Symmetric functional modeling in Life Cycle Assessment

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to the people I love

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Abbreviations and Symbols

α :	Analogy: the portion which is needed to multiply the relevance r'_i of a system element i when it is in the LCI-system, in order to be equal to the system element relevance r_i value when the module is in its initial state
x, …,z:	Substances on the elementary flow
S_{lcax} :	Mass value of substance x in LCI-system elementary flow
S_{ix}:	Mass of the relevant substance x found in system element i
R_M:	Module relevance
r_{limit} :	cut-off limit expressed in relevance units applied on the module subsystem
r_{LCA}	cut-off limit of the LCI-system given expressed in relevance units
r_{iSx}:	Relevance of the substance x found in system element i
r_{iSx}:	Relevance of substance x found in the system element i
r_i:	Relevance of system element i
r_i:	Relevance of system element i
ps.-j	Pseudo system element j
${}_{Out}f_M$	Module product outflow when it is interconnected in the LCI-system
${}_{Out}F_i$:	Product outflow of system element i in its initial state
N_x:	overall normalization factor for substance x
n_{mSx}:	mass normalization coefficient of substance x
LCS:	Life cycle stage, part of an LCI-system
LCI-system	The product system as it is particularly modelled in the LCA study by the analyst consisting of the interconnecting unit processes and modules
LCI	Life cycle inventory
LCA:	life cycle assessment
${}_{In}f_M$	Module product inflow when it is interconnected in the LCI-system

${}_{im.c.}n_{ISx}$:	Environmental impact normalization coefficient of substance x for impact category im.c.
${}_{im.c.}n_{ISx}$:	environmental impact normalization coefficient of substance x per environmental impact category
${}_{Im.c.}I_{LCI}$:	overall environmental impact score of LCI-system in the defined environmental impact category
${}_{Im.c.}I_{iSx}$:	overall environmental impact score of system element caused by substance x in the defined environmental impact category im.c.
${}_{Im.c.}I_{i}$:	overall environmental impact score of system element i in the defined environmental impact category
${}_{im.c.}c_{fx}$:	Characterization factor of substance x in respective env. impact normalization coefficient of substance
im.c.	Environmental impact category investigated in LCIA phase
μ_i :	Mass-multiplier of system element i
ht	Environmental impact category of human toxicity
ss	Environmental impact category of summer smog
ec	Environmental impact category of ecotoxicity
UCPTE	Union pour la Coordination de la Production et du Transport de l'Electricité (today : UCTE, Union pour la Coordination du Transport d'Electricité). It's the European energy production mix investigated in the ETH databank. The following 12 countries are included: Austria, Belgium, Germany, France, Greece, Spain, Switzerland, Portugal, The Netherlands, Ex-Yugoslavia republic, Italy and Luxemburg

Glossary

Allocation: Partitioning the inflows and outflows of a system element to the product system under study [14].

Ancillary material flow: Material flow that is used by a system element producing a product but does not constitute a part of the product i.e. catalyst, effluent etc

Background system: Part of the product life cycle which consists of those process steps on which the ordering party and final decision maker of the LCA study has not direct influence and cannot take actions for changing the product life cycle. (See also foreground system).

By-chain (in germ. Nebenkette): the part of the product system which is not part of the main-chain [21]. (See also main-chain)

Comparative assertion: Environmental claim regarding the superiority or equivalence of one product versus a competing which performs the same function [14]

Cradle-to-gate:. The cradle-to-gate system only includes upstream processes of the product under study. Downstream processing of the manufactured product, its use, the end-of-life and scrap recovery processes are not considered in the inventory

Cut-off criteria: Criteria set by the LCA analyst in order to delimit the development of the LCI-system in the technosphere part which is relevant for the particular study.

Detail level range The detail level range refers to the number of system elements which form the module subsystem and are afterwards aggregated. The lowest possible detail level range limit is in the case of a single unit process. Upper limit of the detail level range is not determined as the number of the aggregated system elements of a module is not restricted. The detail level range is used yet as a rather qualitative attribute of a module.

