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An integrated approach to assessing the environmental and health impacts of pollution in the urban environment: Methodology and a case study

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ABSTRACT

This paper presents a new decision-support methodology and software tool for sustainable management of urban pollution. A number of different methods and tools are integrated within the same platform, including GIS, LCA, fate and transport modelling, health impact assessment and multi-criteria decision analysis. The application of the framework is illustrated on a case study which investigates the environmental and health impacts of pollution arising from different industrial, domestic and transport sources in a city. The example city chosen for the study is Sheffield, UK, and the main pollutants considered are NO_x, SO_2 and PM10. The results suggest that the absence of the current large industrial sources in the city would lead to a 90% reduction of the SO_2 and 70% of the NO_2 ground concentrations, consequently preventing 27 deaths and 18 respiratory hospital admissions per annum for a population of 500,000. Based on the total annual mortality and hospital admissions in Sheffield for the year of the assessment, this means that 0.53% of premature deaths and 0.49% of respiratory hospital admissions would be prevented by the estimated reduction in air pollution.

Keywords: Integrated sustainability assessment; Urban pollution; LCA; Air dispersion modelling; Health impacts

1. Introduction

Current trends in urban development, including growth of road transport, increasing energy demand and rising household consumption, place severe pressure on the urban environment, human health and the quality of life in cities. As a result, poor air quality, solid waste, diffuse water pollution and noise are some of the common environmental problems facing urban areas (UN-Habitat, 2008).

There is a wide range of different approaches to dealing with the environmental and related health impacts in cities. However, it is being increasingly recognised that the most appropriate way of tackling the problems of urban pollution would be to use an integrated management approach which allows consideration of complex interactions between human activities, environmental pollution and human health (see e.g. Pettit et al., 2005; Oudinet et al., 2006). Integrated approaches to urban environmental management are also recognised as

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necessary to improve legislative compliance; indeed, such approaches are increasingly explicitly required by legislation itself, for example in the fields of air quality, waste management and environmental noise (Perdan and Azapagic, 2011).

In an attempt to contribute towards these developments, this paper presents an integrated decision-support framework for more sustainable management of urban pollution, known as PUrE (Pollutants in the Urban Environment). The application of the framework is illustrated here for the first time on a real case study with the aim of demonstrating how environmental and health impacts of pollution can be assessed in an integrated manner. For illustration purposes, the focus is on three main pollutants – NO_x, SO_2 and PM10 – arising from industrial, domestic and transport sources within a city. The case study is based in Sheffield, UK, chosen as a 'typical' medium-size city (0.5 million people) with several large industrial sources, a range of smaller commercial and domestic (heating) sources and significant transportation activities around and within the city. Although the case study focuses on Sheffield, the approach to assessing sustainability and the findings of the study are generally applicable to other similar cities world-wide.

2. Integrated framework for managing urban pollution: the PUrE methodology

The PUrE decision-support framework enables integrated sustainability assessments – environmental, economic and social – of different human activities in the urban environment. Its main novelty is that it integrates a number of different tools within one platform, comprising geographical information system (GIS), life cycle assessment (LCA), substance flow analysis (SFA), air dispersion modelling (ADM), health impact assessment (HIA) and multi-criteria decision analysis (MCDA). The framework is accompanied by a software platform which comprises all of the above tools which have been developed and integrated within the PUrE platform. Related databases are also included. The main advantage of PUrE is that the user can carry out full sustainability assessments within one platform in which the information and data flows between different tools are integrated smoothly, rather than having to search for data from different sources and to use different software applications, trying subsequently to integrate the results. However, the framework is also modular, allowing the use of one or several tools, in cases where full sustainability assessment is not the aim. Additionally, the user can import the data and results obtained from other tools outside the PUrE software, thus increasing the flexibility of the platform. The PUrE framework and software are applicable to and can be used by users from a wide range of sectors, including industry, environmental and waste management, environmental regulation, urban policy-making and planning, government and non-government organisations as well as academia. User guidance is included within the software, enabling the user to navigate through the decision-support framework in relation to the question or problem they are addressing, and guiding them on the tools and data needed for their analysis. As far as the authors are aware, this is a first tool of its kind. The PUrE software is available for free downloads at www.pureframework.org.

The PUrE methodology and the tools are described in detail elsewhere (Azapagic et al., 2007; Pettit et al., 2005, 2011); here we give a brief overview with reference to the case study presented in this paper.

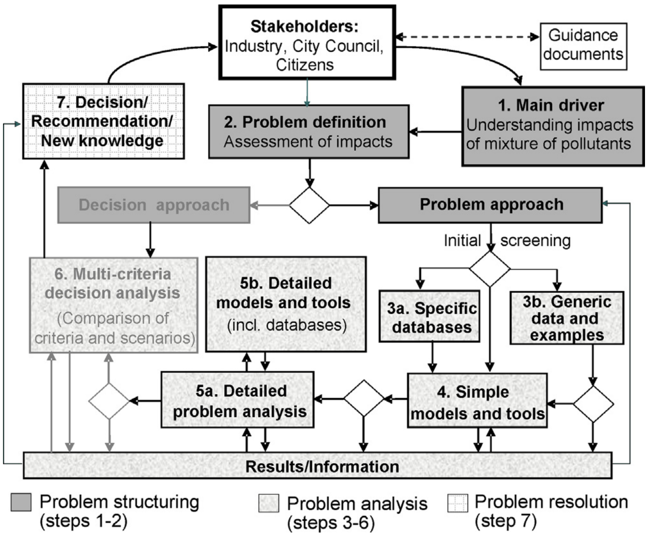

Fig. 1 – PUrE decision-support framework as applied to the case study of Sheffield.

As shown in Fig. 1, the PUrE framework follows the usual decision-analysis approach which consists of three main stages:

(i) problem structuring (steps 1–2);
(ii) problem analysis (steps 3–6); and
(iii) problem resolution (step 7).

(i) *Problem structuring*: the application of the framework starts (step 1 in Fig. 1) with consideration of stakeholders' needs, their main drivers for the sustainability assessment that they wish to carry out and the key questions to be asked through a framework application. Based on these, the user then identifies the sustainability issues of interest which will be used as the decision criteria in the assessment. Any type and number of sustainability issues can be included in the assessment. Examples of environmental sustainability issues that can be considered within the framework include emissions of air and water pollutants, discharges to land, global warming, acidification and photochemical smog; economic issues include investment and operating costs and social aspects can include health impacts, safety and human behaviour. The choice of sustainability issues (decision criteria) determines the modelling tools to be used within PUrE to estimate the values for these criteria. This is then followed by problem definition (step 2 in Fig. 1) which involves defining the systems or activities to be examined, system boundaries and the temporal and spatial scales for the assessment.

