Treatment of uncertainties in green engineering

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Abstract. Uncertainties occurring in engineering are usually dealt with by means of statistical validation. Most value assignments are of statistical nature and thus only valid in a specific statistical way. This fact is, in most cases, only implicitly apparent but nevertheless almost always present. In green engineering this is not true. The calculation e.g. of life cycle assessments (LCAs) is generally based on a vast number of values. These data either cannot be validated in a statistical sense at all or they are too insufficient to be usable for statistical analyses. This means that final results in this field cannot be declared as trustworthy in a way that is common in engineering. In this paper, the method of interval arithmetic is proposed as a way to circumvent this severe epistemological problem. The consequences of the suggested approach are illustrated utilizing two typical examples: (1) Different reliabilities concerning theories for greenhouse effect influences of various chemical emissions on the greenhouse effect and thus on the global warming potential and (2) Situations, where one specific production site differs heavily from the average of the dedicated industrial sector. Computational implementation of the considered concept is briefly discussed. It is shown that misleading results, which may be quite common in this field, can possibly be avoided in the proposed way.

1. Introduction
Whenever a civil engineer makes a statement concerning a technological subject a lot of connotative conditions and theoretical assumptions are implied. Because of this the statement may hold apodictic certainty. All uncertainties that are actual inevitable present are dealt with in an appropriate way defined by good engineering practice and so there is no need to mention them explicitly. The relationship between a single statement and the entirety of the theoretical and standardized background (often called the “state of the art”) must be aware to the addressee of that statement. If this is not the case, the statement may simply appear not be true. This means in consequence, that communication utilizing such statements must first of all solely take place between engineers.

Communicating partners have to speak the same language based on advanced semantics only fully understandable for members of a certain group of experts. External parties will not be able to understand the statement but rather just have to trust in the engineer’s opinion. This confidence is generally speaking justified by experience and covers the expectation that at least the engineers themselves do understand the statement in the abovementioned way. It will be argued that this is not true within the field of green engineering.

As a possible solution for the problem situation mentioned, a recommendation is provided which is based on the use of interval arithmetic and is referred to as the multi-value method. The result is that relevant statements are less precise but more reliable.
2. The problem of multidisciplinarity

Green engineering appears to be a very large field of interest that overlaps with or even covers lots of more specific fields of expertise only one of which is the field of civil engineering. In such a multidisciplinary field scientists of different expertise collaborate in order to find solutions for problems that cannot be solved within the borders of their respective field of expertise. The most prominent problem of this kind is the so called greenhouse effect. Typical statements concerning this problem that an engineer could make or could be requested to make are:

- “This specific technology will reduce the greenhouse effect.”
- “The production of this specific product has a lesser impact on the greenhouse effect as all competitive products.”
- “This specific product or technology must be prohibited because of the implied consequences concerning the greenhouse effect.”
- “The global-warming-potential (GWP) of one item of this specific product amounts to 2450 kg carbon-dioxide-equivalence (CO2-Eq.).”

Again a non-expert external addressee will have the expectation that such statements are true in the way discussed above. Assumed that the respective influence of a technology or a product on the greenhouse effect can be quantified by use of the GWP the first three of the above statements may be reformulated as follows:

- “This specific technology has a negative GWP.”
- “The GWP of the production process of this specific product is lower than the GWPs of all competitive products.”
- “The GWP of this specific product or technology is beyond the statutory scope.”

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Whether or not the GWP is the only relevant parameter that has to be considered and thus the three reformulated statements really mean exactly the same than the original ones will not be discussed here but may be doubted. In the following only the last of the four statements will be investigated more closely. This statement has the same formal structure as the statement

- “The tensile strength of this specific material amounts to 780 GPa.”

In this case, the addressee of the sentence may assume that the stated numerical value was determined on the basis of a sufficient number of tensile tests and is statistically substantiated by the test results in such a way that it may be used as a basis for further calculations. The statement mentioned is falsified by any additional individual test only if the breaking load determined deviates from the given value to a greater extent than is to be expected according to the state of the art. The fundamental verifiability of the statement through an independent test program is an essential basis for its reliability.

The statement

- “The global-warming-potential (GWP) of one item of this specific product amounts to 2450 kg carbon-dioxide-equivalence (CO2-Eq.).”

Obviously cannot be verified in a similar manner. For this reason, this statement is fundamentally more doubtful than the one previously considered. The question now arises as to how such a statement can or must be reformulated in such a way as to achieve greater reliability. Since there is no database available for a statistical evaluation, a weakened formulation of the statement with simultaneous introduction of upper and lower bounds is proposed here:
• “The global warming potential (GWP) of one item of this specific product is very likely to be more than 2200 kg and less than 2720 kg carbon dioxide equivalence (CO₂-Eq.) with 2450 kg CO₂-Eq. as the typical value.”

The procedure proposed here is referred to in the following as the multi-value approach. This approach is therefore based on the fact that all relevant numerical values are represented in the form of number triples consisting of a lower bound, an upper bound, and a typical value between the two. The next step is to clarify how the values of the upper and lower bounds can be determined in the example statement. To make this possible at all, all premises from which the statement discussed here is derived must also be formulated using the multi-value approach.

