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Products in Early Development Phases: Ecological Classification and Evaluation Using an Interval Arithmetic Based Calculation Approach

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***Abstract*—**As a pillar of sustainable development, ecology has become an important milestone in research community, especially due to global challenges like climate change. The ecological performance of products can be scientifically conducted with life cycle assessments. In the construction sector, significant amounts of CO_2 emissions are assigned to the energy used for building heating purposes. Therefore, sustainable construction materials for insulating purposes are substantial, whereby aerogels have been explored intensively in the last years due to their low thermal conductivity. Therefore, the WALL-ACE project aims to develop an aerogel-based thermal insulating plaster that would achieve minor thermal conductivities. But as in the early stage of development phases, a lot of information is still missing or not yet accessible, the ecological performance of innovative products bases increasingly on uncertain data that can lead to significant deviations in the results. To be able to predict realistically how meaningful the results are and how viable the developed products may be with regard to their corresponding respective market, these deviations however have to be considered. Therefore, a classification method is presented in this study, which may allow comparing the ecological performance of modern products with already established and competitive materials. In order to achieve this, an alternative calculation method was used that allows computing with lower and upper bounds to consider all possible values without precise data. The life cycle analysis of the considered products was conducted with an interval arithmetic based calculation method. The results lead to the conclusion that the interval solutions describing the possible environmental impacts are so wide that the result usability is limited. Nevertheless, a further optimization in reducing environmental impacts of aerogels seems to be needed to become more competitive in the future.

***Keywords*—**Aerogel-based, insulating material, early development phase, interval arithmetic.

I. Introduction

As global resource use becomes increasingly drastic and climate change progresses, strategies with effective measures to tackle this development play an increasingly important role in environmental policy. One of the main causes of global warming is energy production, which emits carbon dioxide, a greenhouse gas that contributes significantly to the rise in global temperatures. In particular, the construction sector contributes to climate change with around 32% of global energy demand and 19% of global greenhouse gas emissions [1]. For this reason, intensive research is being conducted into innovative building materials for the building envelope. The aim is to develop building materials that are characterized by sustainable, resource-conserving and energy-efficient production. At the same time, the insulation properties of the building products are optimized so that the lower thermal conductivity also reduces the heat requirement of the buildings during use when installed. In addition, disposal aspects at the end of the useful life of the building material are dealt with, which should make a further contribution to the conservation of resources through high recyclability. Aerogels based on silicon dioxide are a promising material that is being intensively investigated for thermal insulation products due to its very low thermal conductivity of approx. 0.017 W/mK to 0.021 W/mK [2].

The relevance of sustainability aspects means that already at the beginning of product development not only the usual material tests, but also investigations from an ecological point of view are indispensable in order to classify and, if necessary, optimise their current and possible future ecological performance. This is particularly important as about 80% of the later environmental impacts are determined in the early development phase of products [3]. Life Cycle Assessment (LCA) is a scientific evaluation method that maps the current situation and can be reliably analysed with the help of so-called past models and possible future changes. It is regulated by the standards EN ISO 14040 and EN ISO 14044 [4], [5].

Before LCA studies can be created, a large number of decisions have to be made, such as the definition of system boundaries and the allocation rules to be applied. In addition, a large amount of data has to be collected. Cradle-to-cradle analyses thus provide information on the entire life cycle from the extraction of the raw materials required to manufacture the product through to recycling, which takes place after the use phase. Some of the necessary information is not deterministic in nature and therefore cannot be unambiguously determined, or is completely missing at the time of accounting and therefore requires assumptions. This results in LCA studies that involve a large number of uncertainties. However, the existing calculation methods require the input of exact values. While in the construction sector uncertainties due to natural statistical distribution of the components can be taken into account in static calculations with the aid of semi probabilistic safety concepts, not all data required in a balance are probabilistic or the database of ecological information is too small or still missing to consider the uncertainties existing in this way in the LCA studies [6]. When probability distributions are applied, they are therefore often based on

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subjective expert estimates such as the lifetime of a product, which are predicted with the aid of empirical values [7], or the different data are recorded instead, e.g. as mean values. The uncertainties that occur when comparing with previous calculation methods and in particular the resulting results, which suggest robustness due to their exact values, are therefore a widely discussed issue [8], [9].

