.g. explosions and fires. This is typically in contrast to risk assessment of chemicals, where dispersion of chemicals is often planned and forms part of its use. Methods and protocols for risk assessment of chemicals have been developed in several international fora, e.g. EU and OECD [49]. In the risk assessment of chemicals, an exposure assessment including a description of nature and size of exposed targets, as well as magnitude and duration of exposure, is combined with an effect assessment [49–51]. The aim can be to define target values or acceptable risks. In the risk assessment of accidents, the probability for accidents is combined with an assessment of possible consequences of an accident. Risk assessment of accidents is typically done prospectively for different types of projects [52].

4. Discussion

The tools presented above have been described using some characteristics for the tools. Many of the tools are intended to be used as a support in decision-making. A decision context can be described in many dimensions. Moberg et al. [9] uses the following:

- the actor (e.g. a company, a governmental agency, an NGO)
- the scale (e.g. a big, important decision or a small decision)
- the complexity of the decision
- the uncertainty of the decision
- the timing of the impacts (e.g. in the near future or a distant future)
- the activity concerned by the decision (e.g. investment, purchasing, decommissioning, planning, maintenance, research priorities, product development, etc.)
- the object
- the impacts of interest

Activities are related to objects. For example investment, purchasing and product development can all be related to the object product. Different activities can also relate to different objects. For example, an investment can be related to a product or a project. Both activities and objects are therefore of relevance for the decision context.

Within the CHAINET project [6], the following characteristics of a decision framework were identified, the first three as core characteristics and the latter as context characteristics:

- Decision object
- Temporal and spatial characteristics
- Question types (strategic planning, capital investments, design and development, communication and marketing and operational management including purchasing)
- Level of improvement (from incremental improvements to system redesign)
- Importance of subsystem
- Aspiration of decision-maker (defensive followers, continuous improvers or pro-active innovators)
- Level of chain control (the degree of control by an actor in a chain of processes)
- Decision types (from regular and routine decisions to single, unique decisions)
- Decision steps (Issue definition, criteria setting, option generation, option assessment and final decision)
- Cultural context

When linking tools and decision context, some aspects of the context will influence the choice of tool, whereas others will influence how the tools are used, for example if a simplified or a detailed study is performed. The link between tools and decision context will first of all depend on the object of study of the different tools [6,9]. For example, LCA is traditionally used for products and EIA is traditionally used for projects. They cannot easily replace each other, so if the object of the study is a project, EIA is the natural choice rather than LCA or another method developed for another object. The object of the study is therefore a key aspect. This is in turn partly related to aspects such as the activity concerned by the decision and question types. The connection between the tools and the object of study can also work the other way around. If a certain tool is chosen for a particular problem, it implies that the object of study also is determined.

Another aspect which determines the choice of tool is what types of impacts the decision-maker is interested in [9]. For example, if the decision-maker is interested in economic impacts, a tool not including economic impacts is of limited relevance. On the other hand, if the decision-maker is not interested in economic impacts, and perhaps distrusts socio-economic assessments, it is not of much significance in providing this person with results from an economic analysis. Since different tools cover different impacts, this is an important dimension when choosing tools.

Some aspects of the decision context, such as the scale of the decision, will influence the resources put into the analysis. It will thus influence how the tools are used if a screening study, a detailed study, or no study at all is performed. It will however, probably not influence which tool is chosen, for example an EIA instead of an LCA.

Some aspects of the decision context such as the actor, the complexity, the uncertainty, level of improvement, aspiration of the decision-maker and the cultural context can influence what is regarded as relevant questions. They will thus have an influence on what impacts the decision-maker will be interested in, and what object the study should focus on. These choices are influenced by world views and values. The framing of the decision may determine what is regarded as a relevant object to study. The choice of which impact to include is also influenced by views on which types of impacts are possible and meaningful to study [57]. Different stakeholders may therefore find different tools appropriate.

In conclusion it is suggested that the two key aspects of the decision context determining the choice of tools are the object of the study and the impacts of interest. Other aspects will either influence how the chosen tools are used, or have an indirect influence via the key aspects. These two dimensions are used in Fig. 1, where the different tools are summarised.