The actual calculation then is performed on the basis of interval arithmetic. It is not the purpose of this paper to deal with the entire life cycle assessment theory. It is assumed that this theory is well known and therefore reference is made to the relevant literature, e.g. [1, 2, 3] and [4].

Here only individual sentences are to be given, which could function in principle as premises for the examined example in order to explain some consequences of the procedure proposed here in the following. The multi-value approach will be compared with the usual single-value approach on the basis of suitable examples.

3. Methodological prerequisites

Any scientific statement that is of such a nature that it essentially consists of assigning a specific numerical value to a specific metric property of a system or system component is subject to uncertainty. In order for such a statement to be considered "true", the nature of such uncertainties, i.e. the order of magnitude and the causes of the uncertainty, must be known and taken into account in the course of the scientific further use of the statement made.

For the following, it is assumed that the specific numerical value, which represents the core of the content of such a statement, is the result of a calculation process, which in turn is based on input variables and assumptions, which in turn may be subject to uncertainties, and that these input uncertainties are the sole cause of the uncertainty of the final statement.

The uncertainties arising in this context can be of different kinds:

(1) Uncertainties of input variables with continuous value distribution, which are based on the respective method used to determine the value. In particular, the case of measurement imprecision in the case of experimental value determination should be mentioned here.

(2) Uncertainties of input variables with continuous value distribution that are not related to the value determination method. These include, for example, overall or relative surcharges and discounts to be applied on the basis of regulations. The use of estimated values or values from the relevant literature may also fall within this category.

(3) Uncertainties of input variables with discrete value distribution.

(4) Uncertainties concerning the choice of theories and methods.

(5) Other selection uncertainties.

Uncertainties of the abovementioned types are usually dealt with in different ways. A possible standardization of the approach, however, as will become clear in the examples, is the multi-value method proposed here that utilizes interval arithmetic [5, 6].

It is also assumed that the starting point for determining the numerical value in the final statement is fully determined by a finite number of individual decisions and determinations.

4. Two examples

The starting point for the following examples is the existence of a manifestly harmful process in the environment, such as the observation of global warming in general. Scientists from various disciplines are investigating the cause or causes of the process, particularly with regard to the question of whether
and to what extent these are anthropogenic in origin. The individual theories developed here differ in principle with regard to their plausibility, their validity and their relevance. Through a scientific convergence process, one of the competing theories is usually finally recognized as the essential one for the process to be explained. In the case of global warming, this is the theory of the greenhouse effect caused by atmospheric carbon dioxide. However, at least some of the other theories must also be taken into account against the background of the demand for a holistic approach. Difficulties that may arise from this competition of theories are illustrated in the first example.

The second example deals with the problem of assigning standardized ecological data to products or product groups without taking into account a specific manufacturer, e.g. the geographical conditions of the manufacturing process. The question is therefore to what extent so-called generic ecodata can be regarded as reliable data.

Both examples are roughly sketched on the basis of fictitious numerical values using the Multi-Value method proposed here.

4.1. Characterization factors concerning global warming

In addition to the influence of carbon dioxide on global warming in general, the corresponding influence of other emissions on the climate, which may be based on completely different mechanisms, must also be taken into account. In practice, this is done by using so-called characterization factors, whereby the effects of different theoretical and practical causes are summed up mathematically. With regard to general global warming, this means that potentially climate-damaging causes must be converted in such a way that they can each be equated with a carbon dioxide load of the same effect. The problem here is that the characterization factors are of great importance in the life cycle assessment, but that at the same time the accuracy level of the theories on the basis of which these factors are determined is potentially lower than the accuracy level of the theory describing the dominant process. This inaccuracy is completely ignored in life cycle assessments, which can lead to erroneous statements and decisions.

| Emission type | Lower Bound | Calculation Value | Upper Bound |
|---------------|-------------|-------------------|-------------|
| CO₂ [t]       |             | 1                 | 1           |
| XY [kg]       | 8<sup>a</sup> | α                 | 12<sup>b</sup> |
| YZ [g]        | 0<sup>c</sup> | β                 | 50<sup>a</sup> |

<sup>a</sup> The numbers are supposed to be based on theories which are extensively documented and generally regarded as valid.
<sup>b</sup> The basis is a current study.
<sup>c</sup> The basis is a study which doubts the connection between YZj and global warming as a whole and which is currently widely observed and commented on.

The question arises as to how to select the numerical values α and β under the circumstances given in table 1. Relevant cases are listed in table 2.

| Case                   | α   | β   |
|------------------------|-----|-----|
| M (Mean Value)         | 10  | 25  |
| A (Scientific Acceptance)| 8  | 50  |
| S (Safe Side)          | 12  | 50  |
| I (Innovative Approach)| 12  | 0   |
Let us now further assume that three different products are available on the market which are capable of performing one and the same function, i.e. which belong to the same functional unit, but which are produced in different production processes in which different emission quantities are caused. The corresponding figures are compiled for three fictitious example products in table 3. It must be pointed out here that if the multi-value concept is consistently implemented, the emission quantities will also be represented as number triplets. For reasons of brevity, this is not included in the example considered here.

