Background, Aims and Scope. Noise impacts are rarely assessed in Life Cycle Assessment (LCA), probably due to lack of data, to the difficulty of setting up an appropriate assessment method including relevant uncertainties and vagueness and to their site-dependent nature. The evaluation, as well as for odour, cultural and aesthetic impacts, seems to be closely related to human judgements and perception based. Although fuzzy-sets have been developed for this purpose since the late 60s and their usefulness has been proven by successful applications, noise impact assessment approaches have been essentially crisp so far. The aim of this paper is to present a method for noise impact assessment based on fuzzy sets with an application to a simple example.

Methods. The fuzzy noise impact assessment involves: 1) the quality assessment of the site concerned by the noise impact before the occurrence of noise emissions; quality is expressed by a crisp (i.e. non-fuzzy) function depending on variables (the so-called ‘primitives’), which are relevant for the evaluation (e.g. the population density, the type of land use, ...); 2) the fuzzy representation of the primitives, e.g. their evaluation by means of linguistic variables (such as ‘the population density is high’) and by fuzzy numbers; 3) the fuzzy representation of the quality, by fuzzifying the crisp function defined in 1) and 4) the fuzzy representation of the noise impact. In the example, the noise impacts of three processes of coal mining and combustion are assessed.

Results and Discussion. The application example proved the operationability of the method. Primitives and noise impact assessment results are represented by fuzzy numbers and intervals that are more informative than crisp numbers for the interpretation of results. The quality and impact assessment results obtained seem to be coherent with the nature of the processes involved and of the variables characterizing them.

Conclusion and Outlook. Fuzzy intervals and numbers could be more informative and closer to human judgements and perceptions than crisp numbers are, thus improving the pertinence and the interpretation of the results. Despite the increase in sophistication and the fact that the representation of the variables involved in calculations should be developed further (e.g. on the basis of consensus gained in an expert panel), the fuzzy approach seems to be promising for the assessment of noise impacts in LCA.

Introduction

Although two significant attempts were made to assess noise effects of road traffic (Lafleche et al. 1997, Müller-Wenk 2004), noise impacts are rarely considered in LCA. As pointed out by Müller-Wenk, the reasons for this neglect could be mainly the unavailability of appropriate noise assessment methods, as well as the opinion that noise effects are very local and difficult to interpret in relation to other impact categories (Müller-Wenk 2004). Lack of data and uncertainties related to their evaluation could also be considered important reasons.

The evaluation of noise impacts, as well as of odour, cultural and aesthetic ones, seems to be closely related to human judgements and perception based. For example, the nuisance of a noise emission could depend on the type and sensibility of the population exposed. Since the late 60s, fuzzy-sets theory has been developed to represent the vagueness of natural language. The classical set-theory, where it is clearly determined whether an item belongs to the set (e.g. ‘one’) or not (e.g. ‘zero’) has been extended, so that in the fuzzy-set theory, membership degrees also exist between zero and one (Zadeh 1965). Numerous studies and successful industrial applications have proven the usefulness of fuzzy-sets in the modelling of human-related and natural systems. During the last years, fuzzy-set approaches have been more and more developed in environmental science, leading to a ‘fuzzy boom’ in ecological modelling (Silvert 1997, 2000). Fuzzy evaluation of environmental impacts has been investigated, so that approaches (e.g. Borri et al. 1998, De Vita et al. 1995) and methods focusing on specific impact categories or stressors, e.g. pesticides (e.g. van der Werf et al. 1998) were developed. In LCA, fuzzy-sets have already been adopted to better link Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) results and to improve LCA calculations by means of fuzzy expert systems (Thiel et al. 1999, Weckenmann et al. 2001).

