Uncertainty in emission inventories: What do we mean and how could we assess it?

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ABSTRACT

Proper use of emission inventories for atmospheric studies or policy purposes requires information on the uncertainty in the inventory. In this paper we argue that uncertainty in emission inventories should be approached from two perspectives: (i) uncertainty about accurcy is the lack of knowledge about the sources and size of the inaccuracy of an emission inventory and (ii) uncertainty about reliability is the lack of knowledge about the degree to which the emission inventory is meeting user-specified quality criteria. Although several studies have discussed a variety of tools that can be used for the assessment of uncertainty in emission inventories, a systematic approach that distinguishes between uncertainty about accuracy and uncertainty about reliability has not been developed yet. We will present a framework that allows either an assessment of the accuracy or reliability of an emission inventory and we want to show that answers to questions about accuracy and reliability are dependent on the tool for uncertainty assessment that has been applied. This paper presents results from the PhD project 'Uncertainties in emission inventories', performed within the TNO and Wageningen University expertise centre for Emissions and Assessment (Van Aardenne, 2002).

INTRODUCTION

Emission inventories can be used for both policy and scientific purposes. Accordingly, a variety of emission inventories exists, each with different characteristics (Pacyna and Graedel, (1)).

1) For policy purposes, emission inventories are used to
   a) monitor the progress of environmental policy by revealing trends in emission over time;
   b) to check compliance with the obligations of international conventions and protocols, or national emission reduction targets.
2) For scientific purposes, emission inventories are used as input into atmospheric dispersion models that aim at understanding the chemical and physical processes and the behaviour of air pollutants in the atmosphere.

Although the intended application of an emission inventories might be different, users of a certain inventory in many cases apply such an inventory also in another setting. For example, the CORINAIR 1994 emission inventory (2) is collected within a policy oriented programme of the European Environment Agency, but also forms the basis for the LOTOS emission inventory in a scientific application (3).

In both types of applications understanding the uncertainties is an important issue. In policy applications, the quality of the inventory in many cases must meet specific criteria. In scientific applications quantitative uncertainty analyses in most cases should be an integral part in assessing and interpreting the results of a study.

TYPES OF UNCERTAINTY

Although the term "uncertainty" is frequently used, different meanings are given to it in the emission inventory community. For example, McInnes (4) defines uncertainty as *'a statistical term that is used to represent the degree of accuracy and precision of data'*. IPCC/OECD/IEA (5) presents both a statistical definition and an inventory definition. The statistical definition relates uncertainty to sample variance or the coefficient of variation while the inventory definition describes uncertainty *'a general and imprecise term which refers to the lack of certainty (in inventory components) resulting from any causal factror such as unidentified sources and sinks, lack of transparency etc.'* In Van Aardenne (6) the concept "uncertainty" is defined both as lack of knowledge of accuracy and lack of knowledge of reliability.

Uncertainty on accuracy

Accuracy of emission inventory is the extent to which an emission inventory is an exact representation of the emission that has occurred in reality. Emissions of air pollutants from anthropogenic origin are caused by a variety of small and large individual sources such as power plants, industries, motor vehicles or animals. The emissions from these individual sources are usually both variable in time and space. It is practically not possible to monitor each of the emission sources individually and therefore emission inventory compilation will always contain assumptions on interpolation and extrapolation of a limited set of sample data.

The resulting emission inventory is therefore inaccurate. The inaccuracy can be formalized by equation (1)

$$E_{real} = E_{inventory} + \bigcup_{i=1}^{N} e_i \qquad (1)$$

where E_{real} is the emission that has actually occurred,

$E_{inventory}$ the estimate of the real emission and

ε_i represents the inaccuracy (ε) caused by a source of inaccuracy *i*.

The overall inaccuracy $\bigcup_{i=1}^{N} e_i$ is the combined result of N sources of inaccuracy.

Quantifying the inaccuracy using equation (1) for a specific emission inventory is not a straightforward exercise. In order to determine, the overall inaccuracy of an emission inventory, the emission that has occurred (E_{real}) needs to be known. This establishment of the truth (the true emission) is called verification (Webster (7); McInnes, (4)).