According to EN ISO 14044 [5], the analysis of data with regard to data quality and thus also the estimation of errors by their uncertainties is necessary in order to better assess the reliability of the results. However, the existing mathematical methods for error calculation are not suitable for every type of uncertainty and a combination of different methods for error estimation is often not possible [10]. Although current LCA studies are increasingly attempting to take into account the uncertainties that arise [11], the implementation of the procedures is time-consuming and cannot be performed with sufficient reliability in many LCA studies. Therefore, this study presents an alternative, practicable procedure that is suitable for taking a large number of uncertainties directly into account in the LCA. The approach supplements the previous calculation methods with an interval-based method, which was already proposed in 1996 [12]. In this method, in addition to the expected fixed values, all possible and relevant uncertainties in the data basis are specified with the aid of intervals whose lower and upper limit values thus describe the boundary to the impossible or irrelevant and are considered in the conclusion.

The calculation method based on the interval calculation was implemented in the LCA program MultiVaLCA, which was developed at the Institute of Construction Materials at the University of Stuttgart [13] and used in the computations presented in this study.

II. LCA Studies of Products in the Early Development Phase

In the early phases of product development, uncertainties multiply due to the lack of undefined data and pending decisions and forecasts [3], [14]. On the one hand the development is still on the level of the prototypes or even on the laboratory scale, whereby the data can be raised only for this development phase. The manufacturing process on such a small scale cannot be transferred linearly to industrial production. Industrially produced manufacturing processes are usually much more energy efficient, so that the furnaces or reactors used run continuously, unlike prototypes, and the energy required for reheating is saved. Industrial furnaces can also produce a multiple of the product quantities without increasing the energy demand to the same extent. Moreover, synergy effects can often be used in industry, e.g. the waste heat from brick kilns is used to dry the brick blanks, which is usually not yet practiced in the production of new developed bricks on a laboratory scale. If background data are already available for the industrial production process, they can be transferred, but such data are not yet available especially for innovative products such as aerogels.

In addition to changes in the manufacturing process, the product developers also expect to optimize formulations in the early development phase of products. Such decision questions are still open at the time of balancing and can only be predicted qualitatively, i.e. the forecasts are based primarily on empirical values from experts due to the still uncertain data basis. The necessary forecasts about future, then marketable products and their automated production are therefore subject to further uncertainties. Furthermore, the ecological background data available in databases for mapping raw materials and intermediates for innovative products such as aerogels are often still very small or non-existent [3].

III. Dealing with Uncertainties in LCAs

In general, uncertainties can be described as a discrepancy between the measured, calculated or estimated value and the real value [11]. Uncertainties are possible in all four phases of a LCA and over the entire life cycle of a product. They are often differentiated according to their origin. According to [9], [16], a distinction is made between “uncertain data”, “vague data” or “fuzzy data” and “imprecise data”.

The uncertainties relevant to the decision-making process are referred to as “uncertain values” that require particular attention in determination. Uncertain values in the sense of [9], [16] can cause wrong decisions on the one hand, but on the other hand decisions not yet taken can also be the reason of numerical uncertainties. For example, deviations in the numerical values of basic parameters may be due to incorrect decisions about system boundaries or allocation rules to be taken into account. This also applies to assumptions that only have to be made with the help of forecasts, since no existing database can be used. A typical example is the expected service life of a product or its recycling possibilities after its utilization phase, which can only be expected in many years' time, especially for building components. For products in the early development phase, this applies not only to the use and end-of-life phases, but also to the manufacturing and assembly phases. On the contrary, "fuzzy data" or "vague data" are described as data for which the determination of the true value is too complex or even impossible [9], [16]. These are data for which there is necessarily a lack of information because the collection of these data is too complex. One example is the characterisation factors that relate the effects of, for example, different emissions on climate change. On the other hand, "inaccurate data" are often referred to when an accurate value is available but varies [9], [16]. This applies, for example, to deviations from measured data on CO_2 emissions or the necessary water demand of a unit process, but also to estimates. Even if, for example, the data sets used for modelling deviate from the actual values, these can be described as inaccuracies.

