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ORIGINAL ARTICLE

A life cycle methodology for mapping the flows of pollutants in the urban environment

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Abstract This paper presents an integrated life cycle methodology for mapping the flows of pollutants in the urban environment, following the pollutants from their sources through the environment to receptors. The sources of pollution that can be considered by this methodology include products, processes and human activities. Life cycle assessment (LCA), substance flow analysis (SFA), fate and transport modelling (F&TM) and geographical information systems (GIS) have been used as tools for these purposes. A mathematical framework has been developed to enable linking and integration of LCA and SFA. The main feature of the framework is a distinction between the foreground and background systems, where the foreground system includes pollution sources of primary interest in the urban environment and the background comprises all other supporting activities occurring elsewhere in the life cycle. Applying the foreground–background approach, SFA is used to track specific pollutants in the urban environment (foreground) from different sources. LCA is applied to quantify emissions of a number of different pollutants and their impacts in both the urban (foreground) and in the wider environment (background). Therefore, two ''pollution vectors'' are generated: one each by LCA and SFA. The former comprises all environmental burdens or impacts generated by a source of interest on a life cycle basis and the latter is defined by the flows of a particular burden (substance or pollutant) generated by different sources in the foreground. The vectors are related to the ''unit of analysis'' which represents a modified functional unit used in LCA and defines the level of activity of the pollution source of interest. A further methodological development has also included integration of LCA and SFA with F&TM and GIS. A four-step methodology is proposed to enable spatial mapping of pollution from sources through the environment to receptors. The approach involves the use of GIS to map sources of pollution, application of the LCA–SFA approach to define sources of interest and quantify environmental burdens and impacts on a life-cycle basis. This is followed by F&TM to track pollution through the environment and by the quantification of site-specific impacts on human health and the environment. The application of the integrated methodology and the mathematical framework is illustrated by a hypothetical example involving four pollution sources in a city: incineration of MSW, manufacture of PVC, car travel and truck freight.

Keywords Life cycle assessment · Substance flow analysis · Fate and transport modelling · GIS · Urban pollution · Sustainable development

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Notation

$(B_{j,n})_B$	total environmental burden j from the background system n
$(B_{j,n})_F$	total environmental burden j from the foreground system n
$(E_{k,n})_B$	total environmental impact k from the background system n
$(E_{k,n})_F$	total environmental impact k from the foreground system n
B_j	total burden j from all sources (in all foreground systems)

$B_{j,\text{exp}}$ exports of burden j from the foreground systems
$B_{j,\text{imp}}$ imports of burden j into the foreground systems
$b_{j,i}$ burden j from source i
$b_{j,l}$ burden j from source l in the background system n
$b_{j,m}$ burden j from source m in the foreground system n
$B_{j,m}$ total burden j from source m (in all foreground systems)
$e_{k,j}$ relative contribution of burden B_j to impact E_k
x_i mass or energy flow associated with source i
x_l mass or energy flow from source l in the background system n
x_m mass or energy flow from source m in the foreground system n

Introduction

Urban living offers significant benefits to society in terms of employment and education opportunities, access to services, increased mobility, etc. As a result, each year urban areas are gaining an estimated 67 million people—about 1.3 million every week (UN 2006). It is expected that by 2030 about 5 billion people, or 60% of the world population, will be living in urban areas. In developed countries, the proportion of the urban population is expected to be much higher, increasing from the current 75–82% by 2030. Such rapid urbanisation can create enormous stresses on the urban environment and human health (UNEP 1992). These stresses extend far beyond the land that urban areas occupy and immediate pollution generated in cities as urban areas claim the ecological output and life-support functions of both nearby areas and distant regions (McMichael 2002). For example, urban areas take up just 2% of the earth's surface but account for about 75% of wood use. Similarly, 60% of the water withdrawn for human use goes to urban areas—about half of that to irrigate food crops for urban residents, roughly one-third for use by industry and the remainder for drinking and sanitation (O'Meara 1999). However, the wider environmental impact of urban areas is often invisible to urban residents themselves because the ecosystems and activities that support and enable living in cities may be far away. For example, electricity that powers the homes of urban dwellers is often generated outside cities, so that the environmental impact of electricity generation goes largely unnoticed by the urban user of electricity. Similar is true for many other human activities in urban areas: the environmental impacts of supporting urban living through provision of goods and services are often generated elsewhere. This has lead to a well-known problem of urban environmental disconnect whereby urban residents use goods and services without necessarily understanding where they come from, what happens to them after use and what environmental impacts they have generated along the way. And yet, understanding the full environmental impacts of urban activities, occurring both directly in cities and indirectly elsewhere, is essential for devising more sustainable strategies for management of pollution caused by urban living. In other words, a life cycle approach to managing urban pollution is needed to help identify options for reducing the total environmental footprint of human activities in urban areas rather than just shift environmental impacts from one area to another or from one life cycle stage to another.

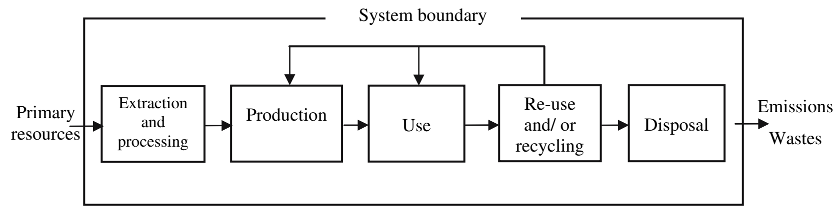
In an attempt to contribute towards this objective, this paper presents a new life cycle methodology for mapping the flows of pollutants in the urban environment and understanding their impacts from ''cradle to grave''. The methodology enables tracking of pollutants from sources (products, process and human activities), through the environment to receptors using four tools: life cycle assessment (LCA), substance flow analysis (SFA), fate and transport modelling (F&TM) and geographical information systems (GIS). A mathematical model has been developed to enable integration of LCA and SFA within a single framework. The methodological approach is illustrated on a case study of a (hypothetical) city with 500,000 inhabitants.

A life cycle approach to mapping the flows of pollutants: integrating LCA and SFA

Similarities and differences between LCA and SFA

Life cycle assessment is a tool for quantifying environmental impacts of human activities from ''cradle to grave'', i.e. from the extraction of raw materials, through the production of products to their use and post-use waste management (see Fig. 1). Therefore, LCA lends itself naturally for use within this framework. SFA enables tracking of substances, including pollutants, through human economy, taking into account flows and stocks in the system, as illustrated in Fig. 2. Integrating LCA and SFA would therefore provide a powerful tool for mapping the flows of pollutants in the environment on a life cycle basis. However, this is not a straightforward task as neither tool is directly applicable to the analysis of the urban environment. Furthermore, although they are similar in some respects, they are also quite different tools, both with respect to the methodology and the types of question that they address. For example, Fig. 3 illustrates a difference related to the scope of the analysis covered by each tool. As depicted in the figure, SFA has a more narrow scope than LCA—while LCA encompases sources, receptors, pollu-

Fig. 1 LCA: life cycle stages considered from ''cradle to grave''



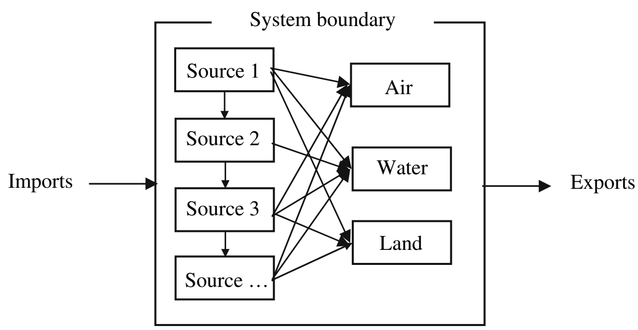


Fig. 2 SFA: Tracking the flows of substances and pollutants into, within and out of an economic system

tants and impacts, SFA concentrates on sources and pollutants only. Furthermore, as shown in Fig. 3, neither tool integrates F&TM. Although there have been some attempts to link LCA and F&TM (for a summary see Appendix 1), the methodology is still evolving and very few LCA studies incorporate it currently.

