SUBSYSTEMS AND GROUPS IN LIFE CYCLE ASSESSMENTS WITH VAGUE INPUT DATA

SUBSYSTEME UND GRUPPEN IN ÖKOBILANZEN MIT VAGEN EINGANGSDATEN

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SUMMARY

When interval arithmetic is used to calculate life cycle inventories in the context of life cycle assessments, the accuracy of the results depends on the topology of the product systems under consideration. In principle, depending on the calculation method used, product systems with a non-tree-like structure can be expected to have result intervals that are far too wide for numerical reasons. This may lead to pessimistic interpretations which are not justified by the product systems. This phenomenon therefore requires further investigation. The problem area addressed is presented systematically in this article. Possible solutions are presented, which are currently being implemented and tested in the prototype-like software MultiVaLCA [1].

ZUSAMMENFASSUNG

Bei der Nutzung von Intervallarithmetik zur Berechnung von Sachbilanzen im Rahmen von Ökobilanzen ist die Genauigkeit der Ergebnisse von der Topologie der jeweils betrachteten Produktsysteme abhängig. Grundsätzlich ist bei Produktsystemen, die eine nicht-baumartige Struktur aufweisen, je nach Rechenverfahren mit unterschiedlichen Ergebnisintervallen zu rechnen, die aus numerischen Gründen auch eine deutlich zu große Breite aufweisen können. Dies kann gegebenenfalls pessimistische Interpretationen zur Folge haben, die im tatsächlichen Produktionsprozess des durch das abgebildete Produktsystem nicht auftreten würden. Dieses Phänomen bedarf somit näherer Untersuchung. Der angesprochene Problemkreis wird in diesem Artikel systematisch dargestellt. Es werden Lösungsmöglichkeiten vorgestellt, die aktuell in der prototypartigen Software MultiVaLCA [1] implementiert und getestet werden.

1. THE TOPOLOGY OF PRODUCT SYSTEMS

For the purpose of calculating the life cycle inventory of a product system, the first step in the process is to clarify what quantities of the intermediates occurring in the product system are required for the target quantity of the target product at the respective interfaces. This leads to the calculation of scaling factors, which quantify the respective intensity of use of each existing unit process. These numerical values in turn can be summarized in a scaling vector (see [2], p. 327 ff). In the simplest case, a product system consists of a chain of successive unit processes (see Fig. 1).

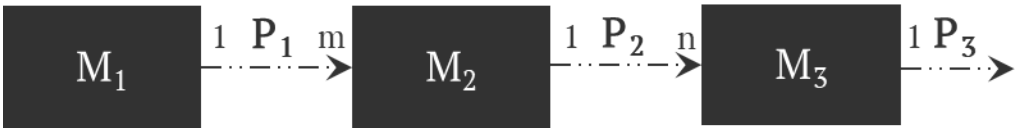

Fig. 1: Linear product system, consisting of three unit processes. The numerical values of the product flows refer to the balance of the individual unit processes before calculation of the scaling vector

The calculation of the scaling vector of such chain-shaped product systems is - for conventional as well as for interval-based life cycle assessments - largely trivial. Here, the solution of the linear algebraic system of equations can be performed "sequentially", i.e. the individual scaling factors can be calculated one after the other, i.e. starting from the final product, step by step backwards along the unit process chain, since then the scaling factors to be calculated are the only unknowns in the individual equations of the unit processes.

In many cases, product systems do not have a chain-like but a tree-like topology (see Fig. 2). The life cycle inventory of a tree-like product system can also be performed step by step as described above.

Here and in the following it is assumed that the resulting system of equations is solvable and that the unambiguity of the solution is guaranteed also on the basis of interval arithmetic. Product systems, where this is the case, can generally be described as unambiguously balanceable systems.

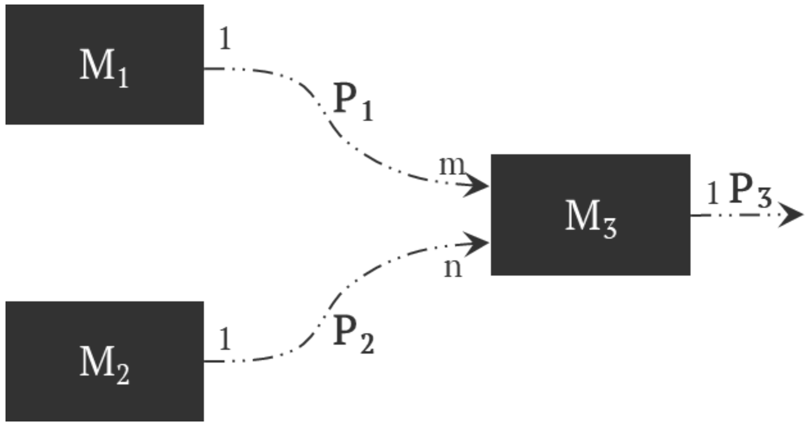

Fig. 2: Tree-like product system, consisting of three unit processes. The numerical values of the product flows refer to the balance of the individual unit processes before calculation of the scaling vector