Another way of classifying uncertainties is to distinguish between random and systematic deviations from the true value [15]. Random deviations are not reproducible, while systematic deviations occur again and again. Examples of a systematically caused error are rounding errors, faulty algorithms or deviations of the measurement data due to measuring instrument errors. Incorrect entries of values or deviations in the measured values of the same measurement, on the other hand, are examples of possible random errors.

Most of the data on which a LCA is based are not available as exact values. Deviations of input data from true value usually lead to indefinite deviations of accounting results, the amount of which depends on how the deviations behave or "spread" in the calculation. There are a number of proposed methods for estimating these errors that aim to retrospectively capture the uncertainties in accounting results. For example, to estimate the errors of "inaccurate data" in the results, analytical methods can be applied, e.g. approximation formulas based on Taylor series developments and Gaussian error propagation laws. In this way, errors in the results caused by inaccurate data, such as measurement errors with small deviations, can be identified. Therefore, it must be known how the balance sheets are mathematically calculated. However, the calculation algorithms are often not disclosed in commercial remuneration programs [16]. By contrast, simulation methods such as Monte Carlo simulation enable random errors to be determined by "inaccurate" input values using probability distributions. However, these simulations require a great deal of time and computational effort.

Scenario or univariate or multivariate sensitivity analyses [16], [17] are suitable for "fuzzy" and "uncertain" data whose deviations cannot be statistically recorded. By varying the input values, these methods can be used to calculate new accounting results that show the influence of the variations on the final results. In sensitivity analyses, the values of the most important parameters are often varied qualitatively or quantitatively. Scenario analyses can also be used to determine possible effects of changes [16], [17]. These can be applied to all kinds of uncertainties, including "inaccurate data". Basically, they can also be used to determine the maximum possible influence of uncertain data on LCA results in order to define the error limits of the results. To this end, scenarios shall be identified for extreme cases where the environmental impact of the product system becomes minimum or maximum. These are the so-called "best cases" or "worst cases" to be expected for a product system. However, balancing all conceivable scenarios by combining the various uncertainties can mean a large number of balances, as the number of possible permutations increases progressively with the number of uncertainties. It should therefore be possible to specifically identify these extreme scenarios. It must be determined which individual deviations have a maximum positive or maximum negative effect on the LCA results in conjunction with which other deviations. The balance sheet is then recalculated with the specified values and the results analysed in the "best case" or "worst case". However, the extreme scenarios are not immediately and clearly legible from all product systems. This can already be the case with simple product systems whose unit process structure is linear or tree-like or at least no longer contains recycling loops. To be able to determine the extreme scenarios exactly, all possible scenarios resulting from a combination of uncertain values must be calculated. This is illustrated in the following by three simple product systems.

IV. Exemplary Product Systems

The three product systems presented here each consist of three unit processes. The fictitious product P can be manufactured by the product systems. The aim of the LCA of these systems is to examine them with regard to the climate change potential GWP. The unit of all elementary flows and intermediate products is simply defined in kilograms, the target product P is stated in units.