Further similarities and differences between LCA and SFA are summarised in Table 1. The table also gives some examples of the types of questions that can be addressed by LCA and SFA.

Therefore, some adaptation and integration of the methodologies is necessary before the two tools can be applied in the context of urban pollution. The following section outlines how this can be done. This is followed by an example to demonstrate how the methodology could be applied depending on the type of questions asked. The final sections of the paper describe the methodology for integration of LCA and SFA with F&TM and GIS.

Methodology for integration of LCA and SFA

In LCA, it is often useful to divide the system into foreground and background, as shown in Fig. 4. The foreground system is defined as a set of activities or processes of direct interest that are delivering the defined functional unit while the background supports the activities in the foreground by supplying the necessary energy and materials. Depending on whether they are generated in the foreground or background, the environmental burdens (use of materials and energy, emissions to air, water and land) are termed ''direct'' or ''indirect'', respectively. This distinction between the foreground and background is particularly useful when it is important to distinguish between local and wider impacts—as is the case with urban pollution. This is normally not possible with the conventional LCA approaches since the impacts are spatially aggregated along the life cycle of an activity or pollution source.

Applying the foreground–background approach can help integrate the two tools. The approach is illustrated in Fig. 5, where the foreground system refers to a source in the urban environment of interest and the background comprises all other supporting activities occurring elsewhere. Similarly, direct burdens refer to pollution released in the urban environment and indirect burdens are generated elsewhere in the life cycle of the activity of interest. In this context, SFA can be used to track a specific substance in the urban environment (foreground) from different sources. LCA provides an envelope around that to consider a number of different substances both in the urban (foreground) and in the wider environment (background). For example, if car travel is the human activity of interest, then

Fig. 3 The scope of LCA and SFA

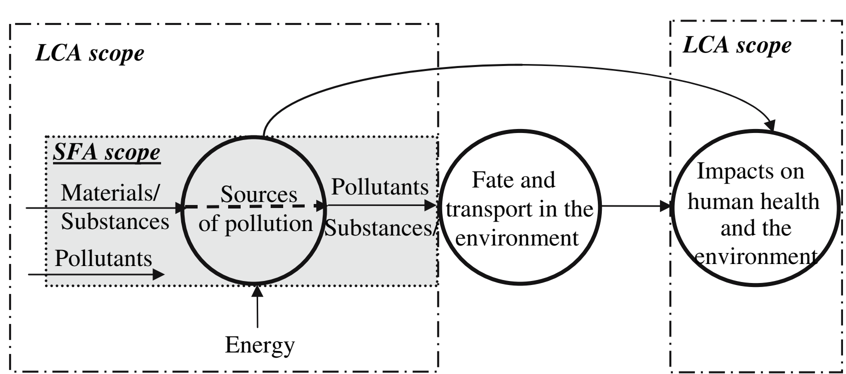


Table 1 Similarities and differences between LCA and SFA and the types of questions they address

Similarities	
Based on systems approach	
Quantify material/substance/pollutant flows	
Consider flows within a certain systems boundary	
Distinguish between direct and indirect flows	
Cannot distinguish between urban and global environment	
Provide results that can be used as an input into fate and transport modeling	
Differences	
LCA	SFA
Geographically non-specific	Refers to a specific geographical area
Quantifies both environmental burdens and impacts	Normally quantifies flows of substances/ pollutants only
Takes into account energy flows	Energy normally not considered
Follows a number of substances from a variety of sources in the life cycle of an activity	Concentrates on one substance and its sources within a certain geographical area
Based on ''functional unit''	Based on the material flows in a certain period, usually 1 year
Examples of questions asked	
In LCA studies	In SFA studies
What are the environmental ''hot spots'' in the life cycle of a product, process or an activity?	Where do the substances come from and where do they go?
Which environmental burdens and impacts are most significant in the life cycle of a product, process or an activity?	What are the main sources of substance flows in one region/country over a certain period of time?
How would marginal/step changes to a product, process or activity affect the environmental impacts on a life cycle basis?	Where and how big are the stocks of materials/substances in the economy/environment?
Which alternative products, processes or activities are environmentally more sustainable?	How can economic activities be dematerialised and how can waste materials be reused?
What are the life-cycle implications of recycling?	Which industrial sources/economic activities should be targeted 2by policy makers for a maximum effect?
How can a policy be defined to ensure minimum environmental impact throughout the life cycle of a product, process or an activity?	

LCA can be used to assess the total (foreground and background) pollution and environmental impacts along the whole life cycle of that activity, from the extraction of the fuel and its refining (in the background system) to the use of a car in the urban environment (foreground system). SFA is applied to assess direct pollution by mapping the flows of individual pollutants from cars and any other activities of interest in the urban environment.

Therefore, the application of this framework produces two ''pollution vectors'': one generated by LCA and one by SFA. The former comprises all the burdens generated by a product, process or an activity on a life cycle basis and the latter is defined by the levels of a particular burden (substance or pollutant) generated by different sources in the urban environment. The vectors are related to the ''unit of analysis'' which is equivalent to the ''functional unit'' used in LCA and represents the level of activity of the source of interest (e.g. treatment of x tonnes of solid waste; travel of y km by car etc). This is further explained by an example which illustrates how this proposed framework for linking LCA and SFA could be applied for the urban environmental analysis. However, prior to introducing the example, we continue here to describe the mathematical model for the integrated LCA–SFA framework.

Note that Fig. 5 shows a total of N foreground and background systems with each foreground having an associated background. However, in reality, in any one analysis there will be one urban environment of interest which will be supported by a number of activities in the background system. Nevertheless, for clarity and the ease of explanation of the mathematical framework, we adopt

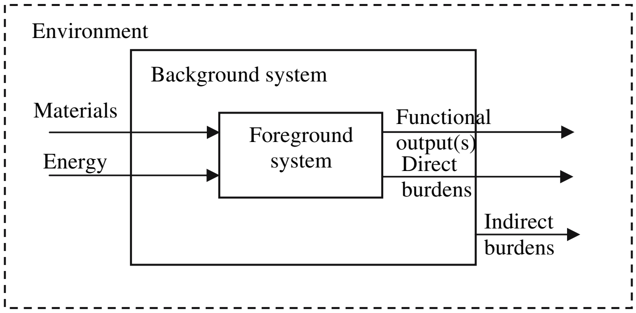


Fig. 4 Dividing the system into foreground and background to distinguish between direct and indirect burdens

the nomenclature whereby each foreground has one associated background system.

Mathematical model for integrating LCA and SFA

The mathematical framework developed here draws on the existing methodology for quantifying environmental burdens and impacts by LCA (ISO 1997) and the flow accounting approaches used in SFA. However, the two methodologies are integrated and adapted using the foreground–background approach outlined in the previous section. This is discussed next.