(ii) *Problem analysis*: within this stage, the user can then choose between two approaches to applying the framework:
(a) the problem-oriented approach or
(b) decision-oriented approach.
The former involves using various tools within the platform, depending on the choice of decision criteria, to estimate the values for these criteria (steps 3–5). For example, if one of the decision criteria is global warming, LCA can be used to estimate the emissions of carbon dioxide equivalent from 'cradle to grave'; or if the interest is in health impacts, health impact assessment can be used to

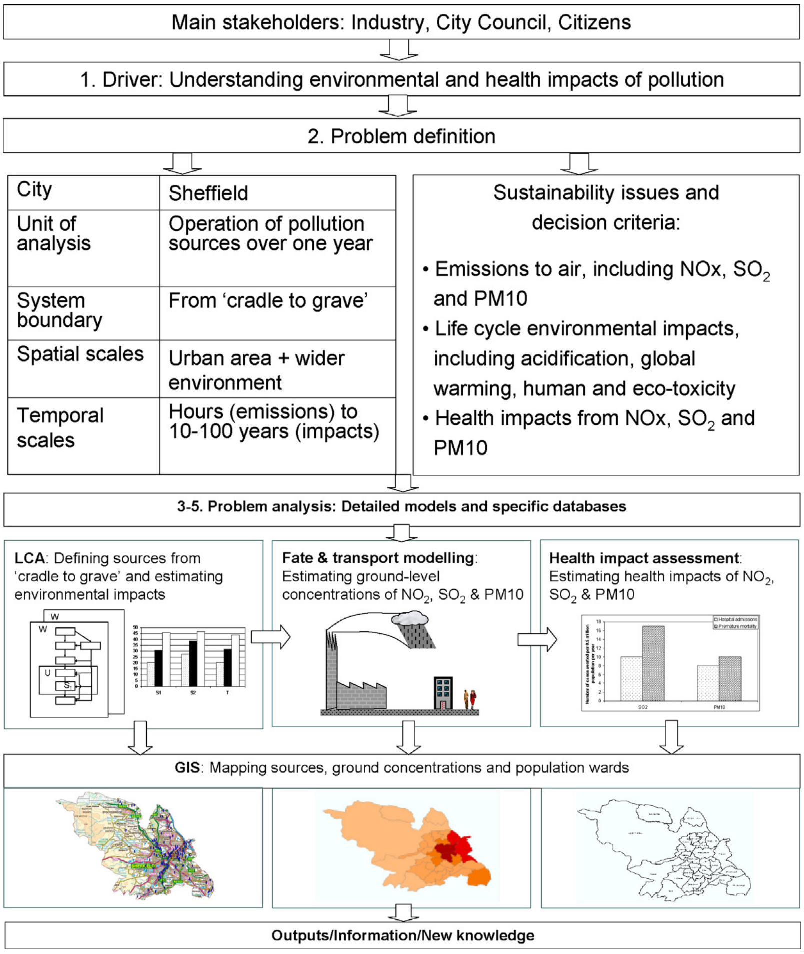

Fig. 2 – Following the PUrE framework step-by-step: problem structuring and problem analysis, showing the tools used in the analysis.

estimate premature mortality or years of lost life. Depending on the question asked, the user may elect to carry out either a simple or a detailed analysis or both (steps 4–5). The former may be appropriate for screening studies to identify the most significant sustainability issues, which can then be investigated further using detailed models. The results of the analysis can be examined in a disaggregated form (e.g. to understand the problem better or to gain new knowledge) or imported into MCDA (step 6) and aggregated using stakeholder preferences (e.g. as an aid in decision-making).

Alternatively, the decision-oriented approach allows the user to use the data and results obtained from previous PUrE applications or from other tools outside PUrE. These results can be imported and used in MCDA in the same way as above.

(iii) *Problem resolution*: in this final step of the framework (step 7 in Fig. 1), the results are used to make a decision or a recommendation or simply to gain new knowledge about the problem being addressed.

In this paper, we follow the problem-oriented approach as the aim is to demonstrate by a case study how environmental and health impacts of pollution can be quantified and evaluated in an integrated way. The case study is defined in the next section, by following the PUrE framework stages as outlined above.

3. Case study

3.1. *Problem structuring*

As shown in Fig. 2, this stage of the PUrE framework starts by identifying the stakeholders and their main driver or question to be addressed in the study. For the purposes of illustration of the PUrE framework, it is assumed that the main driver for the study is gaining better understanding of the environmental and health impacts of pollutants emitted from different industrial, domestic and transport sources in the city of Sheffield (step 1 in Fig. 2). Therefore, the main stakeholders include the industry based in the city, the citizens and the pollution regulators (the Environment Agency and the City Council). In the second, problem definition step, the case study is defined with respect to the unit of analysis, system boundaries and temporal and spatial scales (step 2 in Fig. 2). Here, the unit of analysis is based on the operation and use of industrial, domestic and transport sources in Sheffield over 1 year.

Two types of industrial sources are distinguished here: large Part A processes, regulated by the Environment Agency under the IPPC Directive (EC, 2008) and smaller Part B processes, regulated by the City Council. Part A processes include steel manufacture, municipal waste water (sewage) treatment and other waste management processes. Part B processes include brick and cement works, coating processes, ceramic products, dry cleaning, production of ferrous and non-ferrous metals and waste oil burning (Sheffield City Council, 2009a).

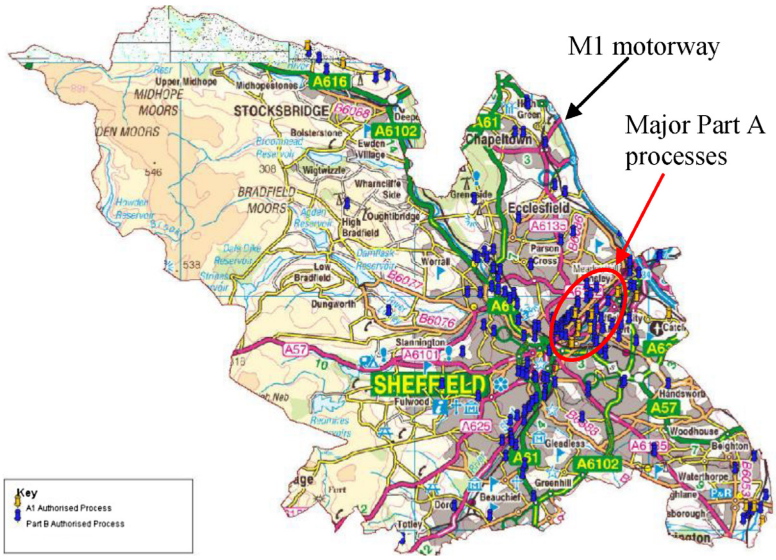

Fig. 3 – GIS mapping of industrial sources and road networks in and around Sheffield. Location data provided by the Sheffield City Council (2009a).

Domestic sources considered are natural-gas boilers used for heating. The transport activities comprise city transport and car and freight transport on the nearby motorway. The location of these sources within and around the city is given in Fig. 3.

As the interest is in both the direct impacts occurring in the city and in the hinterland that supports operation of the sources in the city, the system boundary for the sources of interest is drawn from ‘cradle to grave’, to help understand their full life cycle implications (however, see Section 3.2.1 for more detail). The timescales range from hours and days (e.g. hourly emissions and daily concentrations of pollutants) to 10–100 years (e.g. health impacts and global warming). The main pollutants of interest are NO_x, SO_2 and PM10. Therefore, given the study driver, the main sustainability issues and decision criteria are (Fig. 2):

- emissions to air, including NO_x, SO_2 and PM10;
- environmental impacts, including those related to the three main pollutants, but also other impacts such as global warming, acidification, and human and eco-toxicity; and
- health impacts related to air pollution from NO_x, SO_2 and PM10, measured by increased hospital admissions and premature mortality.

This choice of the sustainability issues determines which tools within the PUrE platform should be used in the problem analysis step, as discussed in the next section.

3.2. *Problem analysis*

To address the above sustainability issues and quantify the environmental and health impacts of the pollutants of interest, it is necessary to use the following tools within the PUrE framework and software platform: LCA, air dispersion modelling, health impact assessment and GIS (step 3 in Fig. 2). Note that MCDA is not used in this case study as the purpose of the study is not to make a decision, but rather to gain further knowledge and better understanding of the impacts of pollution in the city. However, as discussed in Section 2, the outputs of the study can be used as in input into MCDA to aid any future decision making.