However, if the topology of a product system contains nets or cycles, i.e. if the tree structure is disturbed, the solution of the system of equations for the calculation of the scaling vector with the "sequential" approach is only possible by several iterations. Although this is usually possible without problems with the conventional method, it can be advantageous in these cases to use direct solution methods. As is well known, numerous methods are available for this purpose. If, however, as described elsewhere (see [3 - 6]), the entire LCA is processed using interval arithmetic, a fundamental problem arises for product systems that are not structured like trees.

So in interval arithmetic the commutative and the associative law are valid for elementary algebraic operations, but the distributive law cannot be maintained in interval arithmetic [7]. This means, that the sequence of a connexion of two or three operands has no influence on the results, e.g.:

$$[\underline{a},\overline{a}] + [\underline{b},\overline{b}] + [\underline{c},\overline{c}] = [\underline{c},\overline{c}] + [\underline{b},\overline{b}] + [\underline{a},\overline{a}]$$

However, the calculation sequence of two connexions can affect the result, i.e. not all connexions are compatible with other connexions, for example:

$$([\underline{a},\overline{a}] - [\underline{b},\overline{b}]) \cdot [\underline{c},\overline{c}] \neq [\underline{a},\overline{a}] \cdot [\underline{c},\overline{c}] - [\underline{b},\overline{b}] \cdot [\underline{c},\overline{c}]$$

This also means, that the single arithmetic steps cannot be reversed by opposite arithmetic steps, but sometimes lead to a further enlargement of the result interval. In principle is valid, that every single step of calculation leads to an enlargement of the result interval. This numerically caused interval widening has to be prevented or at least limited as far as possible, because otherwise the width of the result intervals cannot be interpreted in the intended way and used for the evaluation of the underlying product system. On the other hand, it is positive that there is no undesired narrowing of the result intervals.

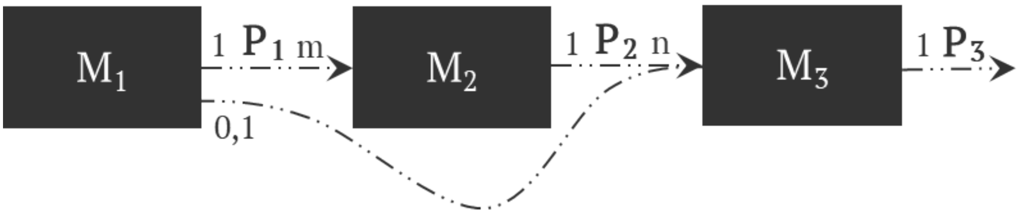

Fig. 3: Product system consisting of three unit processes, whose original chain-like structure is disturbed by the by-product P2 occurring in unit process M1

Two cases with non-tree-like topology can be distinguished in principle: this is the occurrence of an internal by-product (see Fig. 3) and the presence of an internal recycling loop (see Fig. 4).

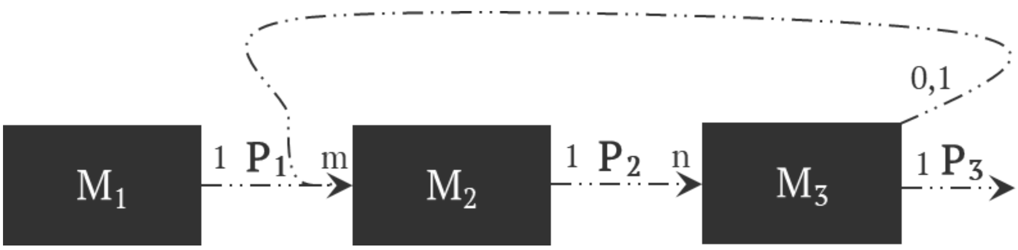

Fig. 4: Product system consisting of three unit processes whose original list-like structure is disturbed by the by-product P1 occurring in unit process M3

Under the assumption that the end product of a product system to be achieved is to be generated and not consumed, it can happen in these two cases that the scaling vector in the result has one or more values with a negative sign. These may be modelling errors based on the assumption that the by-products and recycling streams within the product system can actually all be reused. If this is not the case, the product system must be supplemented by additional unit processes that take over the necessary disposal of the surplus product stream.