However, according to Oreskes et al. (8) verification is only possible in closed systems in which all of the components of the system are established independently and are known to be correct. This means that verification of large-scale emission inventories (e.g. national inventory) is not possible, because it is practically impossible to perform a continuous emission monitoring on each emission source. As a result, the 'real' emission cannot be exactly known. This means that we do not know the exact size of the inaccuracy and this inaccuracy can then only be roughly estimated. We need to know the different sources of inaccuracy *i* in order to gain insight into the accuracy of emission inventories. In many inventories these are not known. Not knowing the accuracy or the sources of inaccuracy in an emission inventory can be defined as uncertainty about accuracy. In other words:

Uncertainty on accuracy is the lack of knowledge of the sources and the size of the inaccuracy.

Uncertainty on reliability

The term reliability can be used to express that one relies or depends upon something with confidence (in this case, the emission inventory). McInnes (4), for example, has defined reliability as trustworthiness, authenticity or consistency. We define reliability as the extent to which one can rely on or trust the emission inventory. The important question that needs to be addressed is: when does one rely or trust an emission inventory? First of all, there is no uncertainty on the reliability of an emission inventory when the inventory is found to be accurate. However, when the accuracy is not known – or even more- when the inventory is found to be inaccurate, this might mean that one cannot rely upon or trust an emission inventory.

The reliability of an emission inventory and the role of accuracy in this is dependent on the intended use of the inventory. In order to understand the chemical and physical processes and the behaviour of air pollutants in the atmosphere, atmospheric modelling studies require accurate estimates of emissions. This means that for scientific purposes the reliability of an emission inventory is directly related to accuracy.

When emission inventories are used for policy purposes, the reliability of the emission estimate in relation to accuracy is different. For example, the Dutch Ministry of Environment formulated reliability of the Netherlands national pollutant emission register (PER) as: “the whole process of construction of emission figures and inclusion of the figures in the PER should be traceable (9).

This definition of reliability does not include accuracy as a condition for reliability of an inventory. The reason for this is that when emission inventories are used for policy purposes, users are more interested in whether the emission calculations are traceable and the complying with agreed upon methodologies or reporting formats (10), (11). In order to achieve this several quality criteria have been defined that are to be met by the emission inventories. In this sense, the reliability of an emission inventory is related to the quality criteria. These quality criteria could include accuracy of the emission estimate but this is not always the case. For the UN Framework Convention on Climate Change (UNFCCC) accuracy is one of the quality criteria for the reliability of greenhouse gas emission inventories. The IPCC good practice guidelines (5) include five quality criteria that should be met (1) transparency, (2) consistency, (3) comparability, (4) completeness and (5) accuracy. Using the IPCC definitions, this means that

3) Documentation should allow for a reconstruction of the emission inventory
4) The same methodologies and consistent data sets should be used for calculation of emission in subsequent years,
5) Emission inventories from different countries can be compared with each other,
6) The emission inventory should include all sources and sinks of greenhouse gases and
7) Emission estimates are systematically neither over nor under the true emission or removals, as facr can be judged and that uncertainties are reduced as far as practically possible.

Based on the discussion above, the lack of knowledge of the extent to which one can rely on or trust an emission inventory is dependent on the criteria set by the users of an emission inventory. In the case of scientific use of inventories the criterion is accuracy. In the case of policy applications different user-specified criteria are defined such as for example transparency, consistency and accuracy. These criteria differ from case to case. Uncertainty on reliability can therefore be defined as follows:

Uncertainty on reliability is the lack of knowledge of the degree to which the emission inventory is meeting user-specified quality criteria.

SOURCES OF UNCERTAINTY

Sources of unreliability

Policymaking needs reliable inventories to ensure the effectiveness of the policy process. The objective here is to have an inventory that is "good enough" rather than "the best possible". The intended user or receiver of the inventory defines "good enough" by selecting and defining a set of quality criteria. A good example of this is laid down in the reporting and review guidelines developed within the Framework Convention of Climate Change (12). Figure 2 shows an overview of possible sources of unreliability caused by not complying with the so-called TCCCA criteria.

Figure 1 Sources of unreliability in emission inventories used for compliance checking.

Unreliability in Emission Inventories

T	Transparency:	✓ *Insufficient documentation*
C	Consistency:	✓ *Different methods applied for different based years* ✓ *Inconsistent activity data*
C	Comparability:	✓ *Deviations of the agreed upon activity and fuel definitions* ✓ *Deviations in sector grouping and aggregations* ✓ *Incomplete reporting*
C	Completeness:	✓ *Omissions of sources and/or pollutants*
A	Accuracy:	✓ *See below*

In policy applications, the main objective of the concept "reliability" is the receiver's understanding of the emission inventory in such a way, that the policy process that it is used for will result in effective and smart decisions.