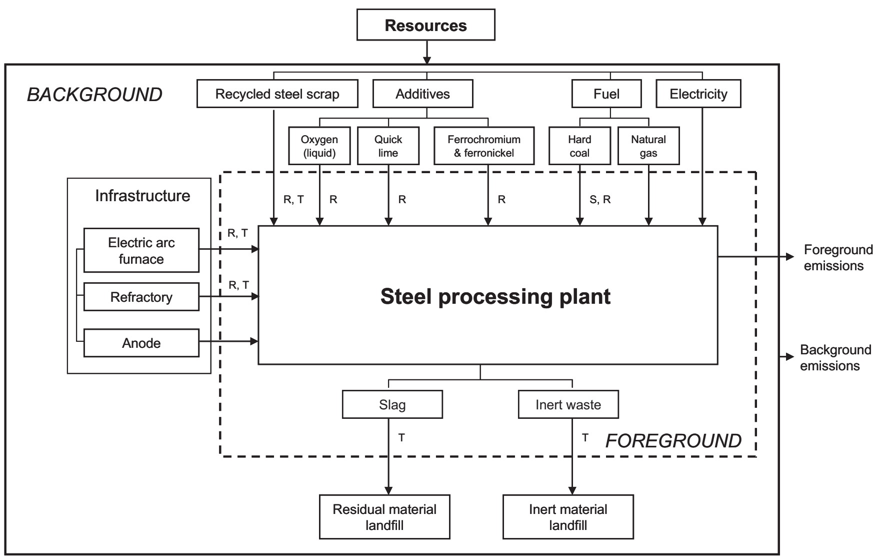

Fig. 4 – Life cycle diagram of steel manufacture, showing activities in the city (foreground) and elsewhere (background) (T – truck transport; R – rail transport; S – ship transport of coal).

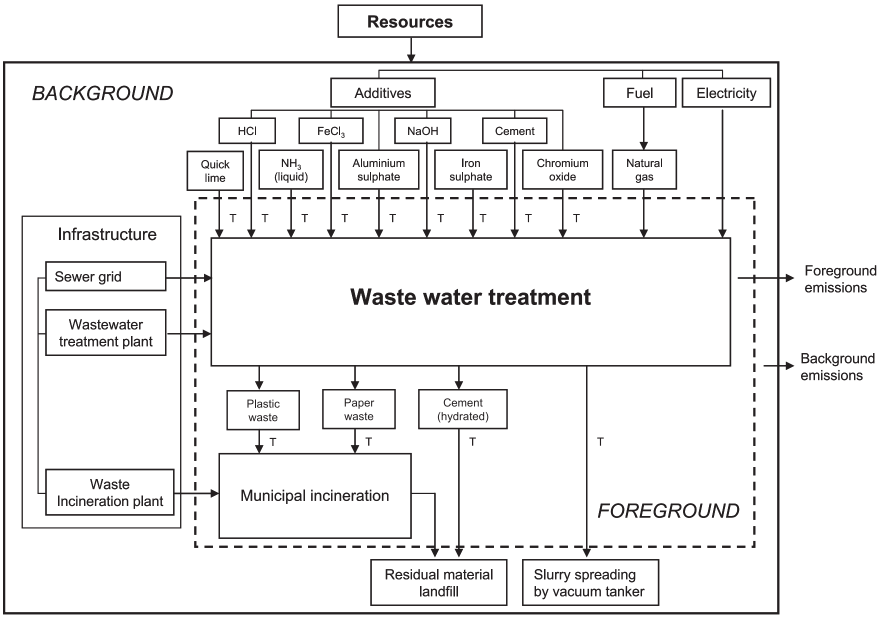

Fig. 5 – Life cycle diagram of waste water (sewage) treatment, showing activities in the city (foreground) and elsewhere (background) (T – truck transport).

LCA is used to define pollution sources from 'cradle to gate' and to estimate their direct impacts in the city and indirect impacts in the hinterland. This is then followed by air dispersion modelling and health impact assessment to determine the fate of the main pollutants of interest (NO_x, SO_2 and PM10) and their impact on human receptors. GIS is used to map the location of the sources and human receptors as well as the ground concentrations of the pollutants in the city region.

The integration of these tools and the flow of data are illustrated in Fig. 2. Further details on the methodology for integrating the tools within PUrE can be found in Azapagic et al. (2007); here we proceed to describe how these tools have been used to obtain the necessary results for our case study.

3.2.1. *Life cycle assessment*

The goal of the LCA study in this case study is to estimate the life cycle impacts of the main pollution sources in Sheffield to help understand both the direct and indirect environmental impacts. Due to a large number of different sources, it is impractical to consider all of them on a life cycle basis. Instead, for illustration purposes, two major industrial processes (Part A) are analysed by LCA in this study: steel manufacture and municipal waste water (sewage) treatment. LCA of transport activities is also included and it considers transport within the city and on the motorway (M1). Part B processes and domestic boilers are not analysed by LCA but are considered in fate and transport modelling and health impact assessment (see Sections 3.2.2 and 3.2.3). The life cycle diagrams for the above sources are given in Figs. 4–7. As shown, the system boundary is from 'cradle to grave'. To distinguish between the direct and indirect emissions and impacts, the system is divided into the foreground (city) and background (hinterland).

As previously mentioned, the unit of analysis (functional unit) is based on the operation of these sources over 1 year (see Table 1 for more detail). LCA has been carried out following the ISO 14044 methodology (ISO, 2006). The direct (foreground) emission data for Part A processes have been obtained from the Environment Agency (2009); direct emissions from transport and all indirect (background) data are from the Ecoinvent v2.0 (Ecoinvent, 2007) and Gabi (PE International, 2007) databases. The LCA modelling has been carried out using the LCA tool developed for the PUrE platform and the results have been validated by modelling the same system in Gabi LCA software (PE International, 2007).

The inventory results for the three pollutants of interest (NO_x, SO_2 and PM10) are shown in Fig. 8a–c. The environmental

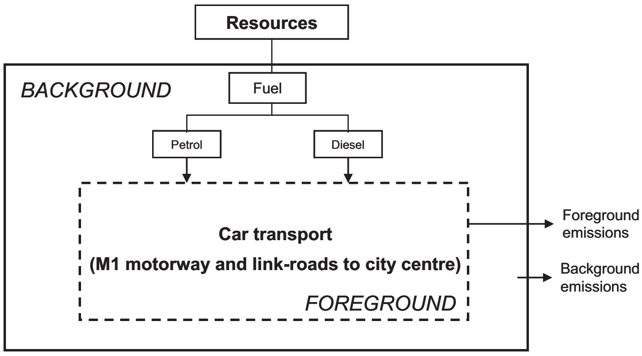

Fig. 6 – Life cycle diagram of city traffic (cars and vans), showing activities in the city (foreground) and elsewhere (background).

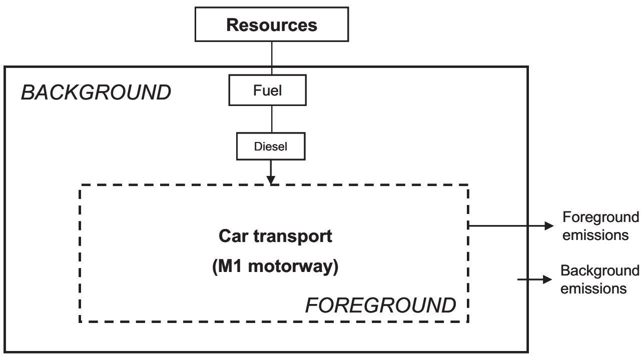

Fig. 7 – Life cycle diagram of motorway transport (cars and lorries), showing activities in the city (foreground) and elsewhere (background).