The first Product System (PS1) consists of Unit Process 1 (UP1), which produces 1 kg of X when executed once (cf. Fig. 1). This produces 1 kg CO_2 as well. In Unit Process 2 (UP2), 1 kg of Y is generated when the process is carried out exactly once, simultaneously releasing 0.2 kg methane. In Unit Process 3 (UP3) 1 piece of the target product P is manufactured when the process is run one time. This requires 1 kg of Y and a certain amount of X. At the time of balancing, the exact quantity is not yet certain, it is between 0.95 kg X and 1.05 kg X. For example, the conventional calculation method uses the mean value, which in this case corresponds to 1 kg X. The mean value is then used for the calculation. The uncertainty of the quantity X can then be taken into account when determining the error limit by scenario analysis, determining the two scenarios in which the GWP indicator value of the product system PS1 becomes minimum or maximum. In this first example, the best and worst case can be quickly identified. A "best case" and a "worst case" exist if the modules with uncertain values contribute to the GWP. This applies to product X, in whose production CO_2 is emitted that contributes to GWP as a greenhouse gas and which flows with an uncertain amount into UP3. Without having to know the closer qualitative value of the characterisation factor of CO_2 emissions (CF_{CO2}) to calculate the GWP, the two extreme cases can be assigned: The "best case" is UP3 with a minimum requirement of 0.95 kg X and thus a minimum CO_2 emission of 0.95 kg CO_2. The worst-case scenario occurs with a maximum requirement of 1.05 kg X and thus a maximum emission of 1.05 kg CO_2 in UP3.

If the product system is now changed so that 0.2 kg Y is produced as a by-product in UP1, the "best case" and the "worst case" are no longer quite so easy to detect. The changed second Product System (PS2) is shown in Fig. 2. In order to estimate the environmental impacts of the system on climate change, the characterisation factors of CO_2 (CF_{CO2}) and CH_4 (CF_{CH4}) must be known, i.e. the contributions of both emissions to climate change potential must be related. Since the reference value of the GWP is CO_2, CF_{CO2} is exactly 1. The characterisation factor of CH_4 is less clear. According to [18], the influence of CH_4 emissions into the atmosphere on global warming is 25 times greater than CO_2. Therefore, CF_{CH4} corresponds to the value 25. With an average demand of 1 kg X, the GWP_{PS2_25} results as the GWP of PS2 with the value 25 for CF_{CH4} as follows:

$$\begin{aligned} GWP_{PS2\_25} &= 1.0 \text{ kg } CO_2 \cdot 1 + 0.8 \cdot 25 \cdot 0.2 \text{ kg} \\ &= 5.0 \text{ kg } CO_2 \text{ eq.} \end{aligned}$$

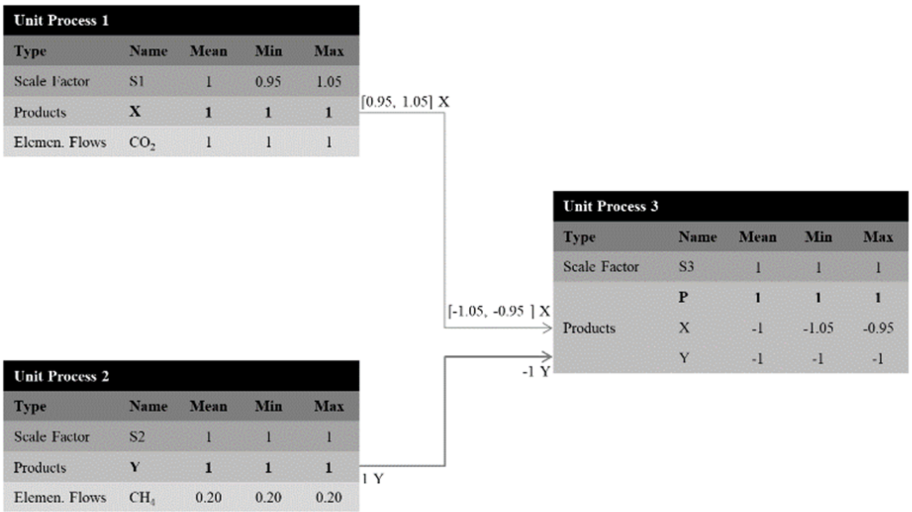


Fig. 1 Exemplary Product System No. 1 (PS1)