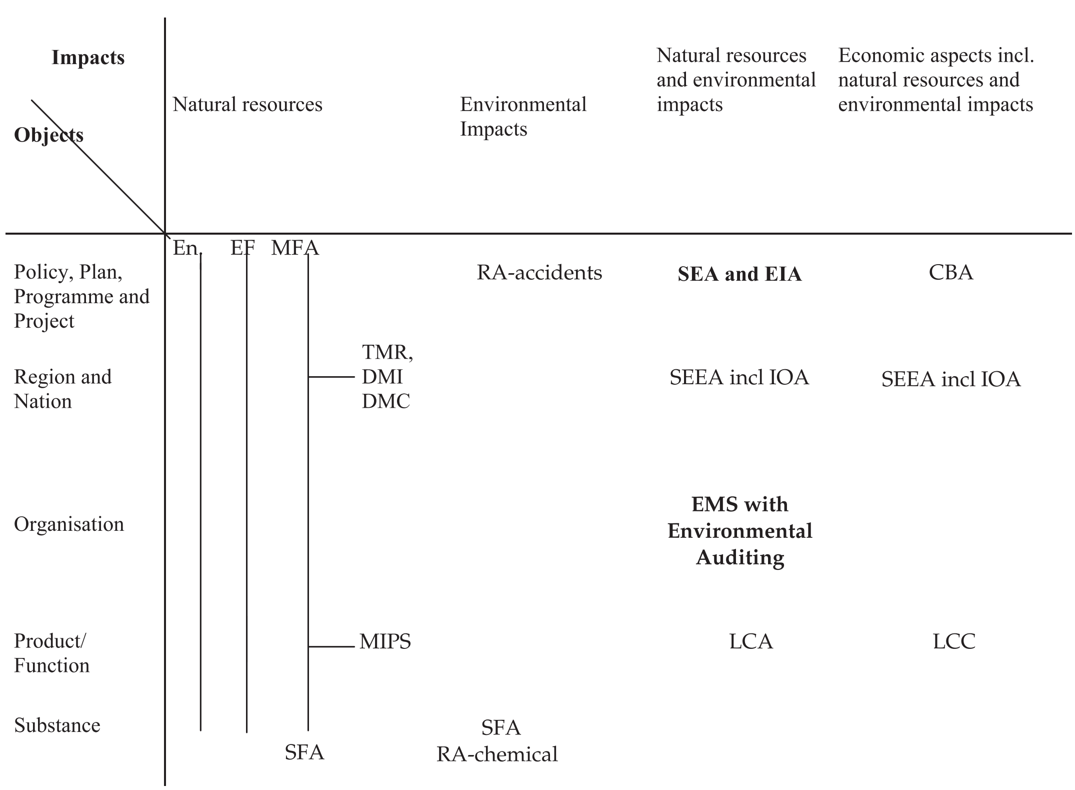

Fig. 1. The tools are shown in relation to their focus, i.e. the object to which the impacts are related and to which aspects are included in the study. Procedural tools are written in bold text. Modified from Ref. [9].

It is interesting to note that in Fig. 1, there is spread of different tools, suggesting that the two chosen characteristics, impacts included and objects studied, are suitable for describing and characterising different tools. Several of the tools focus on natural resources as inputs, either energy, materials or space, and can be used as evaluation methods for a wide range of objects. For tools that focus on both the use of natural resources and environmental impacts, it seems that for each object there is a tool that is the most suitable. For example, if the object under study is a project, EIA is the most suitable tool and cannot easily be replaced by other tools if the focus is on the use of natural resources and environmental impacts. This suggests that there is indeed a need for a large number of different assessment tools. Only with difficulty can different tools be applied on the same object or replace each other.

Fig. 1 also suggests that there are tools available for most objects discussed here, with the possible exception of tools assessing both environmental and economic impacts of organisations and companies. In Fig. 1, procedural tools are written in bold. There are procedural tools available for some objects but not all. This could suggest a need for developing such tools. However, the lack of tools could also be because there is no need for such tools.

As discussed here, many of the most often used tools have specific characteristics as environmental systems analysis tools. An SEA is intended for policies, plans and programmes, whereas EIA is used for planned projects. The tool for studying environmental impacts from nations and regions is SEEA, using different methods within the system. Environmental management systems with environmental auditing are used for organisations, for example companies. The tools LCA and LCC are used on products and services. Risk assessments of chemicals are used for specific substances. Substance flow analysis also has a clear role as a tool for assessing flows and impacts of chemical substances. Bulk flow material analysis, on the other hand, can be regarded as an evaluation method that may be applied to different types of objects resulting in slightly different methods such as MIPS and TMR. The value of bulk flow material analysis is discussed, as it is a proxy method for environmental impacts [53]. In our experiences, combinations of bulk flow material analysis and energy analysis are useful as they both are proxy methods but can complement each other because they typically capture slightly different aspects, but together provide a more holistic picture e.g. [54].

Combinations of methods can be used to provide a more comprehensive picture. Five different types of relationships between tools can be distinguished [1]: consecutive, complementary, competing, encompassing and overlapping. In practice, the latter will normally be the case. An example of a consecutive use of tools is if SEA is used on plans which are later followed up by concrete projects where EIA is used. Tillman et al. [58] compare EIA and LCA in a case study on waste water treatment. They find that the tools are complementary and somewhat overlapping. The EIA provided information on local, site-specific aspects which the LCA did not include. On the other hand, the LCA provided information on global impacts. The two tools use different system boundaries and different objects of the studies. An example of an encompassing method is when exergy analysis is used as a method for life-cycle impact assessment [46].