Table 1 – Definition of the sources considered in LCA, showing the functional unit and the activities in the foreground (city) and background (hinterland).

Sources/activities	Functional unit	Activities in the foreground (city)	Activities in the background (hinterland)
Steel production (scrap steel)	Steel production: 0.45 million tonnes/yr	Scrap transport Production of steel	Production of raw materials and fuels Background transport Electricity generation
Waste water treatment (sewage)	Sewage volume: 122,640 m^3/yr	Waste water treatment Activated sludge processing	Production of chemicals Transport to landfill
City centre traffic	42,000 cars/day	Fuel combustion (~1 km/car·day)	Diesel/petrol production Manufacture and maintenance
Motorway (M1) transport	12,500 lorries/day 112,500 cars/day	Fuel combustion (~10 km/truck·day)	Diesel/petrol production Manufacture and maintenance

Data sources: direct emissions for steel production and waste water treatment from the Environment Agency (2009); all other data from the Ecoinvent (2007) and Gabi (PE International, 2007) LCA databases

impacts, estimated using the CML 2001 method (Guinée et al., 2001), are given in Fig. 9a–c.

The total emissions of the three pollutants of interest (Fig. 8a) indicate that the foreground (city) emissions of NO_x are much higher (by 3.5 times) than the background emissions and are mainly contributed by the emissions from the motorway transport (Fig. 8b). In contrast, the emissions of SO_2 and PM10 are much higher in the background than in the foreground (by up to 30 and 77 times, respectively) and are mainly due to the life cycle of electricity (UK grid) used in the arc furnace for the production of steel (Fig. 8c). Steel manufacture also contributes to most of the SO_2 and half of the PM10 emissions in the foreground; the remaining emissions of PM10 are from motorway transport (Fig. 8b). By comparison, waste water treatment contributes almost negligible emissions of the three pollutants considered, both in the foreground and the background.

Turning our attention to the environmental impacts, we see that the impacts in the background (Fig. 9a) dominate the foreground for all impacts; this is due to the impacts of generating the electricity, used in the steel manufacture (Fig. 9c). Most of the foreground impacts (global warming, photochemical smog, acidification and eutrophication) are mainly due to the motorway transport (Fig. 9b); steel manufacture is responsible for the majority of human and eco-toxicity.

Therefore, these results show that the environmental 'hot spots' in the life cycle of the sources considered are:

- motorway transport, causing the majority of direct NO_x emissions and the related impacts in the urban environment; and
- electricity generation, used in the steel manufacture, causing the majority of the background emissions, particularly SO_2 and PM10 and the related human and eco-toxicity impacts.

This information can be used, for example, by the City Council to focus their attention on optimising the motorway transport around the city rather than within the city as the latter is often assumed to be the main contributing factor to urban pollution. Equally, switching at least partly, to green electricity for the steel manufacture would help to reduce the environmental impacts in the hinterland.

However, it should be noted that this study has considered only a limited number of Part A sources and has not considered Part B processes, so that the relative contributions of different sources discussed here should be interpreted with care – while the absolute values for their impacts would remain the same, inclusion of other sources in the LCA study could potentially change the relative contributions of the sources to the impacts, both in the foreground and in the background.

Having completed the environmental assessment part of the study, we now turn to modelling the fate and transport of the air pollutants of interest to estimate their potential health impact on the city dwellers. Some of the LCA results, particularly direct emissions of the three pollutants, are used as an input into the air dispersion modelling. The LCA environmental impacts are subsequently combined with the results of health impact assessment to analyse the outcomes of the study.

3.2.2. *Air dispersion modelling*

As shown in Fig. 3, the majority of Part A and Part B sources are located in the central and eastern parts of the city. The location of the major and minor city roads (A and B roads, respectively) and the motorway is also shown in Fig. 3. For the purposes of air dispersion modelling, the following sources are considered:

- line sources: M1 motorway, all roads leading to the city centre and all streets within the city centre;
- point sources: all Part A processes and all Part B processes; and
- grid sources: domestic boilers.

The data on terrain, meteorology, traffic flow, pollutant emissions and background concentrations used as an input into the air dispersion modelling have been obtained from the Sheffield City Council (2009a,b). AERMOD (AERMIC, 2009), which is integrated within the PUrE platform, has been used for air dispersion modelling.

In order to assess the human health impacts of the industrial activities of interest in the area, two situations have been modelled:

- current situation: with the large (Part A) industrial sources present in the city; and
- hypothetical situation: assuming that the Part A process were not present in the city.

The latter has been considered to find out if displacing these sources of pollution from the city would have significant health benefits. Although this is a hypothetical option at