Elementary cut-off criterion: The kind of the system related cut-off criteria which investigate the system element’s elementary flow on mass and energy

	basis.
Elementary flow:	The mass and energy flows which enter the LCI-system and are drawn from the environment without previous human transformation or leave the LCI-system and are discarded into the environment without subsequent human transformation [14].
Elementary flows:	The mass and energy flows which either enter the LCI-system and are drawn from the environment without previous human transformation or leave the LCI-system and are released into the environment without subsequent human transformation [14].
e-modules:	The multifunctional, symmetric adjustable in the product tree modules which were developed in the case study and refer to the electricity production in European countries
Environmental impact cut-off criterion:	The kind of the system related cut-off criteria which investigate directly the system element's environmental relevance
Foreground system:	Part of the product life cycle which consists of those process steps of on which the ordering party and final decision maker of the LCA study has direct influence and can take actions for changing the product life cycle. (See also background system).
LCI result:	Outcome of a life cycle inventory analysis that includes flows crossing the system boundary and provides the starting point for life cycle impact assessment [14].
LCI-System element:	see system element
LCI-system:	The product system as it is particularly modeled in the LCA study by the analyst
Life Cycle Impact Assessment (LCIA)	Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential Environmental Impacts of a Product System [14].
Life cycle impact assessment category indicator:	Quantifiable representation of an impact category [14, 19].
Life Cycle Interpretation:	Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are

	combined consistent with the defined goal and scope in order to reach conclusions and recommendations [14]
Life cycle inventory (LCI):	Phase of life cycle assessment involving the compilation and quantification of inputs and outputs, for a given product system throughout its life cycle [14].
Main-chain (in germ. Hauptkette):	The process chain of the product life cycle system with the minimum number of process steps starting from the end-product process step of the LCA’s flow chart and going upwards in the pre-consumption phase and downwards in the past-consumption phase going through all product phases (raw material extraction, production, manufacture, use, recycling and disposal) and finally ending up at the system border with nature [21]
Meta data:	Data supplying information on the numeric data i.e. time, technology, geographical coverage, administrative information, methodological information etc
Modeling units	The system elements on which are applied the cut-off criteria
Module:	The system element (in form of a data template) which results from the aggregation of interconnected system elements describing a life cycle stage
Numeric data:	The information containing the numeric value representing the quantity of energy or mass of a certain substance or material found in the system elements flows.
Product system:	Collection of materially and energetically connected unit processes which performs one or more defined functions
Pseudo system element	System element which is included or excluded from the investigated product system a priori. The pseudo system element is not considered a modeling unit.
Screening LCA	A low detailed and low reliable LCA. *A procedure that identifies some particular characteristic or key issue which associated with an LCA which will normally be the subject of further, more*

intensive, study” [84].

System Element: The units of the LCI-system for which data is been collected. It is an umbrella term which encloses the terms of unit process and module. System elements could be both unit processes and modules

Substance: A substance is an element or a chemical composition. In the inventory tables of some system elements are sometimes treated as one substance also group of substances due to lack of precise documentation.

Streamlined LCA (syn: Simplified LCA): A low detailed and low reliable LCA. *An LCA obtained through a procedure that reduces the complexity of an LCA and therefore cost, time and effort involved in the study. “This may involve exclusion of certain life cycle stages, system inputs or outputs, or impact categories, or may involve the use of generic data modules rather than specific data for the system under study”* [84].

Techno sphere: The global technological system integrating all human activities which are interrelated with technology

Unit process: The smallest and not further divisible balanced product system unit with ascertainable input and output flows

I. Introduction

I-1. Appointing the problem

Life cycle assessment (LCA) is a decision supporting instrument used in environmental management for assessing the environmental aspects and potential impacts associated with a product (or a service system) throughout its life cycle from cradle-to-grave (i.e. from raw material acquisition through production, use, recycling and disposal) [43]. LCA comparisons are made concerning the environmental competence of alternative product life cycles that fulfill the same function (comparative LCAs) [22, 43]. Life cycle assessment is the only environmental decision supporting instrument internationally standardized, which is covered by ISO 14040ff since 1997 [14, 15, 16, 17, 18, 19, 39, 40].