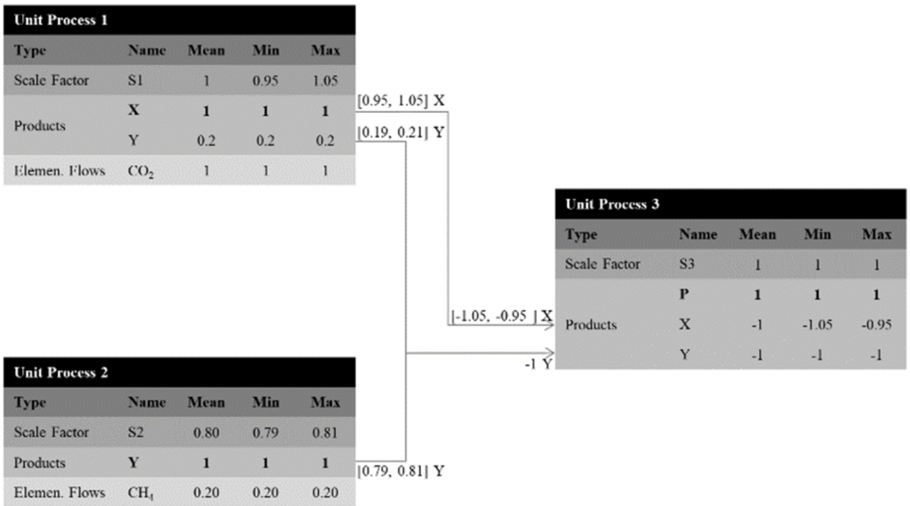


Fig. 2 Exemplary Product System No. 2 (PS2)

With 4.0 kg CO_2 eq. 80% of the GWP_{PS2_25} can be assigned to UP2, i.e. product Y is a significant parameter in this example. A "best case" could therefore be assumed if the production of Y in UP2 becomes minimal (shown in scenario 1, briefly described as SZ1) and analogously a "worst case" with maximum production of Y (shown in scenario 2, briefly described as SZ2).

The SZ1 with a minimum production of Y in UP2 is achieved when the demand of product X in UP3 is set at 1.05 kg X. This leads to a maximum scaling factor value $S1_{max}$ of UP1 with a value of 1.05. This results in a maximum emission of 1.05 kg CO_2, but with a maximum scaling factor of $S1_{max}$, the maximum quantity of byproduct Y with a total of 0.21 kg Y is generated simultaneously, so that the scaling factor of the UP2 with $S2_{min}$, which is 0.79, is minimal, and hence also the emission of methane with 0.79 · 0.2 kg CH_4, which corresponds to a total of 0.158 CH_4. Similarly, the SZ2 can be achieved with a maximum production of Y in UP2 if the demand of X in UP3 is only 0.95 kg X, which leads to a minimum scaling factor value $S1_{min}$ in UP1 of 0.95 and thus a minimum production of 0.95 kg CO_2. At the same time, however, the production of the byproduct Y becomes minimal with 0.19 kg Y, which requires a maximum production of Y with a total quantity of 0.81 kg in UP2. The resulting maximum scaling factor $S2_{max}$ with a value of 0.81 also means a maximum methane emission by UP2 with 0.81 · 0.2 kg CH_4, i.e. 0.162 CH_4. In order to determine the "best case" and the "worst case" qualitatively, a recalculation of the impact assessment is necessary. The $GWP_{PS2\_25\_SZ1}$ as GWP of SZ1 of PS2 and the $GWP_{PS2\_25\_SZ2}$ as GWP of SZ2 of PS2 lead to the following result:

$$GWP_{PS2\_25\_SZ1} = 1.05 \text{ kg } CO_2 \cdot 1 + 0.79 \cdot 25 \cdot 0.2 \text{ kg} = 5 \text{ kg } CO_2 \text{ eq.}$$

$$GWP_{PS2\_25\_SZ2} = 0.95\ kg\ CO_2 \cdot 1 + 0.81 \cdot 25 \cdot 0.2\ kg = 5\ kg\ CO_2\ eq.$$