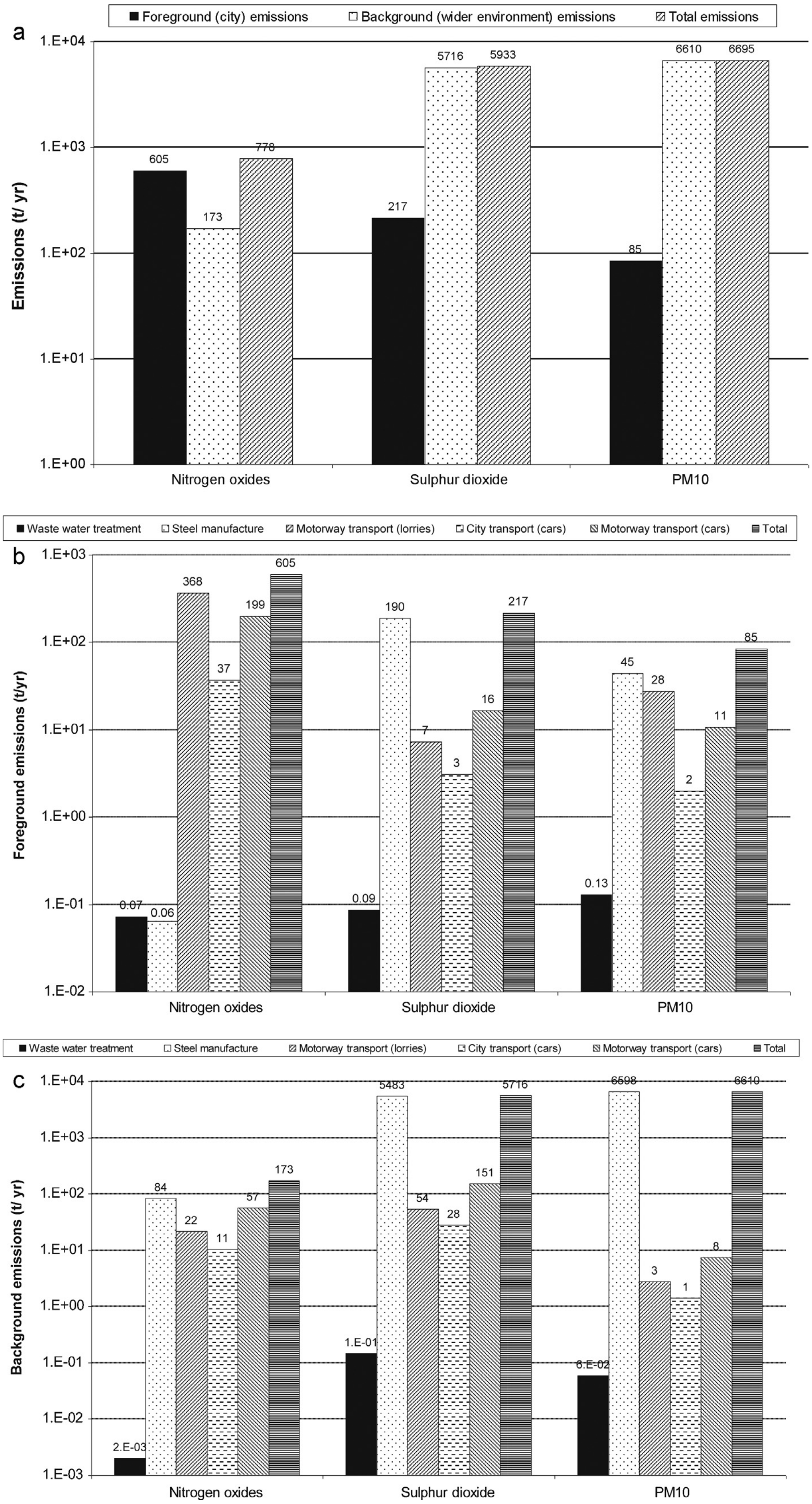

Fig. 8 – Life cycle emissions from the sources of interest in Sheffield: (a) total emissions; (b) emissions in the city (foreground); (c) emissions in the hinterland (background).

present time, given the long-term trend of displacing the manufacturing facilities from cities in the UK to other locations, often abroad, arguably such a scenario could be envisaged in future. Note that in this case study potential economic and other social impacts of such a situation are not considered.

Therefore, the air dispersion modelling has been carried out with and without the emissions from Part A sources. Two seasons have been considered in the modelling, each spanning 3 months: summer (June to August 2006) and winter (December 2006 to February 2007). In each case, the outputs

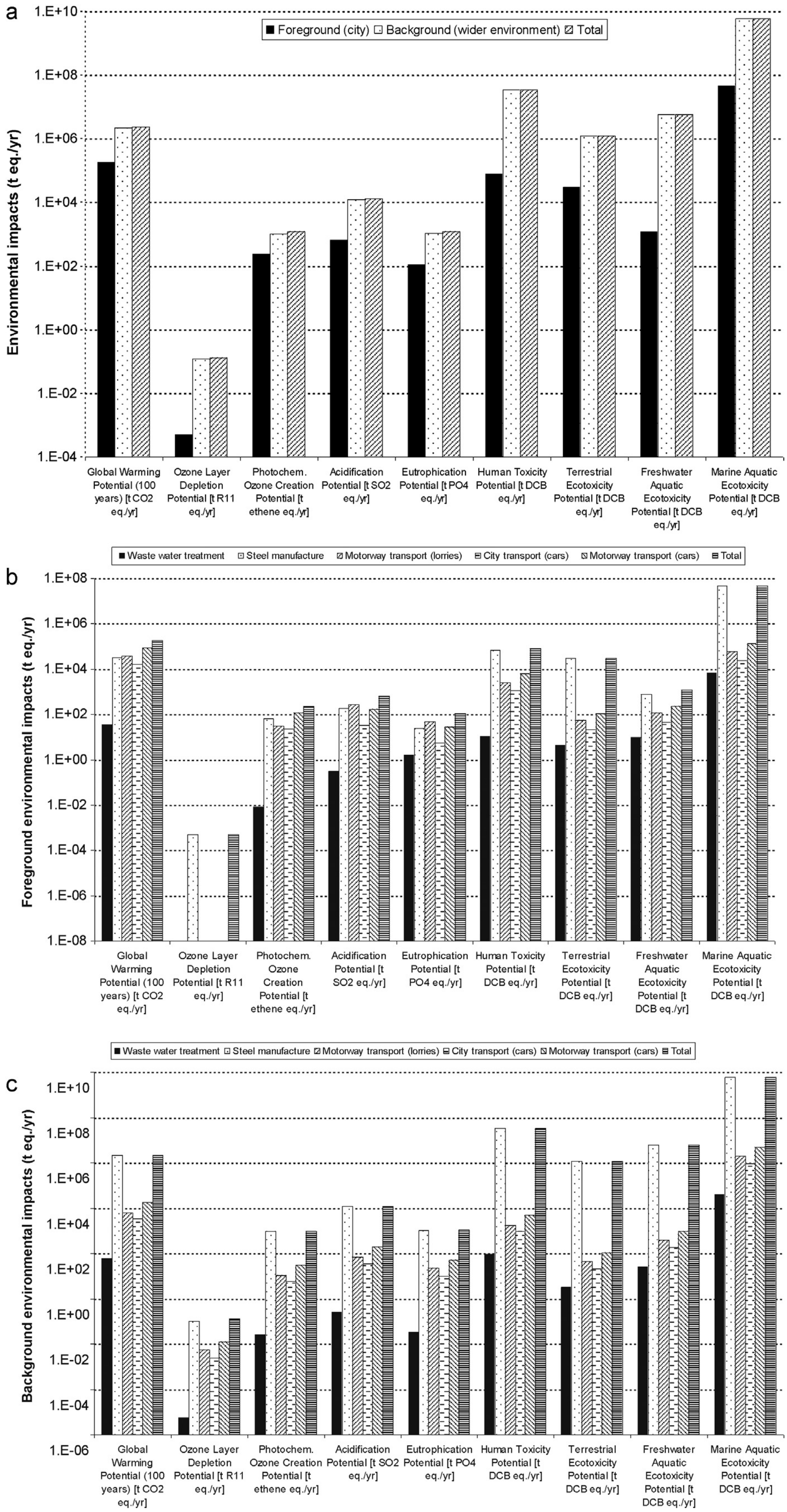

Fig. 9 – Life cycle impacts from the sources of interest in Sheffield: (a) total impacts; (b) impacts in the city (foreground); (c) impacts in the hinterland (background).