There are four stages to a life cycle assessment study, namely the goal and scope phase, the life cycle inventory phase (LCI), the life cycle impact assessment phase (LCIA) and the interpretation phase [14]. In LCI the data of the process steps involved in the product system are collected, they are then modeled and finally the environmental relevant flows of the system are calculated (LCI result). The inventory result is used as the basis for the calculation of the product system's environmental relevance in the LCIA phase. Thus, possible errors in LCI can have a large effect on the final outcomes. LCI is considered as the most time and effort demanding phase of LCA [22, 43].

One important characteristic of LCA is its relative nature. In comparative LCA, the final outcome is the environmental claim regarding the superiority or equivalence of one product life cycle versus a competing product life cycle that performs the same function [14]. Therefore, it is fundamental for the reliability of LCA results to ensure comparability among the modeled product systems investigated.

In the LCI phase where the product tree is modeled, cut-off criteria are used. The practitioner uses them to determine the boundaries of its product system. The use of cut-off criteria is essential as only the relevant for the study processes should be investigated. When processes irrelevant for the study are included in the modeled product tree, or, on the contrary, processes relevant for the study are excluded from the modeled product tree, so called data asymmetries are formed [21]. The delimitation of the product system is necessary for the feasibility of the study. If there was no system delimitation, then almost the whole technosphere would have to be investigated, which is impossible by current means.

At present, there are several proposed cut-off criteria. The selection and definition of the cut-off criterion is made by the practitioner according to the goal and scope of the particular study [14]. The consistent application of the cut-off criterion prevents the formation of data asymmetry and results in a data symmetrically modeled product tree. The data symmetric modeling of the LCI-system ensures the comparability of the LCI-systems in a comparative LCA [21, 22].

Different cut-off criteria or the same one with different cut-off criteria limits applied upon the same product system results in different LCI-systems, hence different LCI results [21, 45]. Thus, in comparative LCA, the product systems are modeled with the same cut-off criterion. However, it has not yet been investigated how the data symmetry of one LCI-system, and thus the reliability of the respective LCI result, is affected by the particular applied cut-off criterion. Furthermore, it is also not clarified how the cut-off criterion, which affects the data symmetry of each LCI-system, also affects the comparability of different LCI-systems in a comparative LCA.

Besides, at present, the use of aggregated data in the form of modules is very common. These modules are supplied from LCA databanks [8, 27, 28, 30, 54, 62]. The use of modules simplifies the LCA analysis and results in a significant reduction of both time and effort [22, 8]. However, the use of aggregated data is not conformed to the symmetric modeling because modules, as the sum of aggregated unit processes, surpass the cut-off criterion limit more easily than single unit processes [22].

Hence, the nowadays commonplace application of aggregated data in the form of fixed modules in the modeling of the product tree causes the generation of data asymmetries. These data asymmetries are erratically spawned within the LCI-system. However, data symmetric modeling of the product tree can be feasible if the modules are not fixed but functional. This module functionality should allow the application of the cut-off criterion to the single unit processes of the module subsystem.

I-2. Goal of the dissertation

The dissertation's goal is the data symmetric functional modeling of the product tree in the LCI phase of LCA. The symmetry refers to the determination of the LCI-system boundaries with the application of cut-off criteria. The symmetric development of the product tree is investigated from the perspective of one LCI-system and from the perspective of more than one LCI-system (case of comparative LCAs). The functionality refers to the development and application of multifunctional modules which are symmetrically adjustable in different positions of the same or different LCI-systems according to the selected cut-off criterion.

The symmetric modeling of the product system ensures the prevention of data asymmetries thus raises the reliability of the LCA's final outcomes. In addition, symmetric modeling ensures the comparability of the alternative product systems investigated in the case of comparative LCA studies. Moreover, the use of multifunctional modules minimizes the time and effort needed for an LCA study and simplifies the instrument, thereby enhancing its operability.