In fact, in PS2, it is irrelevant what amount of X is needed, the interactions of UP1 and UP2 on the GWP are such that they cancel each other out. Even with this simple product system it is not easy to determine whether there are extreme cases without calculating the scenarios, and certainly not which scenarios lead to a best and worst case. If UP3 introduces a further uncertainty that is independent of the need for X, four possible scenarios arise by combining the extreme values. This case is illustrated with Product System No. 3 (PS3) shown in Fig. 3. It is identical to PS2 with the exception of the UP2 emissions, which are only 0.1 kg methane in PS3.

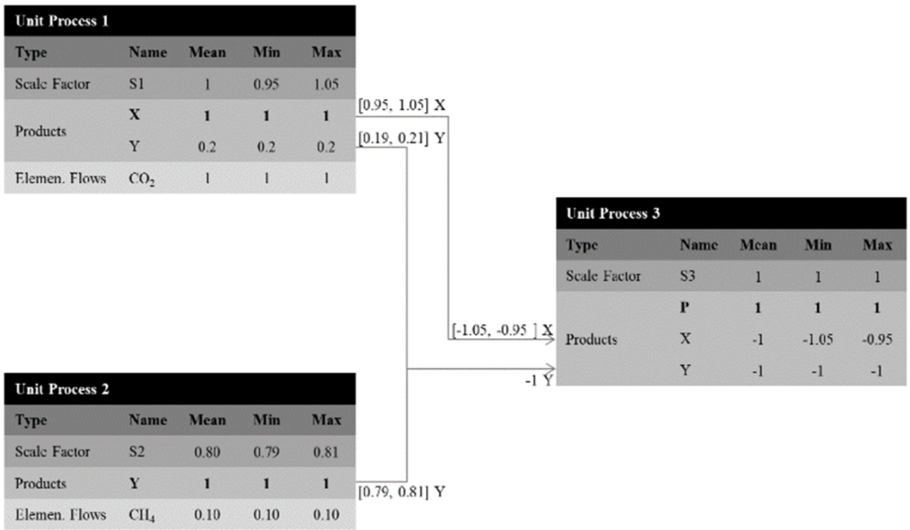


Fig. 3 Exemplary Product System No. 3 (PS3)

Pursuant to [19], the characterisation factor of methane was 21 in 1999, according to [20] the value of CF_{CH4} was 28 in 2016. If the GWPs of the two scenarios are calculated using these factors, the environmental indicator values are:

$$GWP_{PS2\_21\_SZ1} = 1.05\ kg\ CO_2 \cdot 1 + 0.79 \cdot 21 \cdot 0.1\ kg = 2.709\ kg\ CO_2\ eq.$$
$$GWP_{PS2\_21\_SZ2} = 0.95\ kg\ CO_2 \cdot 1 + 0.81 \cdot 21 \cdot 0.1\ kg = 2.651\ kg\ CO_2\ eq.$$
$$GWP_{PS2\_28\_SZ1} = 1.05\ kg\ CO_2 \cdot 1 + 0.79 \cdot 28 \cdot 0.1\ kg = 3.262\ kg\ CO_2\ eq.$$
$$GWP_{PS2\_28\_SZ2} = 0.95\ kg\ CO_2 \cdot 1 + 0.81 \cdot 28 \cdot 0.1\ kg = 3.218\ kg\ CO_2\ eq.$$

The result shows that the GWP value in SZ2 becomes minimal, i.e. at maximum Y production in UP2, if CF_{CH4} gets minimal with a factor of 21 at the same time. In contrast, the GWP value in SZ1 becomes maximal, i.e. at minimum Y production in UP2, if CF_{CH4} is maximal at a factor of 28 simultaneously.