Environmental burdens quantified by LCA

In conventional LCA, the environmental burdens are calculated according to the following formula (Azapagic 2002):

$$B_j = \sum_{i=1}^{I} b_{j,i} x_i \quad j = 1, 2, \ldots, J \tag{1}$$

where $b_{j,i}$ is burden j from process or activity i and x_i is a mass or energy flow associated with that activity (normally expressed in kg and MJ per unit of analysis, respectively). Applying this equation to calculate the environmental burdens in the foreground and background systems we have:

– Foreground system

$$(B_{j,n})_F = \sum_{m=1}^{M} b_{j,m} x_m \quad j = 1, 2, \ldots, J, \quad n = 1, 2, \ldots, N \tag{2}$$

– Background system

$$(B_{j,n})_B = \sum_{l=1}^{L} b_{j,l} x_l \quad j = 1, 2, \ldots, J; \quad n = 1, 2, \ldots, N \tag{3}$$

where:

- $(B_{j,n})_F$ total environmental burden j from the foreground system n
- $(B_{j,n})_B$ total environmental burden j from the background system n
- $b_{j,m}$ burden j from activity m in the foreground system n
- $b_{j,l}$ burden j from activity l in the background system n
- x_m mass or energy flow from activity m in the foreground system n
- x_l mass or energy flow from activity l in the background system n.

Total environmental burdens from both the foreground and background systems can then be calculated as:

$$(B_{j,n})_{F,B} = (B_{j,n})_F + (B_{j,n})_B \quad j = 1, 2, \ldots, J, \quad n = 1, 2, \ldots, N \tag{4}$$

or, substituting Eqs. 2 and 3 into Eq. 4 we have:

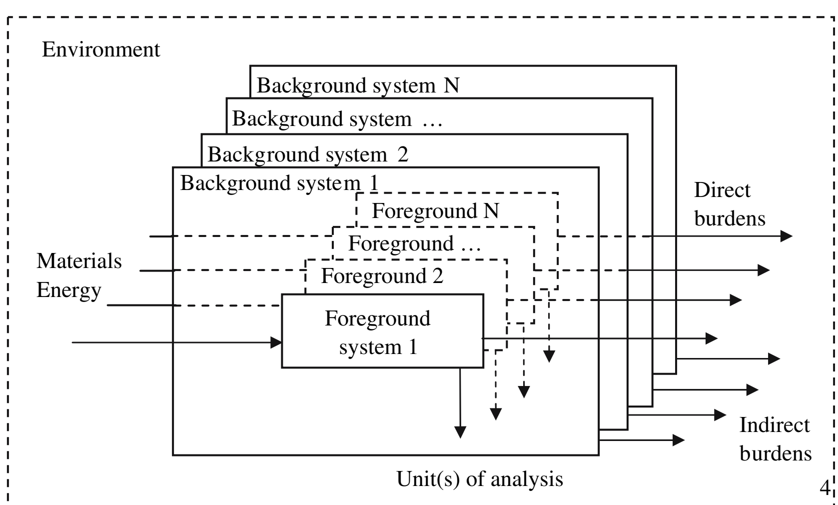


Fig. 5 The conceptual approach to linking LCA and SFA: the foreground represents the urban environment of interest and the background all other supporting activities outside the urban area of interest that ''feed'' into the foreground

$$(B_{j,n})_{F,B} = \sum_{m=1}^{M} b_{j,m}x_m + \sum_{l=1}^{L} b_{j,l}x_l \quad j = 1,2,\ldots,J, \quad n = 1,2,\ldots,N \tag{5}$$

which gives us the total environmental burdens as expressed by Eq. 1:

$$(B_{j,n})_{F,B} = \sum_{i=1}^{I} b_{j,i}x_i \quad j = 1,2,\ldots,J, \quad n = 1,2,\ldots,N, \; I = M + \mathrm{L} \tag{1a}$$

Environmental impacts quantified by LCA

In LCA, the environmental impacts are calculated according to the formula (Azapagic 2002):

$$E_k = \sum_{j=1}^{J} e_{k,j}B_j \quad k = 1,2,\ldots,K \tag{6}$$

where $e_{k,j}$ represents the relative contribution of burden B_j to impact E_k, as defined by the problem-oriented approach (Heijungs et al. 1992). Table 4 in Appendix 2 lists coefficients $e_{k,j}$ for selected burdens.

Using Eq. 6 to translate the burdens into environmental impacts, we have:

– Foreground system

$$(E_{k,n})_F = \sum_{j=1}^{J} e_{k,j}(B_{j,n})_F \quad k = 1,2,\ldots,K, \quad n = 1,2,\ldots,N \tag{7}$$

– Background system

$$(E_{k,n})_B = \sum_{j=1}^{J} e_{k,j}(B_{j,n})_B \quad k = 1,2,\ldots,K, \quad n = 1,2,\ldots,N \tag{8}$$

where:

$(E_{k,n})_F$ total environmental impact k from the foreground system n

$(E_{k,n})_B$ total environmental impact k from the background system n

$e_{k,j}$ relative contribution of burden B_j to impact E_k, as defined by the problem-oriented approach in LCA.

Therefore, the total environmental impacts from the foreground and background systems can be calculated as

$$(E_{\mathrm{k,n}})_{F,B} = (E_{k,n})_F + (E_{k,n})_B \quad \mathrm{k} = 1,2,\ldots,K, \quad n = 1,2,\ldots,N \tag{9}$$

or, substituting Eqs. 7 and 8 into Eq. 9 we get:

$$(E_{k,n})_{F,B} = \sum_{j=1}^{J} e_{k,j}(B_{j,n})_F + \sum_{j=1}^{J} e_{k,j}(B_{j,n})_B = (E_{k,n})_{F,B} = \sum_{j=1}^{J} e_{k,j}\left[(B_{j,n})_F + (B_{j,n})_B\right] \tag{10}$$

which gives us the total environmental impacts as expressed by Eq. 6:

$$(E_{k,n})_{F,B} = \sum_{j=1}^{J} e_{k,j}(B_{j,n})_{F,B} \quad k = 1,2,\ldots,K, \quad n = 1,2,\ldots,N. \tag{6a}$$

Environmental burdens quantified by SFA

In general, the total flow of a particular substance (or pollutant) generated by different sources can be quantified by SFA according to the following formula:

$$B_j = \sum_{m=1}^{M} B_{j,m} + B_{j\,\mathrm{imp}} - B_{j\,\mathrm{exp}} \quad j = 1,2,\ldots,J \tag{11}$$

where B_j is the total amount of substance j from all sources of interest and $B_{j,m}$ is the flow of substance j from source m; $B_{j,\mathrm{imp}}$ and $B_{j,\mathrm{exp}}$ represent imports and exports of substance j in and from the system of interest, respectively.

Using the notation in Eq. 11, and ignoring the imports and exports (these would be accounted for by LCA as the background burdens), we can find out the total environmental burden j from different sources in N foreground systems:

$$(B_j)_F = \sum_{n=1}^{N} (B_{j,n})_F \quad j = 1,2,\ldots,J \tag{12}$$

Thus, substituting Eq. 2 into Eq. 12 we get the total environmental burden j in all foreground systems from a total of M different sources:

$$(B_j)_F = \sum_{n=1}^{N}\sum_{m=1}^{M} b_{j,m}x_m \quad j = 1,2,\ldots,J \tag{13}$$

Therefore, Eqs. 13 and 2 represent a link between SFA and LCA in terms of environmental burdens, adapted for use in the urban environment context.