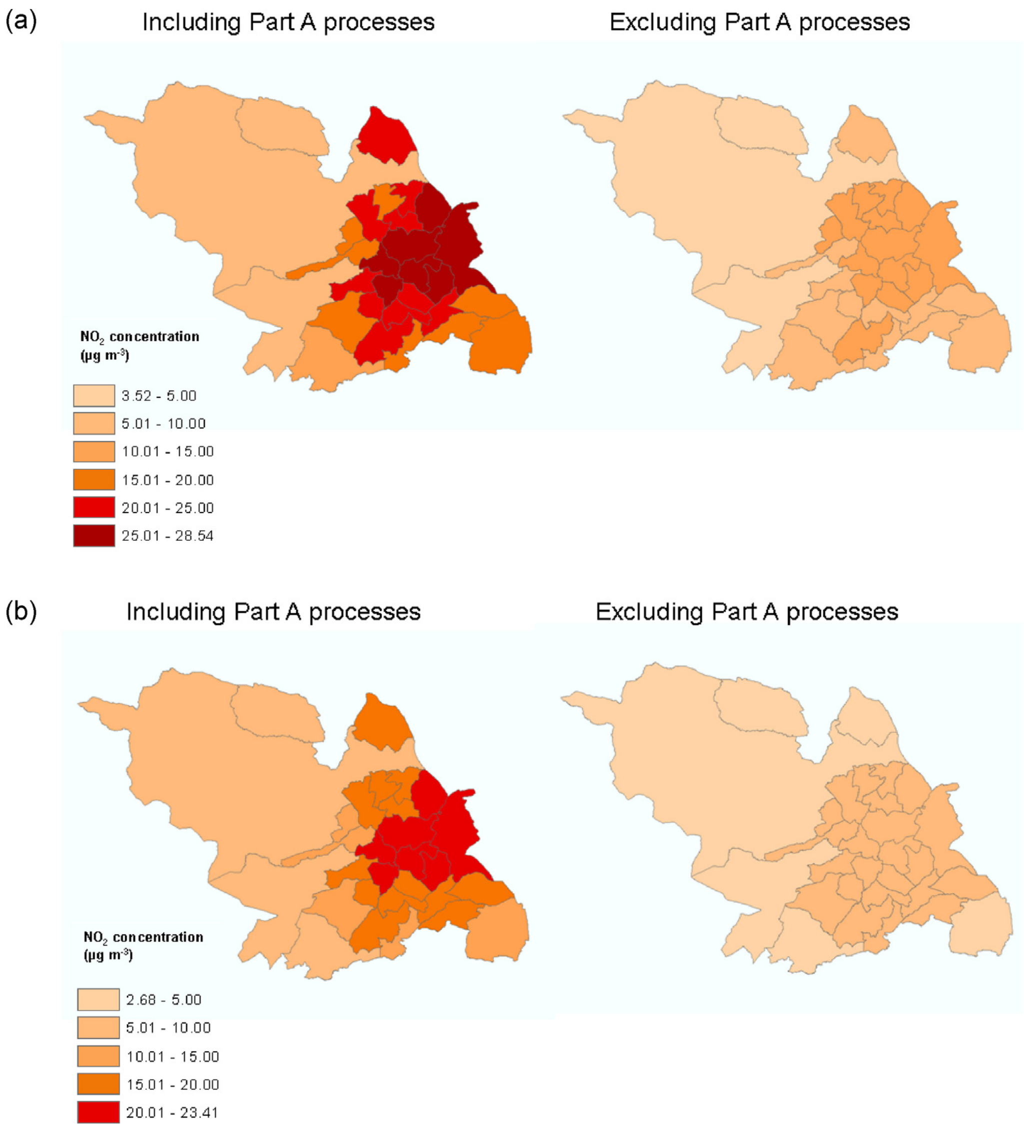

Fig. 10 – Spatial distribution of average daily mean ground NO_2 concentrations by ward, including and excluding Part A industrial processes: (a) winter; (b) summer.

have been mapped in GIS within the PUrE platform to show the air pollutant ground concentrations at the ward level; the latter has then been used to estimate the health impacts (see Fig. 2). The results of air dispersion modelling for the three pollutants with and without Part A processes for the winter and summer seasons are shown in Figs. 10–12.

In general, the results of the modelling show that the ground-level concentrations of all three pollutants are higher in the central and eastern parts of the city, i.e. in the vicinity of the major sources, particularly Part A processes and the motorway. Furthermore, it has been found that the exclusion of Part A processes would lead to a significant reduction in the average daily concentrations. The reduction is most pronounced for SO_2 (by 80–90%) and NO_x (by 65–70%, as NO_2), for both the winter and summer months (Figs. 10 and 11). This suggests that Part A sources contribute significant direct SO_2 and NO_x emissions. A similar trend was noticed from the LCA results (Section 3.2.1), particularly for SO_2; however, note that these and LCA results are not directly comparable, because in the dispersion modelling all Part A processes in Sheffield have been considered, while in LCA only two major Part A processes were considered, for the reasons explained previously.

In the case of PM10, however, the exclusion of Part A emitters leads to a moderate reduction (up to 20%) of the average daily concentrations, for both seasons (Fig. 12a and b), suggesting that other sources contribute more significantly to these emissions, including transport (as demonstrated in Section 3.2.1) and the many Part B processes.

Regarding the difference in the concentrations between winter and summer for the current situation (with Part A sources included in the dispersion modelling), the NO_x (as NO_2) average daily concentrations during the winter appear to be up to 20% higher than in the summer over the period considered. This is probably due to the heating and less favourable weather conditions during winter. This difference is even more pronounced for SO_2, whereby the average concentrations over the winter months are up to 45% higher than over the summer months (with Part A processes included). These results would suggest high dependency of the SO_2 concentrations on the local meteorology. In the case of PM10, there is almost no difference in the average daily concentration between the winter and summer months (Fig. 12a and b) but the high-concentration zone is more spread out during the winter months, again probably due to the less favourable weather conditions.

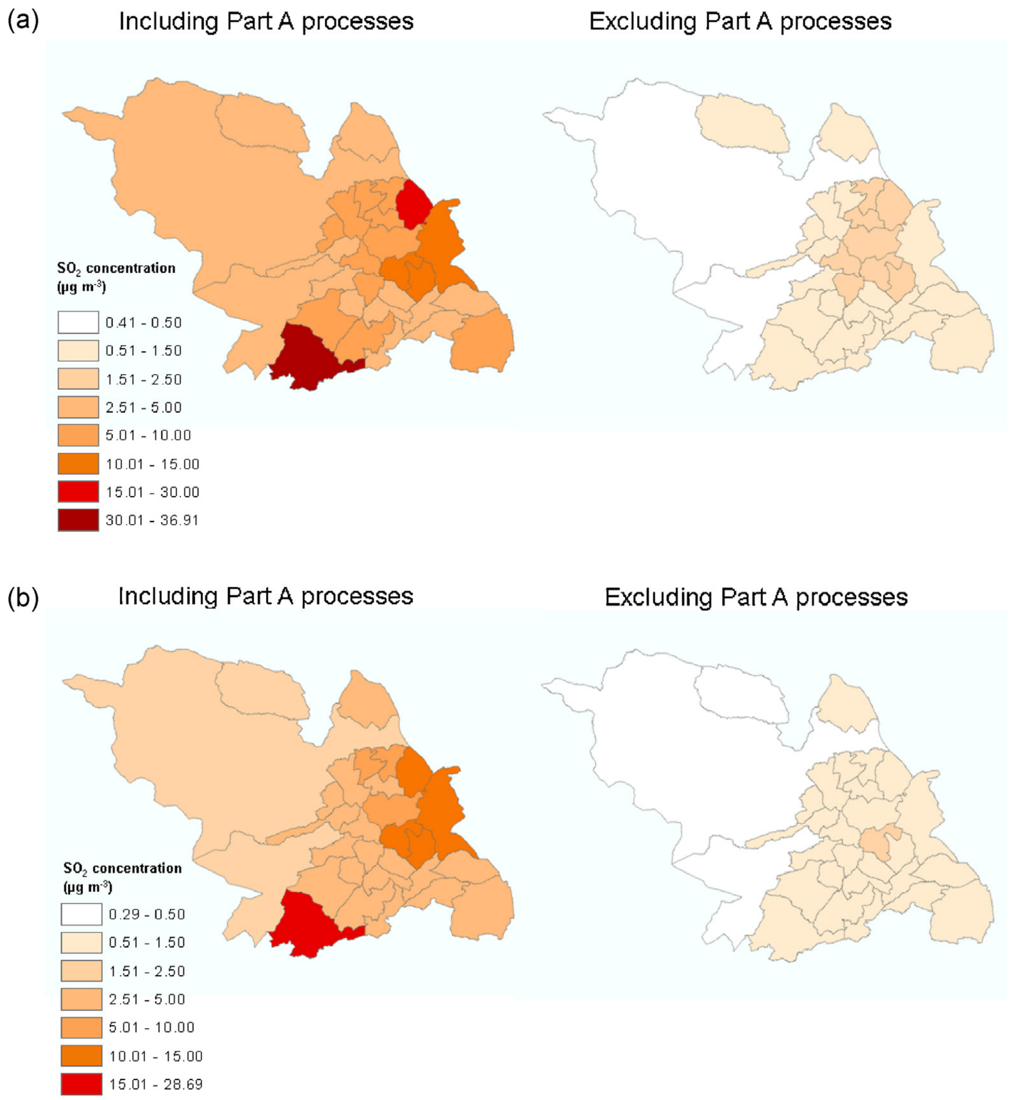

Fig. 11 – Spatial distribution of average daily mean ground SO_2 concentrations by ward, including and excluding Part A industrial processes: (a) winter; (b) summer.