LCA, which is easier to perform, provides fast, highly reliable results and therefore enhances the number of sound decisions taken on the environment. To conclude, LCA lead us closer to a goal of sustainable development.

II. Theoretical Fundamentals

II-1. Life Cycle Assessment (LCA)

Life cycle assessment is a method for assessing the environmental aspects and potential impacts associated with a product and throughout its life cycle (i.e. from cradle-to-grave) from raw material acquisition through production, use, and disposal [14]. The term product is also used to express service systems.

In the LCA there are comparisons made of the environmental competence among alternative product life cycles, which fulfill the same function (comparative LCA) [22, 43]. The product systems are characterized by their function and cannot be defined solely by their final products [14]. This relative comparison is an essential characteristic of LCA.

There are four phases in a life cycle assessment study, namely: the goal and scope, the life cycle inventory (LCI), the life cycle impact assessment (LCIA) and the interpretation phase [14]. The LCA studies are classified according to their detail level as screening, streamlined or full-scale LCAs [5]. The modeling of the life cycle product tree as described in this dissertation takes place in the life cycle inventory (LCI) phase and draws on full scale LCAs, which are more reliable. For screening and streamlined LCAs see also Appendix 1.

II-2. LCI-System

The product tree is developed in the phase of life cycle inventory (LCI). It consists of all the relevant processes that are involved in the product life cycle stages. Flow charts are often being used to demonstrate the product system. The product system as modeled in the LCA is defined as the LCI-system.

In figure 1 the LCI-system is visualized in the ideal form of a clepsydra. This form, though simplified (see also appendix 2), allows a good overview of the whole cradle-to-grave modeled system. Each box represents a process step for which data is being collected. The process steps are linked to each other with mass or energy flows presented with arrows.

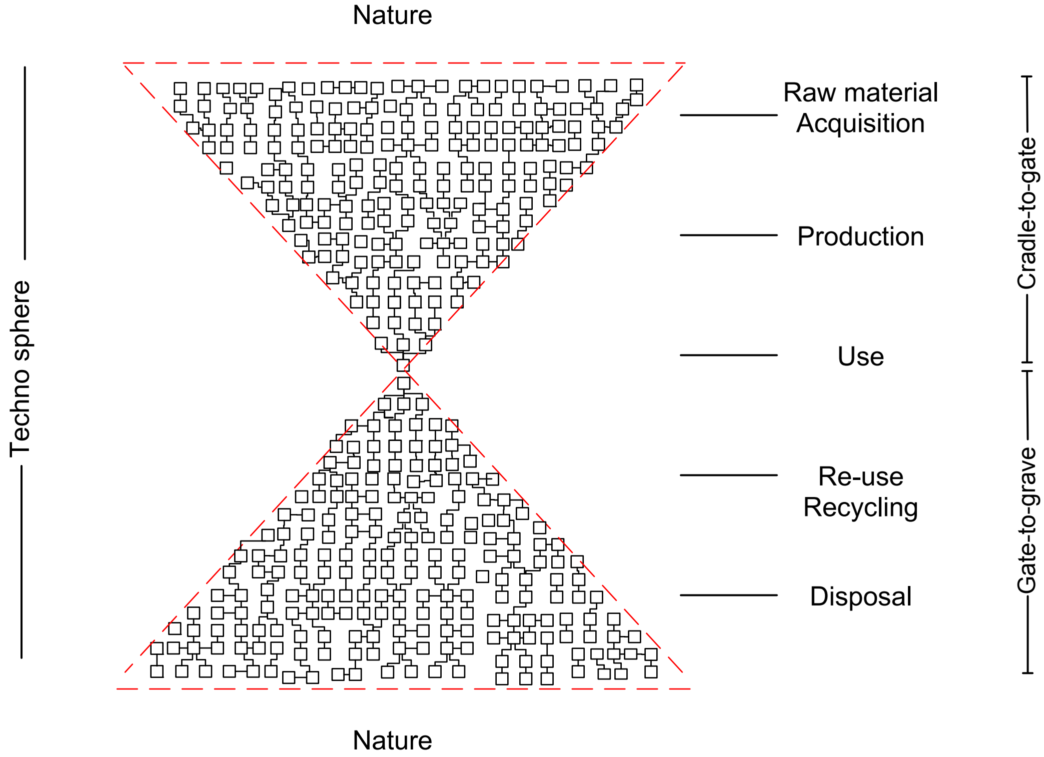


Figure 1. Clepsydra form of the LCI-system (LCA's product system)