2. SUBSYSTEMS

If it is possible or even necessary to delimit or separately model a subsystem within a product system which, when considered on its own, represents a system that can be clearly accounted for and whose associated life cycle inventory can thus be calculated separately, the relevant part can be designated as a subsystem and evaluated accordingly. It is also possible to add a subsystem to a superordinate product system for modelling purposes. In case of chain- or tree-like product systems, any subsystem can be treated in this way (see Fig. 5).

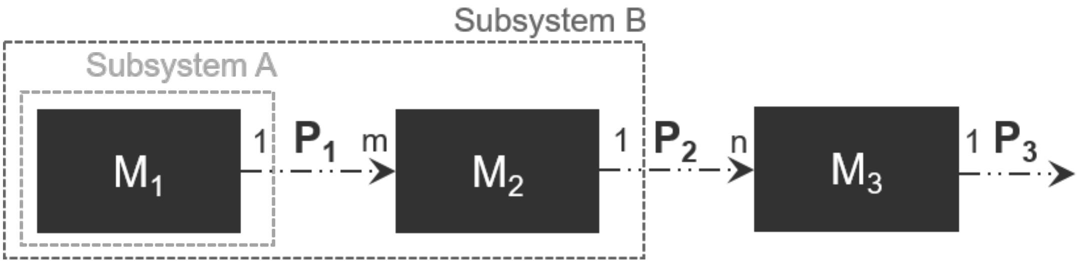

Fig. 5: Linear product system with the two exemplary subsystems Subsystem A, consisting of unit processes M1 and Subsystem B, consisting of Subsystem A and unit process M2

In cases where the chain- or tree-like structure of a product system is disturbed by the presence of internal by-products or recycling cycles, the delimitation of subsystems cannot be arbitrary in the unrestricted manner described.

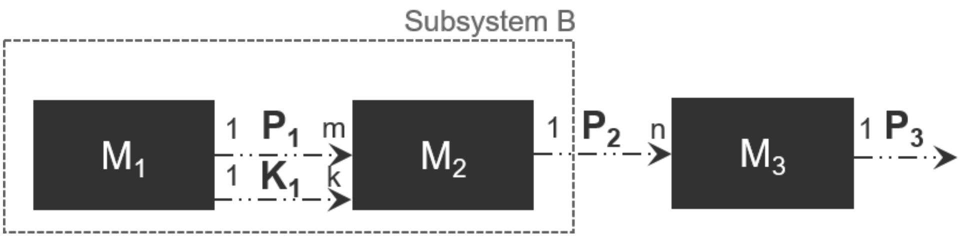

Fig. 6: Product system whose chain-like structure is disturbed by the by-product K1. Therefore the smallest possible subsystem B consists of unit processes M1 and M2

Rather, it is necessary to locate the parts of the system in which the by-products and recovery streams occur and to assign each of these completely to a corresponding subsystem (see Fig. 6).

3. GROUPS

A special case that deserves special attention is when there are several unit processes within the product system that can be used to provide the same intermediate product side by side. A combination of such unit processes is referred to as a unit process group in the following. Unit process groups can be considered the most important special case of the more general groups within a general LCA system.

Product systems that contain unit process groups cannot be uniquely assigned. In order to avoid these difficulties, the available options are usually not recorded as individual unit processes, but as an overall unit process group in which the data from the unit processes are averaged with an appropriate weighting. This approach has the blatant disadvantage that the elementary flows and thus the environmental impacts resulting from the worst of the available options are hidden, so to speak, by grouping the better options with the better variants - possibly even with clear intent. The typical example of the described procedure is the so-called "electricity mix" (see Fig. 7).