For the validation purposes, the dispersion modelling results have been compared to the pollution monitoring data obtained from the Sheffield City Council (2009b). Monitoring data for the time of the year considered in this work have been available from two monitoring stations – Sheffield Centre and Sheffield Tinsley (see Table 2). The former station, located in the heart of Sheffield city centre, captures the contributions to the air pollution from road transport and industrial activities. The latter station, sited in an open industrial-cum-residential area, is representative of the urban industrial environment. In addition, it is close to the M1 motorway and is surrounded by a busy roundabout and a link road.

As shown in Table 2, where data availability enabled the comparison, the air dispersion modelling results are in close agreement with the corresponding monitoring data, suggesting relatively high confidence in the modelled values.

The ground-level concentration results are then used in the next and final step of this case study, to estimate the impacts

Table 2 – Comparison of the measured and modelled values for daily mean concentrations.

Monitoring station	NO_2 ($\mu g\,m^{-3}$)		SO_2 ($\mu g\,m^{-3}$)		PM_{10} ($\mu g\,m^{-3}$)	
	Modelled	Monitored	Modelled	Monitored	Modelled	Monitored
Sheffield Centre (city centre)						
Summer	27.63	NA	6.26	6.48	26.57	26.30
Winter	39.73	40.32	8.37	7.44	23.06	23.45
Sheffield Tinsley (urban industrial)						
Summer	33.18	32.67	5.42	NA	23.71	NA
Winter	45.02	44.56	7.38	NA	26.32	NA

NA = not available

Note: Data shown represent daily mean concentrations of the measured and the modelled pollutants averaged over the three-month period for the winter and summer season, respectively.

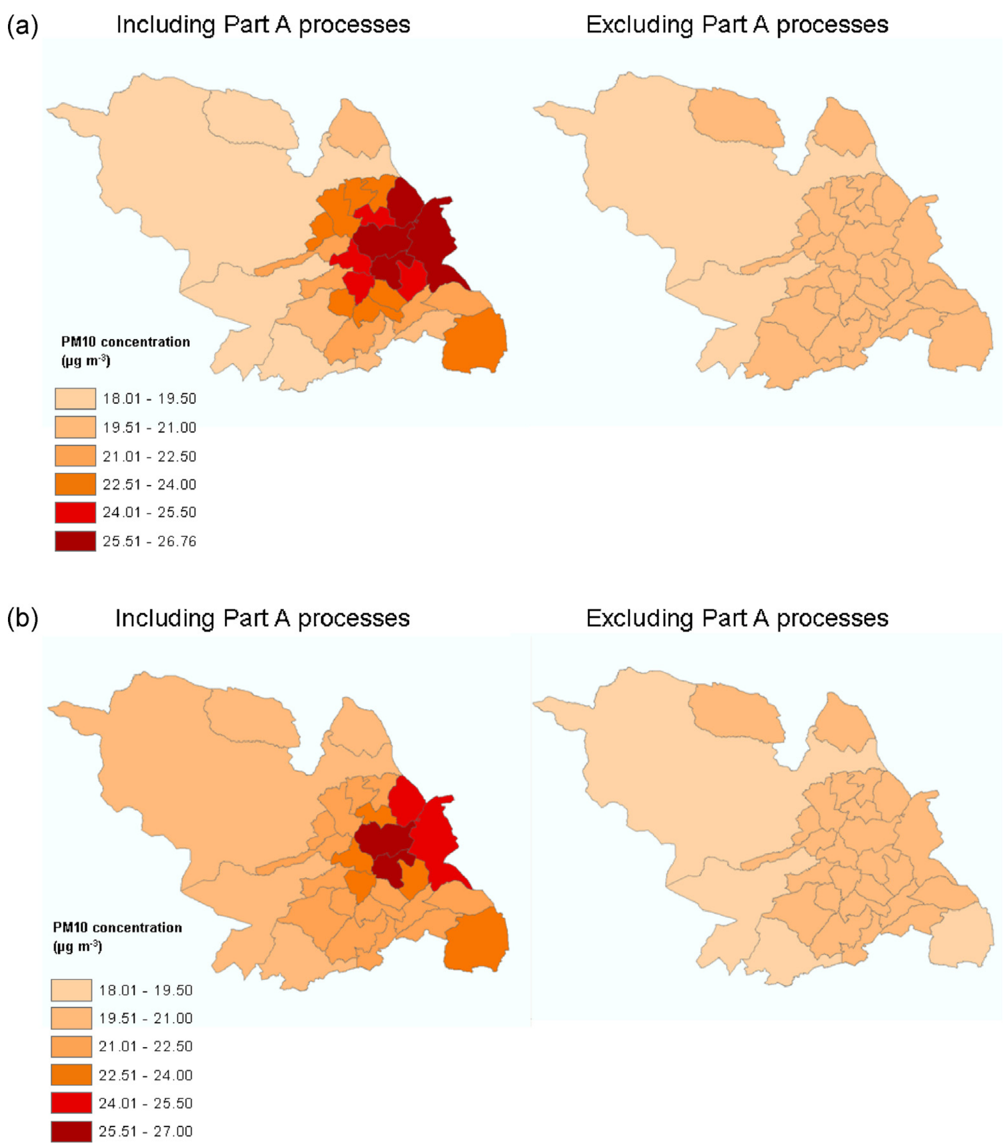

Fig. 12 – Spatial distribution of average daily mean ground PM_{10} concentrations by ward, including and excluding Part A industrial processes: (a) winter; (b) summer.

of the pollution on human health. These results are presented next.

3.2.3. *Health impact assessment*

The health impacts associated with Part A industrial processes have been estimated using exposure–response relationships for SO_2 and PM10, the size of the affected population and the baseline mortality and respiratory morbidity rates. The model used for these purposes and available within PUrE is described in Appendix. The health effects associated with differences in exposure to NO_2 between the two situations (with and without Part A processes) are not considered because of the strong correlation between PM10 and NO_2 in urban areas (Deacon et al., 1997; Vardoulakis and Kassomenos, 2008) so that including these effects may lead to double counting of the health impacts. The exposure–response relationships obtained from time-series epidemiological analyses of daily mortality and respiratory hospital admissions with daily mean pollutant concentrations are used to quantify the acute health effects due to exposure (Brunekreef and Holgate, 2002). In this study, the mortality and morbidity relations for exposure to SO_2 and PM10 are taken from COMEAP (1998) and are used to estimate the expected excess deaths and respiratory hospital admissions due to the emissions from Part A processes. It is assumed that the impacts associated with SO_2 and PM10 are independent and additive. The total health impacts have been obtained by first estimating the impacts at census ward level and then summing across all the wards. This represents a methodological improvement in comparison with other studies which have assumed that the entire urban population was exposed to average concentration levels (Zhao et al., 2009).