In situations in which different products compete with each other and there are no decision-relevant functional differences between them, it is expected that the LCA can be used as a decision-making tool in such a way that the choice ultimately falls on the product that is expected to have the least impact on the environment. In the following, we will examine whether this succeeds in the present example, if only single values (Third column in table 1) are taken into account.

**Table 3.** Fictitious products and associated emission quantities.

| Product | CO₂ [t] | X, Y [kg] | YZj [g] |
|---------|---------|-----------|---------|
| P1      | 20      | 0         | 0       |
| P2      | 10      | 1.2       | 0       |
| P3      | 10      | 0.5       | 5       |

In the course of product selection, it must first be decided which numerical values from table 2 are to be used. Table 4 shows the GWP values for all possible combinations.

**Table 4.** GWP [CO₂-Eq.] for all combinations.

| Product | M | A  | S  | I  |
|---------|---|----|----|----|
| P1      | 20| 20 | 20 | 20 |
| P2      | 22| 19.6| 24.4| 24.4|
| P3      | 140| 264| 266| 16 |

Depending on which characterization factors are used, each of the three sample products can be considered as the optimum. However, this simply means that the question of the optimal choice of product cannot be decided properly with the single value approach. In particular, when using particularly large numerical values for the characterization factors (Case S: Safe Side), it must not be expected that the resulting product choice is better or more correct in any sense than when using other numerical values. Rather, the proposal presented here amounts to considering the upper and lower bounds of the calculated GWP values as final results, which do not appear to be available as a decision criterion in the present case. These values are summarised in table 5.

**Table 5.** Upper and Lower Bounds for the GWP [CO₂-Eq.].

| Product | Lower Bound | Upper Bound |
|---------|-------------|-------------|
| P1      | 20          | 20          |
| P2      | 19.6        | 24.4        |
| P3      | 16          | 266         |
4.2. The “Black Sheep” of an industrial sector

In the second example, a situation is considered in which a specific production site differs significantly from the other production sites in the industrial sector concerned in terms of its circumstances and, consequently, also in terms of the emission quantities caused per unit of quantity of a selected product. If this deviation is such that the emissions of the production site under consideration are significantly higher than those of comparable sites, the latter may be regarded as the black sheep of the industry. However, the following statements also apply mutatis mutandis to the opposite case, where a specific production site performs significantly better than its competitors.

Again, competing functionally identical products have to be considered, this time with a focus on the influence of the specific production location. These can be e.g. two different types of insulating materials, e.g. polystyrene (A) and rock wool (B). For each of the two products to be compared, six production sites (A1 to A6 and B1 to B6) are assumed, each of which is to be counted as a member of an interest group. The CO2 emissions caused per product unit at the various production sites are listed in tables 6 and 7.

| Table 6. GWP [kg CO2-Eq.] for product A at different production sites. |
|------------------|--------|--------|--------|--------|--------|--------|
| A1               | A2     | A3     | A4     | A5     | A6     |
| 400              | 430    | 380    | 1020   | 410    | 360    |

| Table 7. GWP [kg CO2-Eq.] for product B at different production sites. |
|------------------|--------|--------|--------|--------|--------|
| B1               | B2     | B3     | B4     | B5     | B6     |
| 480              | 485    | 475    | 482    | 478    | 480    |

The mean or generic value [7] of the emissions given above is in the case of product A 500 kg CO2-Eq. and in the case of product B 480 kg CO2-Eq. If a decision in favor of product B is made on the basis of these figures, this is simply wrong in five out of six cases, provided that all the plants considered have approximately the same production capacity. Once again, the situation can be improved by using value intervals instead of individual values (see table 8).

| Table 8. Upper and Lower Bounds for the GWP [kg CO2-Eq.]. |
|-----------------|---------|---------|
| Product         | Lower Bound | Upper Bound |
| A               | 360     | 1020    |
| B               | 475     | 485     |

5. MultiVaLCA

Within the framework of green engineering, there is a risk that the overlooking or improper treatment of uncertain information or inaccurate numerical values may ultimately lead to the use of results as a basis for decision-making that cannot claim to be true in a scientifically sound sense. As a possible way out of this dilemma, the multi-value method was presented using two very simple examples, whereby the incorrectness of the usual calculations based on single values could be made clear.
In order to consistently eliminate the potential source of error discussed here, it is necessary without exception to add upper and lower bounds to all numerical values relevant in the course of a calculation and to utilize these value pairs using interval arithmetic for the mathematical evaluations. The software system MultiVaLCA [8] realizes this approach in a very general way for the field of life cycle assessment. Figures 1 and 2 show the two relevant input dialogs of the addressed software.

6. Conclusion
In this article, the necessity and realization of a new approach in connection with life cycle assessments was discussed. The MultiVaLCA program is the first implementation of the new procedure, which is currently undergoing intensive further development. It is to be hoped that the recommendation made here will be adopted by experts so that erroneous decisions based on life cycle assessments and misinterpretations of corresponding studies can be avoided in future.

References
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