By considering the results and the perspectives of such approaches, this article presents an original fuzzy-sets approach to noise impact assessment in LCA. First, a general fuzzy impact assessment methodology is briefly introduced. Then, a specific method for noise impact assessment is presented and applied to a simple example.
1 Fuzzy-Sets Approach to Impact Assessment

A general fuzzy-sets approach to environmental impact assessment could include five phases (Enea et al. 2001):

1. the quality assessment of the site studied, prior to the LCI emissions generating the impact, by means of relevant variables, called 'primitives' (for noise impacts: the existing noise, the type of land use, the population density, ...). Quality has to be assessed since the magnitude of noise impact, for the same LCI emission, varies according to the initial quality of the site;
2. the fuzzy representation of the primitives, by fuzzy numbers or linguistic variables; for example, the type of land use could be characterized by expressions such as 'almost rural' or 'quiet residential' corresponding to given functions; 
3. the fuzzy assessment of the quality, i.e. the aggregation of the fuzzy primitives according to the quality function of step 1, by means of fuzzy aggregation rules;
4. the crisp impact assessment by means of a function depending on the quality of the site, the exposure of the targets and the nuisance of LCI emissions;
5. the fuzzy impact assessment by fuzzifying the crisp function of step 4.

Each step has been widely discussed in literature and will not be considered further in this paper (Canter 1996, Morris et al. 1996, Gupta et al. 1991, Li Xing et al. 1995, Vincent et al. 1997). This general approach is the starting point for the development of a specific method for noise impact assessment in LCA.

2 Fuzzy Noise Impact Assessment in LCA

2.1 Evaluation of the quality of the sound environment

The quality of a site could depend on 1) the existing noise level w expressed as 'weighted decibels with respect to the mean' or 'noise levels' [dB(A)] (Canter 1996) before the occurrence of the LCI emissions of the unit process related; 2) the type of land use and 3) the population density. The latter two are clearly correlated but, for example, some urban areas could have a significant lower population density than others in a time period, so it seems convenient to consider both. Of course, other primitives could be added in specific situations. In the following, some examples of fuzzy representations of these primitives are presented.

2.1.1 Existing noise level

The range of noise levels of the site concerned by the unit processes studied should be estimated by means of in situ measurements before the occurrence of LCI emissions. Since the measurements are time and resource consuming, the estimations are usually based on literature data. In Table 1, for instance, three categories of noise levels with the relative ranges are considered (Canter 1996).

Fuzzy numbers can be defined over these intervals. The membership functions are estimated by the practitioner, considering that the height of a fuzzy number (the highest membership degree) is the most likely value and its shape is usually triangular or trapezoidal. Examples of noise levels are given in Fig. 2c, 3c and 4c.

2.1.2 Type of land use

In order to represent the type of land use, some linguistic variables could be defined, e.g. 'urban', 'residential' and 'rural', whose membership functions, obtained from experts' interviews or knowledge-expert systems on real x-coordinates (e.g. the number of residential houses), could allow an estimation concerning the degree to which the site is 'urban', 'residential' and 'rural'. In this paper, to simplify the calculations, only one linguistic variable 'type of land use' L is considered, defined over the interval [0,2] of abstract x-coordinates l. By definition, when l is close to 0, the type of land use is urban, when l is close to 1, the type of land use is more residential and when l is close to 2, the type of land use is definitively rural. The values assumed by l in the interval correspond to all the nuances between the three. A fuzzy interval associated to the variable 'type of land use' states the membership of the values of l to the set of the variable, i.e. the degree to which the different levels of 'urban', 'residential' and 'rural' belong to the site considered. Examples are given in Fig. 2a, 3a and 4a for the types of land use of Table 3.

2.1.3 Population density

The same type of fuzzy variable used for the evaluation of the type of land use is pertinent for the evaluation of the population density. A variable 'population density' P whose values range in the interval [0,2] of abstract x-coordinates p is considered. By definition, when p is close to 0, the density of population is over 10,000 persons/km²; when p is close to 1, the density of population is between 100 and 10,000 persons/km² and when p is close to 2, the density of population is less than 100 persons/km². As for the type of land use, a fuzzy interval states the membership of the values of p to the set of the variable, i.e. the degree to which the different population densities belong to the site considered. Examples are given in Fig. 2b, 3b, 4b.

Table 1: Categories of noise levels

<table>
<thead>
<tr>
<th>Category</th>
<th>Noise level intervals w [dB(A)]</th>
<th>Mean population density</th>
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<tbody>
<tr>
<td>Noisy urban residential</td>
<td>58 to 72</td>
<td>25,000 persons / km²</td>
</tr>
<tr>
<td>Urban and quiet residential</td>
<td>48 to 58</td>
<td>1,200 persons / km²</td>
</tr>
<tr>
<td>Rural</td>
<td>20 to 48</td>
<td>&lt; 100 persons / km²</td>
</tr>
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