Sources of inaccuracy

Uncertainties in the accuracy of emission inventories can be subdivided in inaccuracies in

1) The emission inventory structure: structural inaccuracy and
2) The values of activity data and emission factors: input value inaccuracy.

Within each category different types of either structural or input value inaccuracy can be defined. The categorisation into structural and input value inaccuracy is comparable with the classification of sources of uncertainty in risk and policy analysis of Morgan and Henrion (13). However the different types of structural and input value inaccuracy are typical for the field of emission inventories.

<u>Structrural inaccuracy</u>

Uncertainty about structural accuracy is the lack of knowledge of the extent to which the structure of an emission inventory allows for an accurate calculation of the real emission. Three important causes of structural inaccuracy are:

1) <u>Inaccuracy due to aggregation</u>, caused by the fact that emissions are calculated on a spatial scale, a temporal scale and for emission source categories that are different from the scale on which the emissions in reality occur. In many cases there is lack of information about the emission processes

and the variability of emission on the required spatial and temporal aggregation level. In such cases, aggregation of the limited data available is needed, introducing inaccuracy.

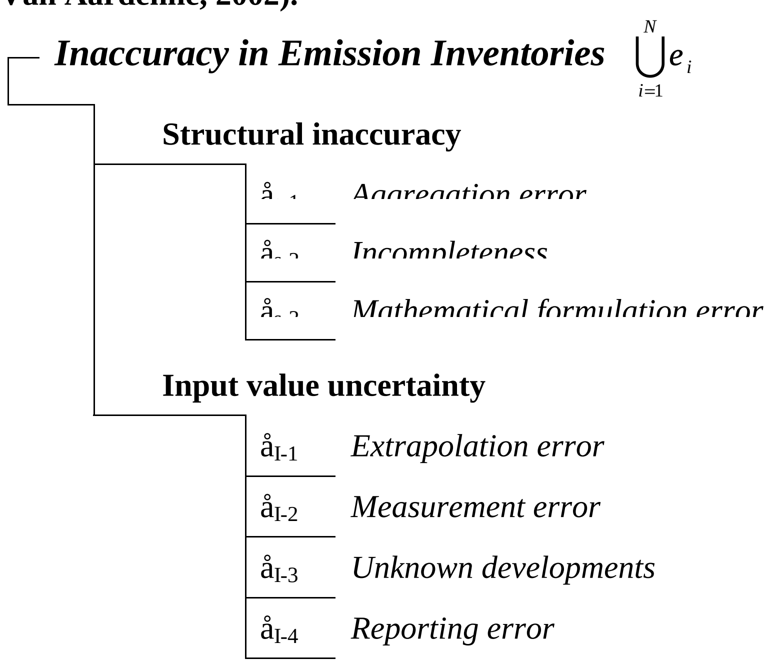
2) <u>Incompleteness</u>: an emission inventory may be inaccurate due to missing emission sources. Incomplete scientific understanding of the emission process can cause this.
3) At a given aggregation level, calculation errors can be a source of structural inaccuracy. Even more, the <u>mathematical formulation</u> may be wrong. For example, the emission factor calculation may wrongly assume that there is a linear relationship between emissions and activities, while in some cases this relation is not linear.

<u>Input value inaccuracy</u>

The equations used to calculate the emission for an inventory of a given structure contain parameters and variables such as emission factors and activity and hence the emission calculation needs input values. Uncertainty about input value accuracy is the lack of knowledge of the values of activity data and emission factors. This type of inaccuracy can be subdivided into four different types: extrapolation error, measurement error, unknown developments and reporting.

Due to lack of measurements of emission rates or activity data, readily available measurements (not specific for the source category, spatial or temporal scale) are extrapolated leading to inaccurate input values (extrapolation error). Errors in the available measurements can lead to inaccurate values of emission factors or basic socio-economic activity data (measurement error). When constructing emission scenarios to analyse possible future trends, information is needed about future emission factors and future socio-economic developments. Due to incomplete understanding of developments in the future (unknown developments), these emission scenarios can never be accurate. When values of emission factors or activity data are accurately known but erroneously reported due to for example typing errors, the input values that are used for the emission calculations will become inaccurate (reporting error).