Figure 1 shows the way in which the physical environment is both the start and end point of the product life. Nature encircles the techno sphere (defined as the global technological system integrating all technical human activities), part of which is the LCI-system under study.

The LCI-system borders (red lines) with nature and with other product systems within the technosphere. The borders within the techno sphere are artificial and set by the LCA analyst using the cut-off criteria and allocation rules [5, 22, 43] where applicable. How these borders are set is further analyzed in the following cut-off criteria LCI-system modeling paragraph.

In the center of the LCI-system is the final product wherein is found the modeled use phase. Going downwards we enter (so far available) the phases of re-use, disassembly and recycling ending up in the final disposal phase. Prior to the use phase are the production and the raw material acquisition phases.

There are two kinds of subdivision of the product system commonly used. The first is in the foreground and the background system [5, 11] while the other in the main chain (in germ. Hauptkette) and the by-chain system parts (in germ. Nebenkette) [21, 22, 34] These terms are used pragmatically and are not standardized [11] (s. also glossary and Appendix 3). Even so, these subdivisions are proved very useful in practice in terms of communication. Both the main-chain and the foreground system form the heart of the LCI-system.

II-3. System elements

The units of the LCI-system for which data is being collected are defined as system elements. The system elements are connected to each other by mass and energy flows form the LCI-system.

The term “system element” is used as an umbrella term for the terms of both unit process and module. A system element could be a unit process or a module.

As unit process is defined the smallest and not further divisible balanced product system unit with ascertainable input and output flows [24, 61]. This definition is slightly different from the one proposed in the ISO 14044 where *unit process is the smallest portion of a product system for which data are quantified when performing a LCA* [19]. The ISO 14044 definition could allow raising misunderstandings when comparing unit processes of different LCA studies and is therefore not adopted (see appendix 2).