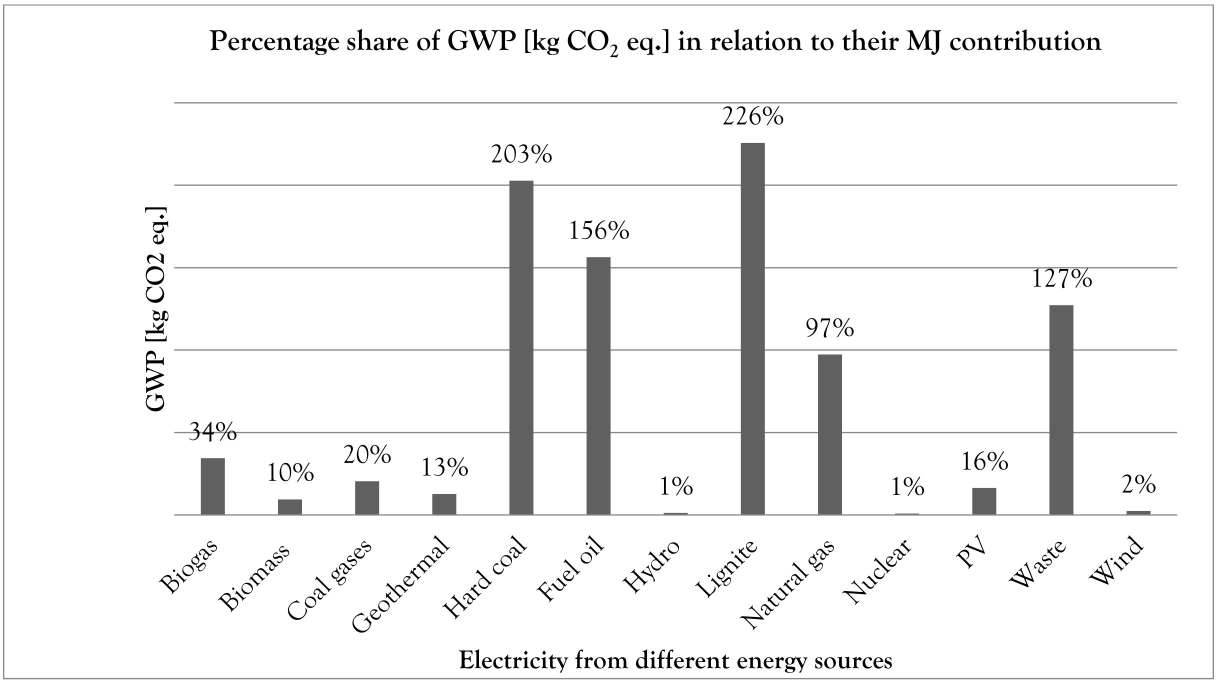

Fig. 7: German electricity mix and its percentage share of GWP in relation to MJ contribution of the respective energy sources

As a (sub)system, the electricity mix represents the composition of the average electricity production of a country. The results of the GWP of the individual energy sources are standardised in the diagram in such a way that those energy sources have a GWP of more than 100% whose expansion would lead to a deterioration in the GWP of the overall electricity mix and at the same time their reduction would lead to an improvement in the GWP of the overall electricity mix. Similarly, the expansion of those energy sources whose GWP is below 100% in the figure would lead to an improvement in the GWP of the electricity mix - at the same time, this also means that a reduction in these energy sources can lead to a deterioration in the GWP of the overall electricity mix. The weighting factors required in such cases therefore represent the averaged factor values of the country. This prevents the possibility of a targeted improvement of a product system through the concrete selection of a favourable individual unit process or at least through the explicit exclusion of a particularly unfavourable individual unit processes. Within the framework of the interval-arithmetic approach, averaging is dispensed with completely. Instead, an aggregated unit process is ultimately calculated that takes into account the respective extreme values of all available options as upper and lower limits of the data intervals and thus continues to fully consider both "the best" and "the worst" processes for power generation.

In this context, the interval-based method favours two things: On the one hand, if the information base is insufficient - and the resulting large interval width is usually too wide - the transparent presentation of the results makes it immediately obvious that the significance is too low and more precise information is required. On the other hand, the interval representation in product development enables the early identification of improvement potentials, so that "bad" representatives can be recognized early and excluded as processes with high environmental impact.

4. IMPLEMENTATION IN MULTIVALCA

The implementation of the two described concepts can be done in two fundamentally different ways. In case of an explicit implementation, unit processes representing the results of the life cycle inventory of subsystems or groups of unit processes would be added to the database in form of real unit processes. An obvious advantage of this approach is that each corresponding calculation has to be performed only once and the obtained results are available as output data for future calculations of larger product systems containing the corresponding elements. On the other hand, the disadvantage is that any subsequent modification of individual unit processes within the subsystems or unit processes groups will invalidate all data sets based on an earlier version of the corresponding unit process. In the case of an implicit implementation, the subsystems and unit process groups are declared, but the associated Life Cycle Inventory calculation is always only performed in the course of the calculation of a modified product system in which they are included as components.