Figure 2 Categorisation of inaccuracy in emission inventories. See text for detailed description. (Source: Van Aardenne, 2002).



When using the categorisation of inaccuracy one should realize that there is a relation between the different types of inaccuracy and that the distinction between different sources of inaccuracy is not always very strict. For example, structural inaccuracy, due to aggregation can be caused by lack of information or the variability of the emissions in space, time and emitting sources. This makes it impractical to calculate the emissions on the scale on which the emission processes occur in reality. At the same time lack of information and variability of the emissions could lead to extrapolation of available activity data and emission factors. This means that for the same reasons (lack of information, variability) different aspects of the emission inventory become inaccurate (structure, input values).

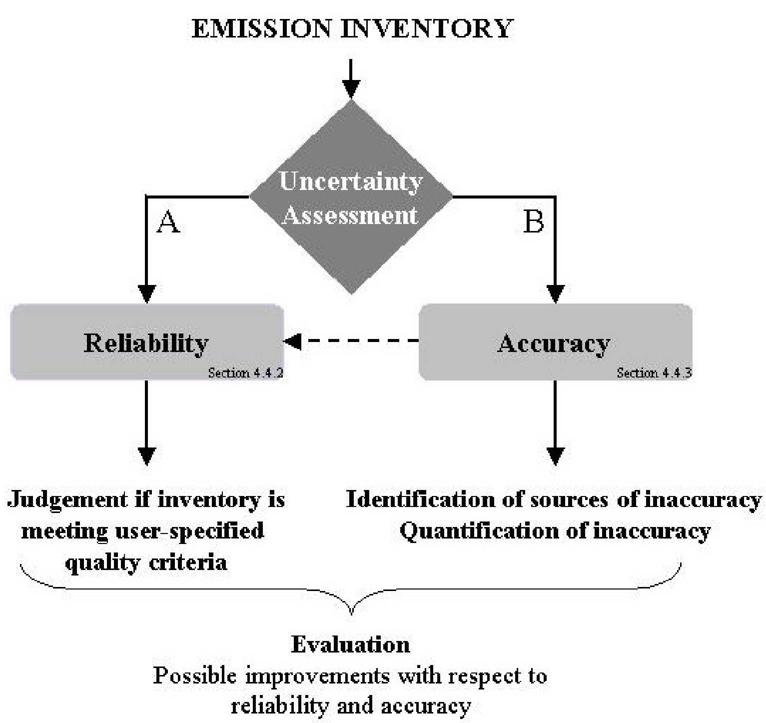
The categorisation presented here allows for a systematic discussion of the sources of inaccuracy. It focuses on the question: *which part of the emission inventory is inaccurate and why*?.

ASSESSMENT OF UNCERTAINTY

Here we present a framework that can be applied to emission calculations, typically used in large-scale emission inventories. The framework addresses both the different types and sources of uncertainty, taking into account the different tools available for the assessment of uncertainty. The ultimate goal of this framework is to make the accuracy and reliability of an emission inventory known.

The framework as depicted in Figure 3 consists of two paths that can be followed. Path A addresses uncertainty about reliability and results in the judgement whether the emission inventory meets the criteria that are set by the users of an emission inventory. Path B addresses uncertainty about accuracy through identification of the sources of inaccuracy in an inventory and through qualification or quantification of the inaccuracy of an emission inventory. In the situation that accuracy is one of the criteria set by the users of an inventory, the results from path B are used as information source for the assessment of reliability.

Figure 3 Assessing uncertainties in emission inventories. Source: Van Aardenne (6).



Application of these two paths results in both an assessment of the accuracy and reliability of an emissions inventory. This may reveal how the inventory can be improved with respect to reliability and/or accuracy.

Path A: assessment of uncertainty about reliability

The assessment of uncertainty about the reliability of emission inventories depends on quality criteria defined by the user of the inventory, which in turn are associated with the specific purpose of the inventory. For emission inventories used for policy purposes usually a set of quality criteria can be, or have been, defined. The approach for assessment of reliability depends on these criteria as defined by the users of the emission inventory. Reliability or the extent to which the inventory is meeting the quality criteria can be assessed through peer review. This method is an independent review of the inventory and results in the judgement whether or not the inventory meets the criteria and, if not, why not. For emission inventories prepared for scientific purposes, the accuracy of the emission inventory is typically considered the most important (if not only) quality criterion. In such cases,, information from Path B is needed in order to judge to what extent the inventory is inaccurate.