The three product systems PS1, PS2 and PS3 are highly simplified, fictitious systems. Product systems usually have much more complex structures with a larger number of unit processes, which in turn consist of a multiple of inputs and outputs, mostly based on uncertain values. For such systems, it is difficult to identify the two extreme cases, and it is extremely time-consuming to calculate all permutations that occur. Instead, it makes sense to record the error limits in a LCA by recording indefinite values directly as intervals and calculating them as result intervals. This procedure is explained in Section V.

V. Alternative Calculation Method Based On Interval Arithmetic

The method presented in this study supplements the previous calculation methods with an interval-based method in which the uncertainties are directly taken into account within the calculation. All uncertain values in the database are defined by intervals. As with conventional calculation methods, the typical main value is entered, too. This can be, for example, the mean value or the median or the expected value. The lower and upper limits describe the limit of the impossible or potentially irrelevant. Within these limits, all intermediate real numbers are also possible or potentially relevant (see Fig. 4).

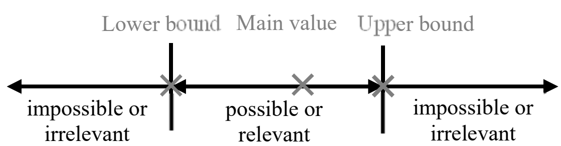


Fig. 4 Interval with main value, lower and upper bound

By the comparison over intervals, the manual determination of the uncertain parameters, which is increasingly time-consuming in complex systems, is superfluous on the one hand, on the other hand not all scenarios must be calculated, which would be necessary e.g. for the determination of the "Best Cases" and "Worst Cases". Since the error limits have already been taken into account, the analyses for error estimation after completion are also omitted. In addition, possible changes in the database can be taken into account by entering upper and lower limits and cannot be analysed using sensitivities.

The results of the life cycle assessment carried out in this way are result intervals and not precise values. The interval contains all possible or potentially relevant environmental impacts that may result from the analysed product system. In contrast to conventional methods, which only provide results with exact values, but with uncertainties, the results based on interval arithmetic are not exact values but result intervals. As a consequence, they are not precise, but contain all recorded uncertainties. The more uncertainties exist and the larger the individual deviations are, the more uncertain the LCA results can be, which is reflected in large interval widths of the result intervals. However, while the results determined with fixed values are rarely reproducible due to the many assumptions and their deviations from the true values can therefore be very large, result intervals always contain the actual and true values. In over and above this, the interval size can provide statements for the uncertainties in the LCA.

The procedure is now demonstrated on the PS3 Product System (compare Fig. 4). The uncertain required quantity of X in UP3, which is between 0.95 kg X minimum and 1.05 kg X maximum, can be represented by the demand interval, which is [-1.05, -0.95] kg X. Values between 0.95 kg and 1.05 kg are also possible. The definition of the required quantity of X means that the scaling factor S1 of UP1 can only be represented as the interval [-1.05, -0.95], which in turn results in a scaling factor S2 of UP2 of [0.79, 0.81]. The resulting emissions are also calculated as intervals. The CO_2 emission of UP1 is [0.95, 1.05] kg CO_2, the methane emission of UP2 is [0.079, 0.081] kg CH_4. The characterization factor of CH_4 is described by the interval [21, 28]. The result is a GWP with [2.609, 3.318] kg CO_2 equivalent.

The result interval contains all true and possible or potentially relevant values that the product system can assume and therefore also includes all results of the balanced extreme scenarios. It also shows that the limit values of the result interval are smaller and larger than the environmental indicator values determined in the "best case" and "worst case". As long as the exact demand for X cannot yet be defined, the interval arithmetic approach leads to all states that arise for the unit process and thus for the entire product system being in the range of the possible or probable relevant, including those states that result from superposition. In concrete terms, this means that the scaling factor of UP1, which occurs several times in the calculation, can assume the minimum value $S1_{min}$ with a value of 0.95 at one point and the maximum value $S1_{max}$ of 1.05 at another point. Thus, in the calculation, with a production of 1.05 X in UP1 only 0.95 · 0.2 kg Y can be produced as a by-product, i.e. 0.19 kg Y. This can only be eliminated if the uncertain values can be determined more precisely or the width of the result interval can be at least reduced if one or more of the uncertain values can be determined more closely. At the same time, the interval width therefore always provides a statement about the quality and accuracy of the underlying data, i.e. it provides information about the uncertainties present in the balance sheet and thus also about the significance of the results. With this approach, the presented results are no longer apparently precise, but reliable and robust.