Environmental impacts quantified by SFA

Although this is not normally part of SFA, we can also calculate the environmental impact k from burden j in a foreground system n as:

$$(E_{k,n})_F = e_{k,j}(B_{j,n})_F \quad k = 1, 2, \ldots, K, \ n = 1, 2, \ldots, N \tag{14}$$

The total impact from all sources in the foreground is then equal to:

$$(E_k)_F = e_{k,j}(B_j)_F \quad j = 1, 2, \ldots, J, \ k = 1, 2, \ldots, K \tag{15}$$

or substituting Eq. 12 into 14 we have:

$$(E_k)_F = e_{k,j} \sum_{n=1}^{N} (B_{j,n})_F \quad j = 1, 2, \ldots, J, \ k = 1, 2, \ldots, K \tag{16}$$

Finally, substituting Eq. 2 into 16, we can calculate the total environmental impact from burden j from different sources in the foreground system:

$$(E_k)_F = e_{k,j} \sum_{n=1}^{N} \sum_{m=1}^{M} b_{j,m} x_m \quad j = 1, 2, \ldots, J, \quad k = 1, 2, \ldots, K \tag{17}$$

Therefore, Eqs. 17 and 7 link SFA and LCA in terms of environmental impacts, adapted for application to urban pollution. This mathematical framework is now illustrated by an example.

Applying the integrated LCA–SFA methodology: an example

To illustrate how the above LCA–SFA framework can be applied, we consider a hypothetical city with approximately 500,000 inhabitants. The following selected human activities and sources of pollution are assumed within the city, typically found in a city of this size:

– incineration of municipal solid waste in a mass-burn municipal solid waste incinerator with the capacity of 200,000 tonnes/year;
– car travel by 100,000 petrol-fuelled cars each travelling an average of 5,000 miles per year within the city;
– goods freight by 50,000 diesel-fuelled trucks each travelling on average 5,000 miles per year within the city; and
– manufacturing of polyvinylchloride (PVC) in a plant producing 120,000 tonnes/year.

Figure 6 shows the activities in the foreground and the background, with the incineration, car travel, freight and manufacture of PVC being located in the foreground (i.e. in the city) and the auxiliary materials (i.e. ammonia for cleaning up the incinerator flue gas, petrol and diesel for the cars and trucks, respectively, and ethylene, chlorine and oxygen for the PVC plant) being brought from the background to enable the four activities in the foreground. The air and water emissions from these four sources are also in the foreground, while the solid waste from the incinerator and PVC plant is disposed of in the background. Note that, for the ease of graphical representation, there is only one foreground and background system—following the notation in Figure 5, each of the activities would have been shown in a separate foreground with the associated background system.

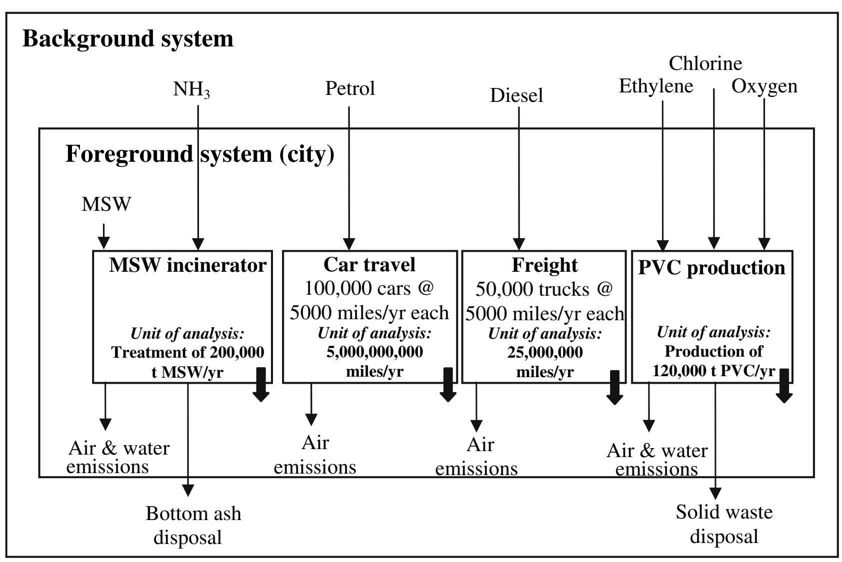


Fig. 6 An example illustrating application of the integrated LCA–SFA framework

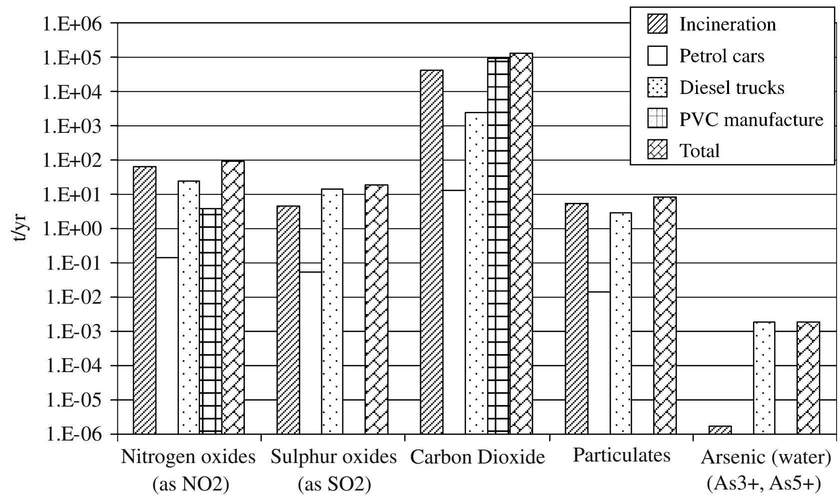


Fig. 7 LCA–SFA results for selected environmental burdens from all sources in the foreground (urban environment)

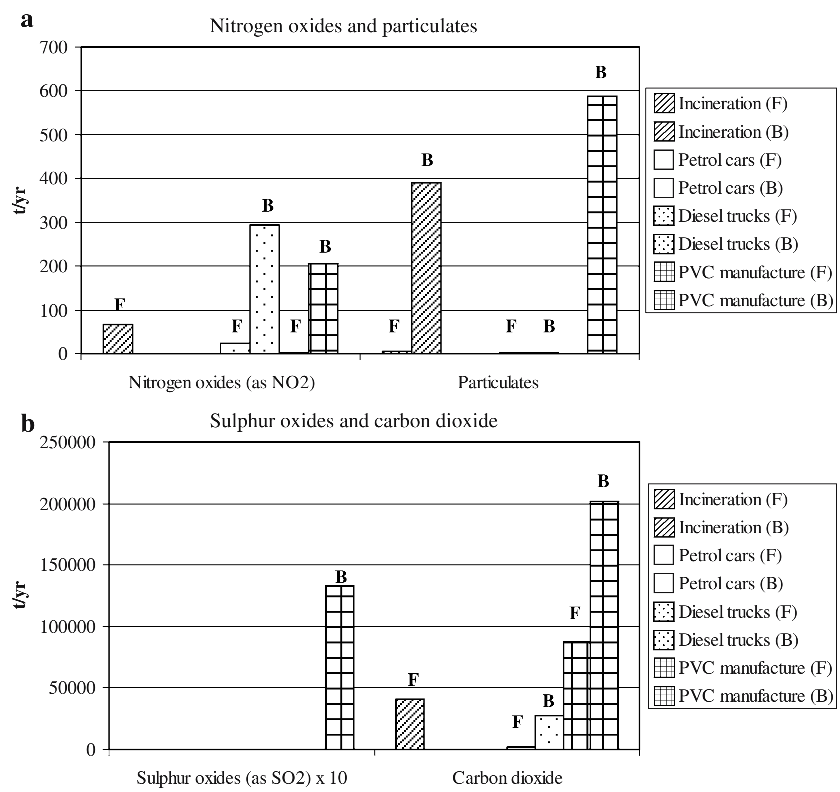


Fig. 8 Combined LCA–SFA results for selected environmental burdens in the foreground and background. **a** Nitrogen oxides and particulates. **b** Sulphur oxides and carbon dioxide