The results of the health impact assessment shown in Fig. 13 indicate that the SO_2 emissions from Part A processes contribute annually to about 10 excess hospital admissions and 17 premature deaths per 500,000 inhabitants. Similarly, the emissions of PM10 are responsible for 8 additional hospital admissions and 10 premature deaths. Therefore, in total, these two pollutants from Part A processes contribute to 18 excess respiratory hospital admissions and 27 deaths per annum for the population of 500,000. To put these results in context, the total annual number of deaths in Sheffield was 5030 and the total annual number of respiratory-related hospital admissions was 3725 in the year of the assessment. Therefore, 0.53% of premature deaths and 0.49% of respiratory hospital admissions would be prevented by the estimated reduction in air pollution.

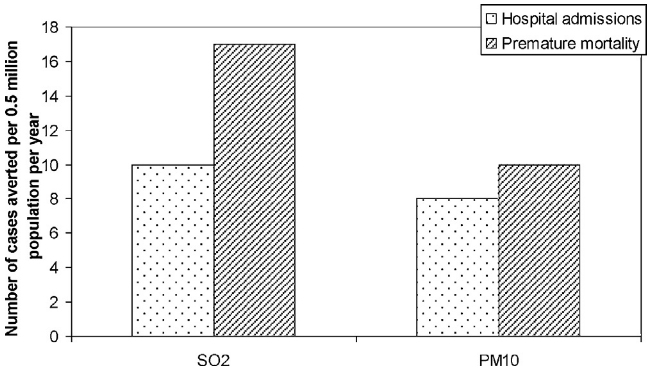

Fig. 13 – Health impacts of PM10 and SO_2: number of estimated premature deaths and hospital admissions that would be prevented in the absence of Part A processes.

These results should, however, be interpreted with care as they relate only to the impacts of reducing the SO_2 and PM10 concentrations by removing the large industrial emission sources from the city. They do not take into account any secondary health impacts associated with the resulting socio-economic impacts if these plants were to be displaced elsewhere. Furthermore, no uncertainty analysis has been carried out to identify the confidence intervals for the health impact results – this has been outside the scope of this study as the main aim has been to illustrate the application of the PUrE methodology rather than to carry out detailed health impact assessments. However, uncertainty analysis is available within PUrE (for the methodology, see Dorini et al., 2010).

4. Concluding remarks

Following the completion of both the environmental and health impact assessments, the results are combined to be analysed together. With respect to the driver for the case study considered here (gaining better understanding of the impacts of pollution in Sheffield), the following specific as well as generic conclusions can be drawn.

4.1. *Environmental impacts*

The LCA results indicate that the urban emissions of NO_x are much higher than in the hinterland and are mainly contributed by the nearby motorway transport. These results are in contrast to the usual expectation that city transport is responsible for most NO_x pollution and further demonstrate the need for quantitative analysis of pollution on a case-by-case basis. The emissions of SO_2 and PM10 are much higher in the hinterland and are mainly due to the life cycle of electricity used in the production of steel. For the same reason, the environmental impacts for all impact categories are much higher in the background than in the city area. While the case study has considered only a limited number of sources within the city, these results indicate that supporting the activities in the urban environment can exert greater pressures on the ecosystem services in the hinterland than in cities.

Air dispersion modelling suggests that the ground-level concentrations of the three pollutants considered are much higher in the vicinity of major pollution sources. In the absence of these sources, significant reductions of ground-level concentrations have been estimated. The highest reduction is found for SO_2 (80–90%) and NO_2 (65–70%), suggesting that major industrial sources contribute significantly to the direct emissions of these pollutants. In the case of PM10, however, the exclusion of these sources leads to a moderate reduction of the concentrations (up to 20%), suggesting that other sources, including transport, may play a more significant role.

4.2. *Health impacts*

The results of the health impact assessment suggest that in the absence of the major industrial sources in the city, 27 premature deaths and 18 respiratory-related hospital admissions would be avoided per annum for the population of half a million. This represents 0.53% and 0.49% of the total annual premature deaths and respiratory-related hospital admissions in Sheffield, respectively. However, these results should be interpreted with care, due to the inherent uncertainty associated with health impact estimations. Furthermore, the results do not take into account any secondary health impacts associated with the resulting socio-economic impacts if these plants were to be displaced elsewhere.

Although the above results are specific to the case study considered here, they illustrate the importance of integrated sustainability assessments and point out that supporting life in cities has impacts on the hinterland that are often neglected. Equally, they demonstrate that the accepted 'wisdoms' on the contribution of different sources to pollution need to be examined on a case-by-case basis to ensure more sustainable management of pollution in the urban environment. Finally, the case study demonstrates how the PUrE methodology can be used to quantify environmental and health impacts in similar cities in other countries.

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Appendix A. Health impact assessment model

This Appendix describes the health impact assessment model used to calculate the difference in the expected annual mortality between two situations – current (with Part A processes) and hypothetical (without Part A processes). The counterpart equations for the morbidity calculations are very similar, but with the mortality rates and exposure-mortality relative risks (RRs) being replaced respectively with hospital admission rates and exposure-hospital admissions incidence RRs.

Assume that the city of interest has m wards (j = 1,...,m) and that we are concerned with a mixture of n weakly-correlated air pollutants (i = 1,...,n). The temporal unit of analysis is taken to be 1 year. Denote the concentrations levels of the n pollutants for the current situation a (with Part A processes) and hypothetical situation b (without Part A processes) by $\{e_{i,j,a},\quad i = 1, \ldots, n,\quad j = 1, \ldots, m)$ and $\{e_{i,j,b},\quad i = 1, \ldots, n,\quad j = 1, \ldots, m)$ respectively, where $e_{i,j,a}$ is the concentration of pollutant i in ward j for situation a and $e_{i,j,b}$ is the concentration of pollutant i in ward j for situation b.

Denote by $\{s_i, \quad i = 1, \ldots, n)$ the short-term mortality relative risks (RRs) associated with the pollutant concentrations. If we assume that each of the pollutant exposure–response relationships is linear, then the constant slopes of the RR–exposure relationship rather than the RRs per se are required for the mortality calculations.

Let μ_j be the size of the population of ward j and σ be the expected annual mortality rate of the city (usually expressed per 100,000 of the resident population). The expected annual number of deaths in ward j is $\theta_j = \sigma \times \mu_j$. The difference in the expected annual number of deaths between the two situations in ward j which is attributed to the associated differences in the concentration of pollutant i is then given by:

$$\delta_{i,j} = s_i \times (e_{i,j,b} - e_{i,j,a}) \times \sigma \times \mu_j \tag{1}$$

If we assume that the health effects associated with the weakly-correlated pollutants are additive, then the difference in the number of deaths in ward j between the two situations attributed to all the pollutants is:

$$\Delta_j = \sum_{i=1}^{n} \delta_{i,j} = \sum_{i=1}^{n} s_i \times (e_{i,j,b} - e_{i,j,a}) \times \sigma \times \mu_j \tag{2}$$

Summing the deaths over all the wards in the city gives the expression for the required difference in the expected annual number of deaths between the two situations:

$$\Gamma = \sum_{j=1}^{m} \Delta_j = \sum_{j=1}^{m} \sum_{i=1}^{n} s_i \times (e_{i,j,b} - e_{i,j,a}) \times \sigma \times \mu_j \tag{3}$$

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