Path B: assessment of uncertainty about accuracy

Following path B will result in the identification or qualification or quantification of the uncertainty about accuracy in an emission inventory. We distinguish between internal and external assessment of uncertainty on accuracy. In the literature several methods that can be applied for the assessment of uncertainty in emission inventories can be found. We identified methods that can be applied for either an internal or external assessment. This identification of methods is based on several studies of uncertainty, sometimes with a different focus (5), (14), (15).

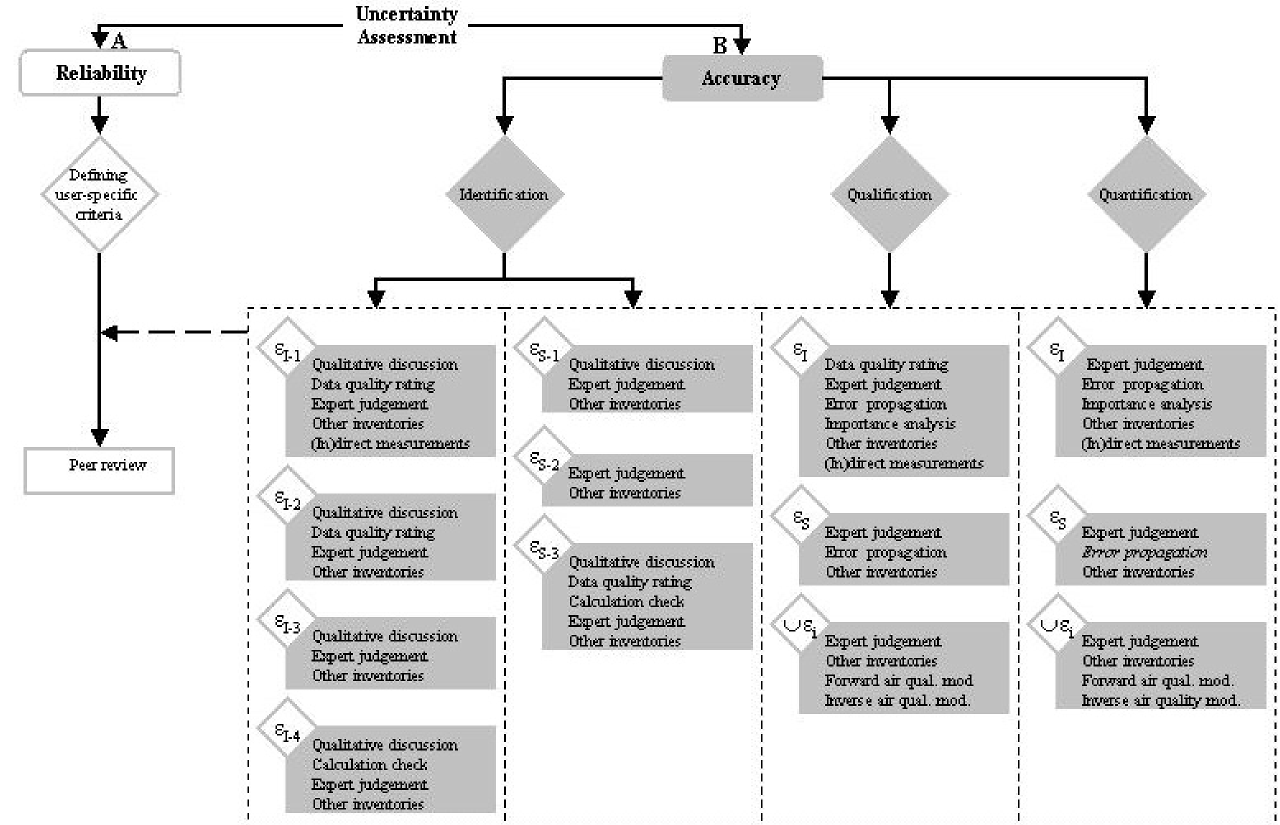
1) In an internal assessment, the methodology and information used to construct an emission inventory form the basis for the identification and the qualitative or quantitative assessment of the inaccuracy ($\cup\varepsilon_i$). We distinguish six tools for internal uncertainty assessment: (i) qualitative discussion, (ii) data quality ratings, (iii) calculation check, (iv) expert estimation, (v) error propagation, and (vi) importance analysis.
2) In an external assessment of inaccuracy, the differences between the emission inventory and other, independent, information is used to identify or quantify inaccuracies in the emission inventory. As discussed above, the emission that has actually occurred (E_{real}) needs to be known to determine the inaccuracy ($\bigcup\varepsilon_i$) of an emission inventory ($E_{inventory}$). In an external assessment, the external emission estimate ($E_{external}$) is treated as an independent estimate of the real emission and the inaccuracy of the emission inventory can be estimated from the difference between $E_{external}$ and $E_{inventory}$. Given the fact that E_{real} is unknown by nature, the strength of external assessment tools largely depend on our confidence in $E_{external}$ as an indicator of the real world emissions. Four tools for the external assessment of inaccuracy are distinguished here: (i) comparison with other emission inventories, (ii) comparison with direct or indirect measurements, (iii) performance of forward air quality modelling studies, (iii) comparison with results from inverse modelling studies.