To quantify the environmental burdens and impacts in the foreground and background systems from these sources, LCA and SFA have been carried out using databases available within the WISARD (EA 2003) and SimaPro 5.1 (PRé Consultants 2002) software packages. The analysis is based on a ''unit of analysis'' which is shown in Figure 6 for each of the four sources of interest. For example, the unit of analysis for the incinerator is ''treatment of 200,000 tonnes of MSW per year''. This is equivalent to the functional unit in LCA. The LCA–SFA results, calculated using Eqs. 2 and 13 for selected foreground burdens are shown in Fig. 7. Figure 8 shows the combined results for both the foreground and background systems calculated using Eqs. 5 and 13. The environmental impacts in the foreground are shown in Fig. 9 and for the combined foreground and background results are given in Fig. 10. These have been calculated using Eqs. 7 and 17 and 10 and 17, respectively.

For example, Fig. 7 shows that the largest source of CO_2 emissions in the foreground in this example is the PVC manufacture generating around 88,000 t/year. The next largest source of CO_2 is MSW incineration with just over 42,000 t/year. Similar results are noticed for the other

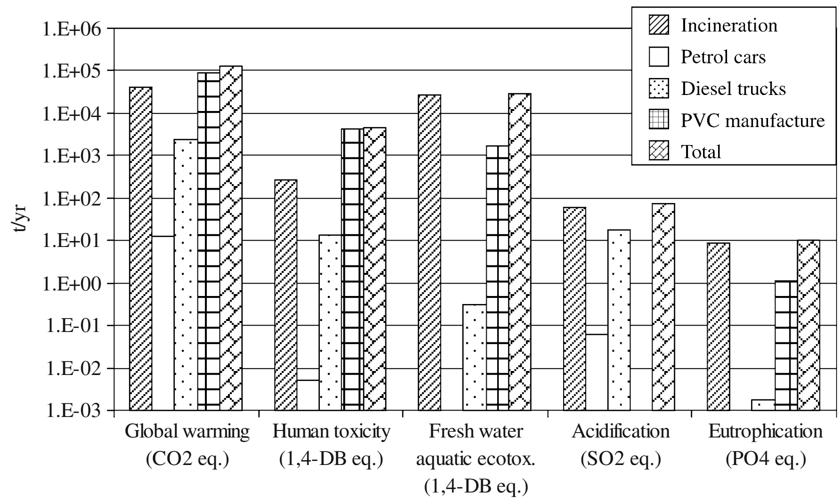


Fig. 9 LCA–SFA results for selected environmental impacts in the foreground

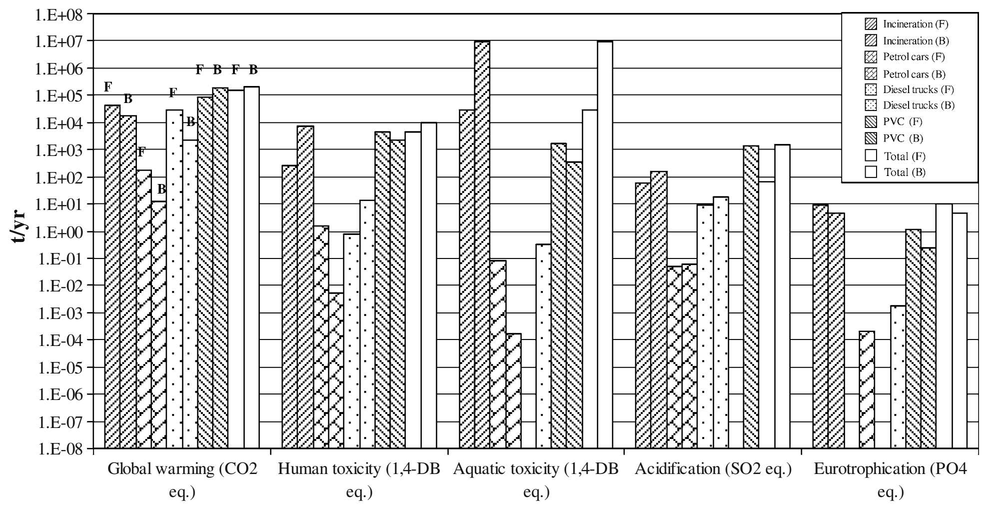


Fig. 10 Combined LCA–SFA results for selected environmental impacts in the foreground and background (Legend: *F* foreground; *B* background; note that each impact category shows first the results for the foreground, followed by background, as shown for global warming)

environmental burdens: from the four sources considered in this example, MSW incineration and PVC manufacture are the largest sources of pollution in the urban environment. Comparing the direct emissions from the PVC manufacture with the PVC-related CO_2 emissions in the background (Fig. 8b), we notice that at around 194,000 t/year the emissions in the background are 2.2 times higher than in the foreground. Similar is true for the other sources: with the exception of MSW incineration, the majority of the emissions considered here are in the background system, generated by the activities that support the four activities in the urban environment.

Analysing the results for environmental impacts in Fig. 9 (calculated taking into account all environmental burdens in the life cycles of the four sources not only those shown in Figs. 7 and 8), we notice that PVC manufacture and MSW incineration, respectively, are the largest sources of impacts in the foreground. The exception to this is acidification which is mainly generated by incineration and freight. Comparison of the impacts in the foreground and background in Fig. 10 shows a varied picture. For example, global warming potential, human and aquatic toxicity from car travel are higher in the foreground (i.e. in the city) than in the background, while the opposite is true for acidification and eutrophication. Freight, on the other hand, has a significantly higher global warming potential in the foreground than in the background while all other impacts from this activity are higher in the background than in the foreground.

In the example of MSW incineration it is also interesting to note what happens with the environmental burdens and impacts if the system is credited for the environmental impacts avoided by recovering energy from waste. Since MSW incineration displaces the need for an equivalent fossil fuel-based energy output, for every 41,000 t CO_2 eq./year of global warming potential generated by incineration in the foreground, 75,000 t CO_2 eq./year are avoided in the background by not using the fossil-fuel based system. Therefore, the total global warming effect for MSW

Table 2 Example questions that could be answered by applying the integrated LCA–SFA framework in the example of the (hypothetical) city

Questions	Answers
Where are the environmental ''hot spots'' in the life cycle of the sources considered—in the urban environment (foreground) or elsewhere (background)?	Elsewhere (background) for the majority of impacts (see total (F) & total (B) in Fig. 10)
Which environmental burdens and impacts are most significant in the life cycle of an activity—or in other words, what are the relevant environmental sustainability indicators?	Varies, depending on the activity (Fig. 10)
What are the major sources of pollutants in the urban area over a certain period of time?	PVC production and MSW incineration (Figs. 7 and 9)
How would certain human activities affect the urban environment?	The foreground burdens and impacts are shown in Figs. 7 and 9
What effects does a certain activity have on the health of urban dwellers?	MSW incineration and PVC production have highest health effects in this example (Fig. 9)
What is the wider environmental cost of supporting certain activities in the urban areas?	The background burdens and impacts are shown in Figs. 8 and 10
What is the ''avoided burden'' of reusing waste materials?	34,000 t CO_2 eq. /year is saved by recovering energy from MSW
Which industrial sources/economic activities should be targeted by policy makers for a maximum effect?	In this example, MSW incineration and PVC production

incineration is negative at –34,000 t CO_2 eq./year (not shown in the figures).