VI. LCA Study of Aerogel-Based Plaster in an Early Development Phase

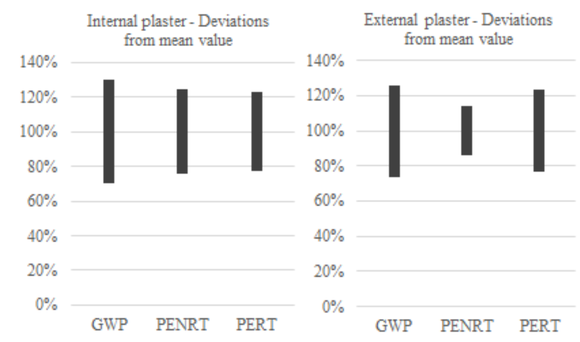
The approach presented was used to evaluate two aerogel-based thermal insulation plasters for exterior and interior applications that are currently being developed as part of the Wall ACE project. The calculations took into account the manufacturing phase of the plasters. In addition, the GWP in kg $2CO_2$ eq., the non-renewable primary energy demand PENRT in MJ and the renewable primary energy demand PERT in MJ were taken into account. In the development phase of products, the exact formulation of these is usually not yet defined and is therefore subject to constant change. The aim of the study was therefore to analyse the influence of deviations in the formulation of plasters during product development using the interval-critical approach. The calculation was carried out with the LCA program MultiVaLCA. The changes that have occurred so far or the remaining uncertainties in the formulations were recorded as intervals in order to illustrate the uncertainties in the early development phase.

Since the database of the programme is still under construction and thus no interval-based ecological background data are available for the preliminary products of the plasters, the ecological data sets of the preliminary products are entered as fixed values. Only the quantities required for the production of the plasters are therefore subject to uncertainties. The results are not suitable for comparative analyses with other plasters.

The declared unit of the interior plaster is 1 m² for a layer thickness of 5 cm that of the exterior plaster is 1 m² for a layer thickness of 10 cm. The interior plaster consists of approx. 25-70 m% cement, approx. 5-25 m% lime, approx. 25-50 m% aerogel granulate and approx. 1-2 m% additives. The exterior plaster consists of approx. 45-60 m% binder mixture, approx. 10-35 m% mineral light aggregates, approx. 25-40% aerogel granulate and approx. 0.5-1.5% additives.

Calculating the interior plaster results in a GWP of 38.1, 70.3 kg CO_2 equivalent, a non-renewable primary energy requirement of 734.2, 1214.6 MJ and a renewable primary energy requirement of 564.7, 892.0 MJ per m² and 5 cm layer thickness. This leads to deviations from the mean value of approx. 30 % for GWP, approx. 25 % for PENRT and approx. 22.5 % for PERT (see Fig. 5).

The balance of the exterior plaster shows a GWP of 65.3, 111.4 kg CO_2 eq., a non-renewable primary energy demand of 1208.0, 1589.7 MJ and a renewable primary energy demand of 922.9, 1496.6 MJ. The deviations from the mean value amount to approx. 26 % for the GWP, approx. 13.5 % for the PENRT and approx. 23.5 % for the PERT (cf. Fig. 5). These deviations can be regarded as significant. In addition, further assumptions about the utilization phase and the disposal as well as the consideration of uncertainties in the characterization factors can lead to further, potentially very large deviations in the final results.



(a) (b)

Fig. 5 Deviations from mean value of internal plaster (a) and external plaster (b) in percent

VII. Conclusion

It has been shown that interval arithmetic makes it possible to avoid misleading conclusions in LCA studies, especially in cases where a large number of decisions have not yet been taken.

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