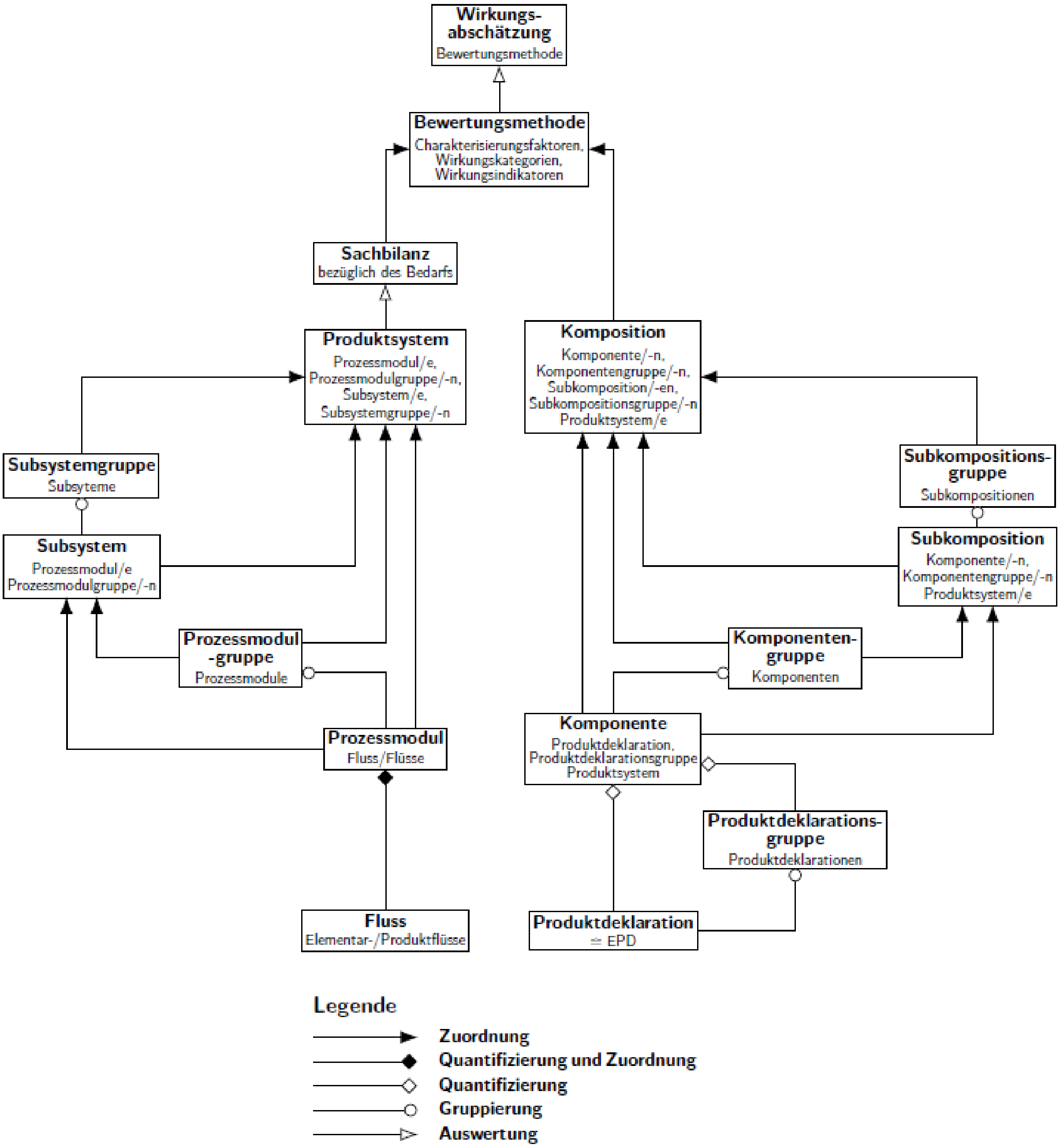

Fig. 8: Systematic structure of the MultiVaLCA program: on the left-hand side unit processes and systems are used to enter life cycle inventories, on the right-hand side results of life cycle assessments (e.g. EPDs) for individual components (in the picture: compositions) [8]

The two concepts discussed in section 2 Subsystem and section 3 Groups have been implemented in MultiVaLCA in the implicit way and first tests have been carried out regarding the performance of this approach. From the point of view of the user this means that at those places in the program dialog where a previously recorded single unit processes can be entered, the entry of a subsystem or a unit processes group is also possible. This is made possible by the special class hierarchy shown in Fig. 8.

5. SUMMARY AND OUTLOOK

The concepts of the subsystems and groups within the product system discussed above were consistently implemented within the interval arithmetic calculation method within the software MultiVaLCA. An unintentional widening of the result intervals could be avoided and/or reduced in first experimental calculations. In the course of the investigation of larger and more complex product systems the procedure is to be further optimized. Overall, it can be assumed that the proposed procedure will be ready for practical application in the foreseeable future. In addition to the realization of the numerical aspects presented in this thesis, an optimization of the user interface is also aimed at in the course of the corresponding further development.

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