This type of analysis can also give us an idea of the relative significance of the impacts both locally and globally to help determine the relevant sustainability indicators overall or for each source. For example, Fig. 9 shows that contribution to global warming from incineration, PVC manufacture and truck freight is more significant than from car travel. Contribution to aquatic toxicity is more significant from incineration and PVC than from other sources while, for example, acidification appears not to be a relevant sustainability indicator for PVC production. Understanding which impacts are relevant for what sources can help target the right environmental problems for a maximum effect.

Therefore, by applying the integrated LCA–SFA approach to the analysis of environmental burdens in this example, we have been able to offer answers to some of the questions listed in Table 1. For illustration, answers to some of these questions, as obtained in this example, are summarised in Table 2.

We now turn our attention to developing further the LCA–SFA framework to enable integration with fate and transport modelling (F&TM) and GIS.

Integrating LCA, SFA, F&TM and GIS

As shown in Fig. 3, tracking the flows of pollutants from sources through the environment to the receptors will require incorporation of site-specific considerations, such as spatial distribution of pollution sources and receptors. While the integrated LCA–SFA methodology presented here enables identification and quantification of environmental burdens and impacts in the urban environment (and elsewhere), it does not tell us where exactly within the urban environment the sources of pollutants and receptors are situated nor where the pollutants will eventually end up and how they will affect the receptor at that point. To enable that, the LCA–SFA methodology has to be integrated within a GIS platform and with F&TM. The proposed methodology for integration is outlined below and its application illustrated on the example presented in the previous section.

As illustrated in Fig. 11, the integrated methodology consists of the following four steps:

1. Spatial definition of sources in GIS;
2. Definition of sources using the LCA–SFA methodology;
3. Quantification of burdens (and optionally, potential impacts) at source using the LCA–SFA methodology; and
4. F&TM and quantification of the environmental impacts at the receptor end (end point) for mapping in GIS.

Although the following explanation follows the four steps in sequence, the methodology is modular so that different steps can be used in isolation or in different combinations, depending on the goal of the study and the needs of the user. The emphasis here is on the urban environment; however, the methodology could be applied in a wider context.

Spatial definition of sources in GIS

The first step of the integrated methodology involves definition of sources in the urban environment, their geographical position and spatial distribution. The sources

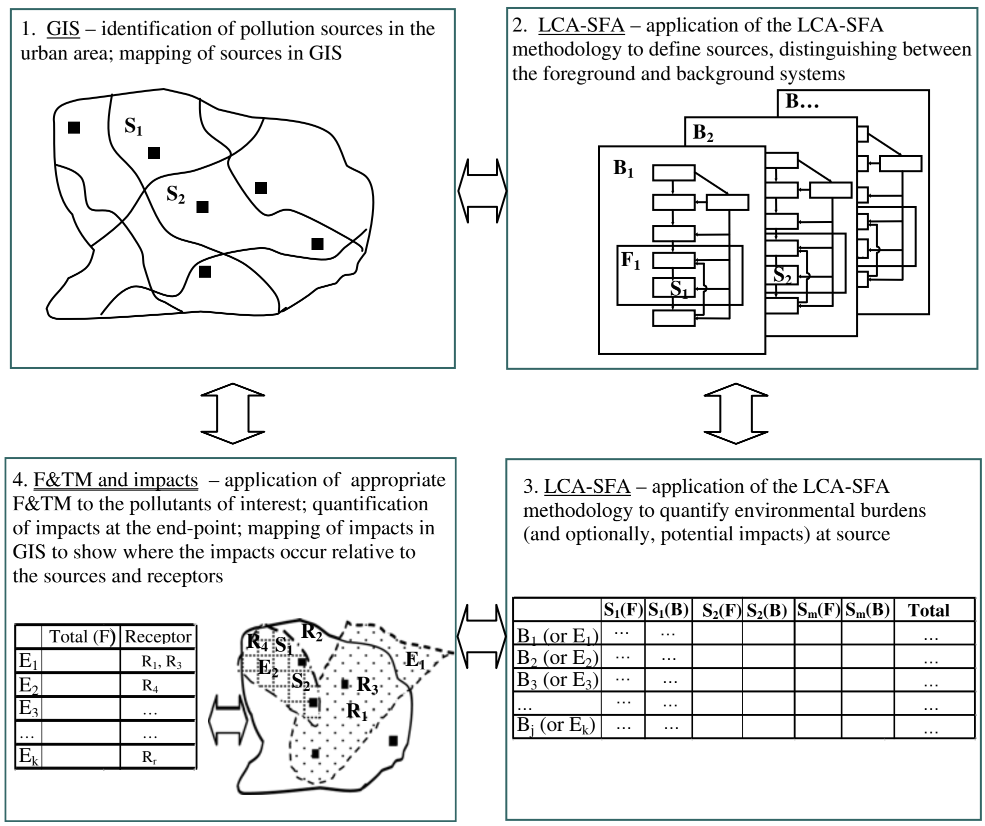


Fig. 11 Integrating LCA, SFA, F&TM and GIS (*F* foreground; *B* background; B_j environmental burden; E_k environmental impact; R_r receptor; S_m pollution source in the foreground)

of interest are then mapped onto GIS maps to show their location.

Applying this step to the example of our city presented in the previous section, the four sources of pollution considered (MSW incineration, car travel, truck freight and PVC manufacture) would be first mapped in GIS. As MSW incineration and PVC manufacture are point sources, their location is easily defined by their latitude and longitude coordinates. The car travel and freight are diffuse sources, distributed throughout the urban area, so that their mapping is more difficult and would probably span several map sectors. In most cities, however, car travel and freight are more intensive in certain parts than in the others, so that it may be possible to simplify the mapping by concentrating on the ‘‘hot spots‘‘.

Definition of sources using the LCA–SFA methodology

This (and the following) step of the methodology involves application of the integrated LCA–SFA methodology as described in the section on *Methodology for integrating LCA and SFA*. In this step, the sources of interest are defined taking a life cycle approach and distinguishing between the activities in the foreground (city) and background (wider environment). This part of the integrated methodology has been illustrated on our example in the previous section.

Quantification of burdens and impacts using the LCA–SFA methodology

This step is also part of the integrated LCA–SFA methodology and involves quantification of environmental burdens and potential environmental impacts from the sources of interest using the equations defined in section on *Mathematical model of integrating LCA and SFA*. Selected impact factors $e_{k,j}$ for calculating potential environmental impacts by problem-oriented approach used in LCA are given in Table 4 in Appendix 2.

In our example, we have quantified five environmental burdens from the four sources of interest in both the foreground and the background. We have also quantified five potential impacts. These impacts are potential rather than actual because they are calculated at the point of release with one pollutant theoretically contributing to several impacts, the approach normally used in LCA. To find out the actual impacts, F&TM has to be carried out first and then the impacts calculated at the point where pollutants reach the receptor. This is part of the final step of this methodology.