The different methods have different capabilities to identify qualify and quantify uncertainty on accuracy. Table 1 presents these differences and the extent to which application of these methods will result in an assessment of uncertainty about accuracy.

The information on different capabilities and different sources of inaccuracy in an emission inventory has been combined into a FRamework for Assessment of Uncertainty in Large-scale Emission INventories (FRAULEIN). FRAULEIN is presented in Figure 4. The framework for uncertainty assessment can be used for a systematic analysis of the uncertainty in emission inventories. It combines information from different fields of study such as other emission inventories, atmospheric modelling, air quality measurements and statistics. The framework can be used to perform a four-step assessment of inaccuracy: identification, qualitative assessment, quantitative assessment, and prioritising further research.

Starting point of the four-step approach is the framework as shown in Figure 4, which presents a complete overview of the use of all tools in the various parts of the analysis. From Figure 4 it is clear that most tools can be used in more than one part of the assessment. Therefore, in the four-step approach we have chosen to assign each tool to one specific step only. This choice was based on our understanding of the tools and their use in practice in the literature. Obviously this does not lead to a unique choice, but we judge that the four steps and the tools assigned to each of them will help scientists and practitioners in achieving a good assessment of uncertainty about inaccuracy in emission inventories.

Figure 4 A systematic FRamework for the Assessment of Uncertainty in Large-scale Emission INventories (FRAULEIN).



<u>Step I: Identification</u>

In the first step major causes of inaccuracy can be identified using expert views, qualitative discussion and other inventories. These three tools will enable the user to identify inaccuracies in the structure and in the input values of the emission inventory. In this step both uncertainties in sources of emission and estimation method can be traced.

<u>Step II: Qualification</u>

The second step takes the analysis to a qualitative assessment and eventually a ranking of the inaccuracies. This takes us one step further in the direction of full quantification of the inaccuracy. The tools used in the first step may be used again in an attempt to derive more than just identification from them. In addition the tools data quality ranking and direct and (in)direct measurements can now be used.

<u>Step III: Quantification</u>

The third step aims at a full quantification of the inaccuracies. Again, tools used in earlier steps may be stretched to gain a beginning of an insight in the quantitative value of the inaccuracies. In addition, the tools error propagation, importance analysis and forward and inverse air quality modelling can be used

Step IV: Evaluation

The nature this final step of the assessment differs from earlier steps. Whereas steps 1-3 gradually improve the insight in the cause and size of the uncertainty about accuracy, step 4 uses these results to assist in prioritising future research. The most important uncertainties could then be reduced first, taking into account that it is sometimes very difficult if not impossible to reduce a large uncertainty.

Table 1 Overview of different methods for the assessment of uncertainty about accuracy.