There are several aspects of the tools which need to be considered when several tools are to be used in combination. For example:

- Degree of site-specificity. As discussed above, some tools are generally site-specific, whereas others are generally site-independent. Between these two extremes, there may be a continuum with different types of site-dependency [55].
- Degree of time-specificity.
- Type of comparison. Most methods include some sort of comparison, either between different alternatives, or within a studied system or against a reference.
- Degree of quantification.
- System boundaries which are largely determined by the object under study.
- Impacts included.

Differences between tools with regard to these aspects can determine if and how different tools can be used in combination. If two tools are identical with respect to all these aspects, they may be competing. If there are differences, they answer different questions. This means that they can complement each other by adding different types of results. If tools are to be used sequentially or encompassing, it is important that the tools are compatible when information is to be transferred between them.

As described above, different tools have been developed and used mainly for accounting purposes, and others for change-orientated studies. In Fig. 2, a tentative division of tools as accounting and change-orientated is made in relation to how they have normally been applied. Since both accounting and change-orientated studies are useful depending on which question is to be answered, it is of interest to discuss whether the same types of methodologies and data can be used for both types of studies, or if adaptations should be made.

Within the LCA world there is a growing awareness that there may be a need for different sets of data and methodology depending on whether the tool is used for

Type of study / Objects	Accounting	Change-orientated
Policy, Plan, Programme and Project		**SEA, EIA**, CBA
Region and Nation	TMR, IOA SEEA	Economic policy models with input from SEEA
Organisation, Company	Environmental Auditing	
Product/ Function	LCA	LCA
Substance	SFA	SFA, RA-chemicals

Fig. 2. A tentative divisions of some tools as accounting and change-orientated in relation to how they have been used and to what extent prospective or retrospective data and methodology are used. Procedural tools are written in bold text.

accounting or change-orientated studies. The choice of data is discussed briefly here. In change-orientated studies, the data used should ideally reflect the actual changes taking place. This would normally imply using some sort of marginal data. This is in contrast to accounting studies, where average data may be more appropriate for reflecting what was actually used [15]. For example, if an extra MJ of electricity will be used if a certain choice is made, this MJ is not likely to come from the average electricity production, but rather from a marginal source of electricity and this should be reflected in a change-orientated study. It is clear that there are different types of marginal data and that the relevant marginal data may be difficult to identify and may depend on the scale of the change, the time-period and other factors (e.g. [56]). Often a distinction is made between a short-term marginal assuming the current capacities without any new investments and a long-term marginal including also the possibilities for new investments. The difference between change-orientated studies and accounting studies may also have repercussions for other parts of LCA methodology such as choice of system boundaries (e.g. [15]) and impact assessment methodology [40,41]. While it has been recognised that in most cases change-orientated prospective studies are generally of largest interest, in practice many LCAs have been performed using data and methodology appropriate for retrospective, accounting studies.

The discussion on differences between accounting and change-orientated studies seems to be largely lacking for other tools. However, it may be the case that some of the conclusions from the discussion within the LCA world can be valid for other tools as well. For example, for other tools it also seems reasonable to use some sort of marginal data for change-orientated studies and average data for accounting studies. Fig. 2 suggests that there may be some tools lacking. When the focus is on nations and regions, some economic methods are available for change-orientated studies, whereas other methods used within the SEEA are mainly used for accounting studies. For organisations and companies too, there seems to be a lack of methods for prospective, change-orientated studies. This may be because we have failed to find such methods, or because there has not been any perceived need for such methods, but there may also be a genuine need for developing new methods to fill this hole.

SEEA, bulk flow MFAs, such as TMR, and Environmental Auditing have mainly been used for accounting purposes. However, it is clear that many interesting applications lie in change-orientated studies. It would, therefore, be of general interest to discuss how these tools can be applied to prospective studies. What types of changes in methodology and data would be appropriate?

Acknowledgements

This work was financially supported by the Foundation for Strategic Environmental Research, the Swedish Waste Research Council at the Swedish EPA and the Swedish Ministry of Defence. Discussions with colleagues at fms (especially Jessica Johansson and the late Peter Steen) have been useful. We are grateful for the help we received from a number of specialists on the tools we describe. This paper is a further elaboration of papers presented at a Conaccount workshop [11] and the LCM Conference [7]. Comments at these meetings and later from Viveka Palm and Anders Wadeskog at Statistics Sweden have been valuable.

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