F&TM, quantification and GIS mapping of environmental impacts at the receptor end

Fate and transport modelling enable tracking the flows of pollutants from the point of release through the environment to receptors. Depending on the scope and objectives of the study, different fate and transport models can be applied (e.g., air and water dispersion with single or multi-compartment models).

The concentrations of pollutants obtained by F&TM are then used to quantify the related impacts on human health and the environment at the receptor end. Various approaches can be used for these purposes, including health impact analysis (Cleall et al. 2005) and life cycle impact assessment methods, such as CML baseline method (Guinée et al. 2001) and Eco-indicator 99 (Goedkoop and Spriensma 2001). As shown in Fig. 11, these data can then be imported into the GIS platform to map the areas and receptors affected by the quantified impacts.

For example, the emission of SO_2 from MSW incineration could be modelled using an air dispersion model to find out how far from the source it will be deposited at the ground level and at what concentration. The acidification impact of this SO_2 concentration at the identified distance from the source can then be calculated using Eq. 14 (or Eq. 6) and the acidification factor for SO_2 listed in Table 4. The air dispersion and deposition of SO_2 can then be mapped onto the GIS maps to show the spread of the pollutant and the area affected by acidification from incineration (for an illustration, see step 3 in Fig. 11). The same procedure can be repeated for the other three sources; the total acidification impact from all sources can then be calculated using Eq. 17.

Figure 11 shows that this whole process is iterative and that the earlier steps may be revisited in the light of the outcome of the later ones. Alternatively, each step could be undertaken on its own, depending on the scope and type of analysis and decision-making problem.

Conclusions

Tackling the challenge of urban pollution requires an integrated and systematic approach in order to understand the sources of pollution, fate of pollutants and their subsequent impact on the environment and human health. The methodology presented in this paper is an attempt to provide such an approach. By integrating LCA, SFA, F&TM and GIS within the same framework, it is possible to provide answers to a range of questions related to sustainable management of urban pollution. These range from process—and product-related to human activity—and policy-related questions. One feature of the methodology is that, while it focuses on the urban environment, it also helps to understand the wider environmental implications of the activities that support urban living but occur elsewhere in the life cycle, often far away from the urban area of interest. This is important to ensure that reduction of pollution in the urban environment is not carried out at the expense of ''other'' environments. Integration of GIS within this framework enables visualisation of the relationship between pollution sources, fate of pollutants and their impacts and as such can be used as a communication and decision-support tool. Further work will include development of a software platform to support this methodological development.

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Appendix 1: Integrated LCA and F&T models

See Table 3

Table 3 Multimedia fate models used in conjunction with LCA (Hertwich et al. 2002)

Model	Remarks
EQC ChemCAN	Steady-state multimedia models that describe the regional partitioning of chemicals. Currently used by DuPont and the USEPA in some scoring applications, as well as in some LCA case studies where exposure factors were added
SimpleBOX 1.0, 2.0; Uniform System for the Evaluation of Substances (USES) 1.0, 2.0; European Union System for the Evaluation of Substances (EUSES); USES-LCA	SimpleBOX is a steady-state multimedia model; recent release is an evaluative model with nested boxes (local, regional, continental, global). USES and EUSES combine SimpleBOX with an exposure model both for humans, ecosystems, and a limited number of animals. EUSES was developed for risk screening in the European regulation of hazardous chemicals. USES-LCA is a modified version of USES 2.0, which has been adapted for calculating human and ecological toxic equivalency factors and includes sea compartments
CalTOX	Integrated fate and exposure model for humans, used by Cal-EPA for hazardous waste site assessment and in some USEPA tools for HTP calculations. Steady-state model version is used typically, although a time-dependent representation of the soil compartment exists
Total risk integrated methodology (TRIM)	Describes the spatial distribution of pollutants by using a large number of adjacent boxes for each compartment. Exposure assessment for both humans and ecosystems. Complicated by the level of spatial and temporal representation

Table 3 continued

Model	Remarks
Modular approach	The mass balance is developed in two separate steps: (1) Exposure is calculated for each medium in an independent module based on the steady-state mass balance within the medium, accounting for transfer to other media as a sink but assuming that there is no feedback transfer (2) Compartments are connected on the basis of intermedia transfer factors to determine the first-order increases in concentration. It thus becomes possible to determine the level of coupling between compartments or to couple single-medium models

Appendix 2: Definition of environmental impacts in the problem-oriented approach in LCA

(Adapted from Azapagic et al. 2004)

Non-renewable resource depletion includes depletion of fossil fuels, metals and minerals. The total impact is calculated as

$$E_1 = \sum_{j=1}^{J} \frac{B_j}{ec_{1,j}} \quad (-) \tag{A1}$$

where B_j is the quantity of a resource used per functional unit and $ec_{1,j}$ represents the estimated total world reserves of that resource.

Global warming potential (GWP) is equal to the sum of emissions of the greenhouse gases multiplied by their respective GWP factors, $e_{2,j}$:

$$E_2 = \sum_{j=1}^{J} ec_{2,j} B_j \quad (\text{kg}) \tag{A2}$$

where B_j represents the emission of greenhouse gas j. GWP factors $ec_{2,j}$ for different greenhouse gases are expressed relative to the global warming potential of CO_2, which is therefore unity. The values of GWP depend on the time horizon over which the global warming effect is assessed. GWP factors for shorter times (20 and 50 years) provide an indication of the short-term effects of greenhouse gases on the climate, while GWP for longer periods (100 and 500 years) are used to predict the cumulative effects of these gases on the global climate.

Ozone depletion potential (ODP) indicates the potential of emissions of chlorofluorohydrocarbons (CFCs) and other halogenated HCs for depleting the ozone layer and is expressed as

$$E_3 = \sum_{j=1}^{J} ec_{3,j} B_j \quad (\text{kg}) \tag{A3}$$

where B_j is the emission of an ozone depleting gas j. The ODP factors $ec_{3,j}$ are expressed relative to the ozone depletion potential of CFC-11.

Acidification potential (AP) is based on the contributions of SO_2, NOx, HCl, NH_3, and HF to the potential acid deposition, i.e. on their potential to form H+ ions. AP is calculated according to the formula:

$$E_4 = \sum_{j=1}^{J} ec_{4,j} B_j \quad (\text{kg}) \tag{A4}$$

where $ec_{4,j}$ represents the acidification potential of gas j expressed relative to the AP of SO_2, and B_j is its emission in kg per functional unit.

Eutrophication potential (EP) is defined as the potential of nutrients to cause over-fertilisation of water and soil, which can result in an increased growth of biomass. It is calculated as:

$$E_5 = \sum_{j=1}^{J} ec_{5,j} B_j \quad (\text{kg}) \tag{A5}$$

where B_j is an emission of species such as N, NOx, NH_4^+, PO_4^{3-}, P, and COD and $ec_{5,j}$ are their respective eutrophication potentials. EP is expressed relative to PO_4^{3-}.

Photochemical oxidants creation potential (POCP) is related to the potential of VOCs and NOx to generate photochemical or summer smog. It is usually expressed relative to the POCP classification factors of ethylene and can be calculated as:

$$E_6 = \sum_{j=1}^{J} ec_{6,j} B_j \quad (\text{kg}) \tag{A6}$$

where B_j are the emissions of the species participating in the formation of summer smog and $ec_{6,j}$ are their classification factors for photochemical oxidation formation.