Method	**Description**	**Capabilities**	**Limitations**
Qualitative discussion	Discussion of known or expected sources of inaccuracy	✓ Identification of different causes of input value and structural inaccuracy (except ε_{S-2})	✓ Provides only preliminary insight into sources of inaccuracy ✓ Limited by understanding of emitting process ✓ No qualification or quantification
Data quality rating	Expression of relative accuracy of input values by assignment of alphabetical or numerical scores	✓ Systematic identification of εI-1 and ε_{I-2} ✓ Qualification of most inaccurate parts of inventory	✓ Only relative scores ✓ Assignment of scores is subjective ✓ Only assessment of input value inaccuracy
Calculation check and evaluation of mathematical formulation	Check on calculation and mathematical formulation	✓ Identifying εI- 4 and ε_{S-3} ✓ Correct inventory for ε_{I-4} and ε_{S-3}	✓ Only assessment of εI- 4 and εS- 3 ✓ Limited by knowledge of emitting process
Expert judgement	Asking experts to give estimate of inaccuracy	✓ Identification of ε_I , ε_S ✓ Qualification/quantification of ε_I , ε_S, $\cup\varepsilon_i$	✓ Clear rationale for assessment is often missing ✓ Assessment is subjective
Error propagation	Calculation of inaccuracy in inventory induced by inaccuracy in input values (in theory also for structure)	✓ Quantification of ε_I , ε_S ✓ Based on calculation results, qualification of ε_I , ε_S	✓ Only assessment of input value inaccuracy ✓ Lack of empirical data
Importance analysis	Calculation of (relative) importance of inaccuracy in input value to inaccuracy of inventory	✓ Qualification and quantification of εI	✓ Only assessment of input value inaccuracy ✓ Lack of empirical data
Other inventories	Comparison of different (independent) inventories	✓ Identification of ε_I , ε_S ✓ Qualification and quantification of ε_I , ε_S, $\cup\varepsilon_I$	✓ Availability of independent emission estimates ✓ Uncertainty about accuracy in other inventory
Direct and indirect measurements	Comparison of input values of inventory with measurement results	✓ Identification of ε_{I-1} and ε_{I-2} ✓ Qualification of ε_I ✓ Quantification of ε_I and $\cup\varepsilon_i$	✓ Only identification of εI-1 and εI-2 ✓ Lack of continuous monitoring of each emission source
Forward air quality modelling	Comparison of modelled atmospheric concentrations with atmospheric concentrations measurements	✓ Qualification and quantification of $\cup_{\varepsilon I}$	✓ No identification of εI , εS ✓ Difficulties in distinguishing between measurement error, emission error and model error ✓ Representativeness of measurements
Inverse air quality modelling	Comparison of emission inventory with emissions calculated by an atmospheric dispersion model using atmospheric concentration measurements as input	✓ Qualification and quantification of $\cup_{\varepsilon I}$	✓ No identification of εI , εS ✓ Difficulties in distinguishing between measurement error, emission error and model error ✓ Representativeness of measurements

DISCUSSION AND CONCLUSIONS

In this paper we have shown that uncertainty can be seen from different perspectives (accuracy vs. reliability) and that a variety of causes of uncertainty and a variety of methods for assessment of uncertainty exists. The discussion of the different capabilities of methods and the framework for assessment of uncertainty in large-scale emission inventories (FRAULEIN) provide guidance on the methods that can be used to identify, qualify or quantify the different sources of uncertainty in an emission inventory.

It is important to realize that in theory, some methods may seem to be the best choice to analyse a particular emission inventory, however in practice the method may seem to be a second-choice option or requires information from other methods for uncertainty assessment. Based on Table 1 and Figure 4, expert judgement may seem to be capable to perform all tasks of an uncertainty assessment. However, the limitation of the method is that often a clear rationale is missing and that the judgement is subjective. Another example is the method of inverse air quality modelling. This could provide a powerful tool for the quantification of the overall inaccuracy if not for limitations such as the difficulties in distinguishing between measurement error, emission error or model error or the fact that measurements are often not representative for use in an inverse study.

Developers and users of emission inventories should be aware of the distinction between uncertainty about accuracy and uncertainty about reliability. This makes the purpose of the assessment of uncertainty clear and enables a clear communication of what is meant with uncertainty and more important what not. It is important to realize that many emission inventories are prepared for policy purposes and that an inventory that is considered to be reliable for policy purposes, however, may not be accurate enough for scientific analysis.

When the methods for uncertainty assessment have been prescribed, the framework shows which sources of uncertainty about accuracy can be identified, qualified or qantified and which sources not. An example in this is the method of error propagation. Error propagation is a widely used tool for the assessment of inaccuracies in emission inventories. Furthermore, the IPCC good practice guidance (5) prescribes error propagation as a tool to assess the accuracy of national greenhouse gas inventories. It is important to realize that when error propagation is used only the inaccuracy due to input value uncertainty (ε_I) is assessed and not the structural inaccuracy (ε_S) nor the overall inaccuracy of the inventory

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