Table 4 Relative contribution ($e_{k,j}$) of selected burdens (B_j) to impacts (E_k), as defined by the problem-oriented approach in LCA [see Eq. 6 and (A1)–(A8)]

Impacts (E_k)	Resource depletion	Global warming 100 years (GWP)	Ozone depletion (ODP)	Acidification (AP)	Eutrophication (EP)	Photochemical smog (POCP)	Human toxicity (HT)	Aquatic toxicity
Relative contribution ($e_{k,j}$) to impacts E_k Burdens (B_j)	$e_{1,j}$ (world reserves)	$e_{2,j}$ (kg CO_2 eq./kg GHG)	$e_{3,j}$ (kg CFC-11 eq./kg ODP subst.)	$e_{4,j}$ (kg SO_2 eq./kg AP subst.)	$e_{5,j}$ (kg PO_4 eq./kg EP subst.)	$e_{6,j}$ (kg C_2H_4/kg POCP subst.)	$e_{7,j}$ (kg 1,4-DB/kg of HT subst.	(m^3/mg)
Coal reserves	8.72E + 13 t							
Oil reserves	1.24E + 11 t							
Gas reserves	1.09E + 14 m^3							
CO_2		1						
NOx				0.7	0.13			
SO_2				1				
CH_4		21				0.007		
Aldehydes (avrg.)						0.443		
Chlorinated HCs (avrg.)		400	0.5					
CFCs (avrg.)		5,000	0.4					
Other VOCs (avrg.)		11	0.005			0.007		
HCl				0.88				
HF				1.6				
NH_3				1.88	0.33			
As							A: 30,000	A:290,000
							W: 880	W:160,000
							S: 490	81,000
Co							A: 9,000	A: 7,200,000
							W: 99	W: 5,800,000
							S: 61	S: 2,900,000
Cd							A: 160,000	A: 1,500,000
							W: 23	W: 290,000
							A: 90	S: 150,000
Hg							A: 1,200	A: 1,600,000
							W: 250	W: 280,000
							S: 200	S: 220,000
Ni							A: 38,000	A: 5,000,000
							W: 310	W: 3,000,000
							S: 160	S: 1,500,000
Pb							A: 360	A: 9,000
							W: 12	W: 1,500
							S: 180	S: 880

Table 4 continued

Impacts (E_k)	Resource depletion	Global warming 100 years (GWP)	Ozone depletion (ODP)	Acidification (AP)	Eutrophication (EP)	Photochemical smog (POCP)	Human toxicity (HT)	Aquatic toxicity (m^3/mg)
Relative contribution ($e_{k,j}$) to impacts E_k Burdens (B_j)	$e_{1,j}$ (world reserves)	$e_{2,j}$ (kg CO_2 eq./kg GHG)	$e_{3,j}$ (kg CFC-11 eq./kg ODP subst.)	$e_{4,j}$ (kg SO_2 eq./kg AP subst.)	$e_{5,j}$ (kg PO_4 eq./kg EP subst.)	$e_{6,j}$ (kg C_2H_4/kg POCP subst.)	$e_{7,j}$ (kg 1,4-DB/kg of HT subst.	
Zn							A: 110 W: 0.57 S: 0.35	A: 89,000 W: 18,000 S: 9,400
Phenols								A: 0.77 W: 0.016
Nitrates					0.42			
Phosphates					1			

A air; *W* water; *S* soil

Human toxicity potential (HTP) is calculated by taking into account releases toxic to humans to three different media, i.e. air, water and soil:

$$E_7 = \sum_{j=1}^{J} ec_{7,jA} B_{jA} + \sum_{j=1}^{J} ec_{7,jW} B_{jW} + \sum_{j=1}^{J} ec_{7,jS} B_{jS} \quad \text{(kg)} \tag{A7}$$

where $ec_{7,jA}$, $ec_{7,jW}$, and $ec_{7,jS}$ are human toxicological classification factors for substances emitted to air, water and soil, respectively, and B_{jA}, B_{jW} and B_{jS} represent the respective emissions of different toxic substances into the three environmental media. The toxicological factors are calculated relative to 1,4 dichlorobenzene (1,4-DB).

Aquatic toxicity potential (ATP) can be calculated as

$$E_8 = \sum_{j=1}^{J} ec_{8,jA} B_{jA} + \sum_{j=1}^{J} ec_{8,jW} B_{jW} + \sum_{j=1}^{J} ec_{8,jS} B_{jS} \quad (m^3) \tag{A8}$$

where $ec_{8,jA}$, $ec_{8,jW}$, and $ec_{8,jS}$ represent the toxicity classification factors of different substances emitted to air, water and land, respectively, that may reach waterways and affect aquatic organisms. B_{jA}, B_{jW} and B_{jS} represent the respective emissions of different toxic substances into the three environmental media. ATP is also expressed relative to 1,4 dichlorobenzene (1,4-DB).

References

Azapagic A (2002) Life cycle assessment: a tool for identification of more sustainable products and processes. In: Clark J, Macquarrie D (eds) Handbook of green chemistry and technology. Blackwell Science, Oxford, pp 62–85

Azapagic A, Perdan S, Clift R (eds) (2004) Sustainable development in practice: case studies for engineers and scientists. Wiley, Chichester, pp 446

Cleall PJ, Seetharam SC, Thomas HR, Chalabi Z, Dowie J, Leonardi G (2005) Development of a framework for integrated health impact analysis of geoenvironmental pollution. In: Barla G, Barla M (eds) In: Proceedings of the 11th international conference on computer methods and advances in geomechanics, vol 3, pp 93–100

EA (2003) WIZARD: Waste integrated systems assessment for recovery and disposal. LCA Software. Environment Agency for England and Wales, Bristol

Goedkoop M, Spriensma R (2001) The eco-indicator 99: a damage oriented method for life cycle assessment, methodology report, 3rd edn. 22 June 2001, Pré Consultants, Amersfoort, The Netherlands

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, van Oers L, Wegener Sleeswijk A, Suh S, Udo de Haes HA, de Bruijn H, van Duin R, Huijbregts MAJ (2001) Life cycle assessment: an operational guide to the iso standards. Parts 1, 2a& 2b. Kluwer Academic, Dordrecht

Heijungs R et al (eds) (1992) Environmental life cycle assessment of products: background and guide. MultiCopy, Leiden

Hertwich E, Jolliet O, Pennington D, Hauschild M, Schulze C, Krewitt W, Huijbregts M (2002) Fate and exposure assessment in the life-cycle impact assessment of toxic chemicals. In: Udo de Haes H, Finnveden G, Goedkoop M, Hauschild M, Hertwich E, Hofstetter P, Jolliet O, Klöpffer W, Krewitt W, Lindeijer E, Müller-Wenk R, Olsen S, Pennington D, Potting J, Steen B (eds) Life-cycle impact assessment: striving towards best practice, SETAC, pp 101–122

ISO (1997) ISO/DIS 14040: Environmental management: life cycle assessment. principles and framework. ISO, Geneva

McMichael AJ (2002) Environmental change and human health: extending the sustainability agenda. In: Munn T (ed) Encyclopedia of global environmental change, vol 3. Wiley, New York, pp 130–145

O'Meara M (1999) Reinventing cities for people and the planet. Worldwatch Paper. Worldwatch Institute, Washington, D.C. (147), p 68

Pré Consultants (2002) SimaPro 5.1. LCA Software. Pré Consultants, The Netherlands

UNEP (1992) Urban air pollution in mega-cities of the world. Blackwell, Oxford

United Nations (2006) Population division. World Urbanization Prospects: The 2003 revision. New York, UN, 11 March 2006