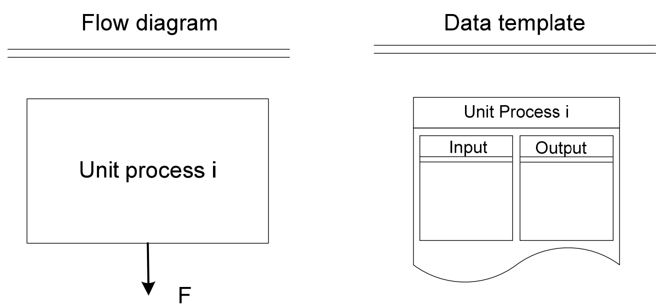


Figure 2. Unit process visualized in a flow diagram and as a data template

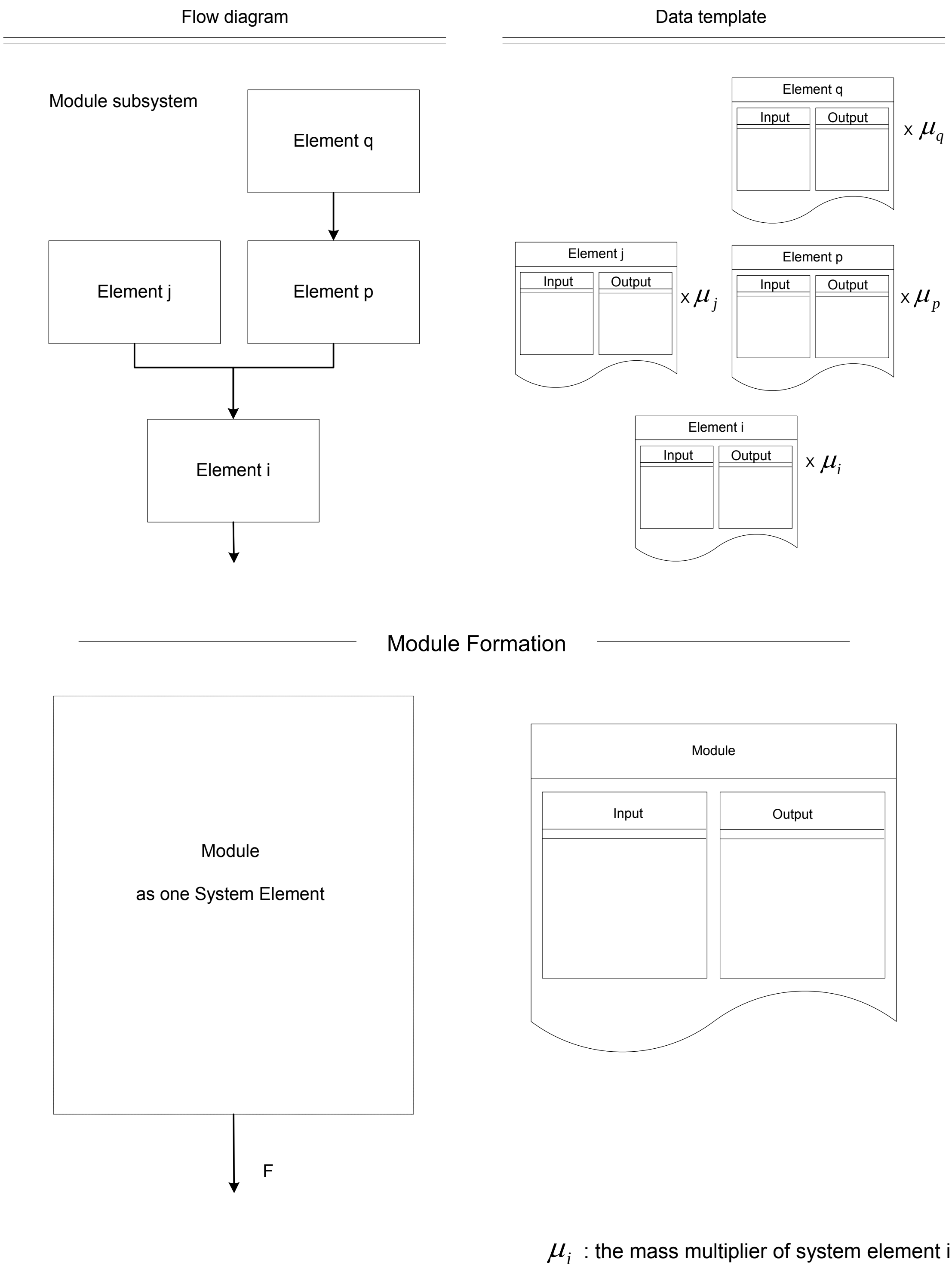


Figure 3. Module formation visualized in a flow diagram and in a data template

Interconnected unit processes could form a subsystem describing a product life cycle stage (LCS). The numeric input and output data of the mass and energy flows of this LCS subsystem can be aggregated as shown in figure 3. The system elements elementary flows are not visualized in figure 3 (s. §II-4) but are aggregated respectively. The data template that results from the aggregation of the interconnected unit processes describing an LCS is a module. The definition of a module is broadened by including the aggregation of interconnected system elements (i.e. unit processes and modules) as this is the case in many contemporary available databank modules [8, 9, 10, 62]. Note, that this definition differs from the older one used in the German ISO 14040 series 1998 which refers to the ISO defined unit process term [15, 16, 17, 18, 39, 40].

In the fix modules mostly only descriptive information about the module subsystem is given (s. also II-5). There are very few exceptions of databank modules [27] that also support the analyst with the module subsystem. The descriptive information about the module subsystem is not sufficient to allow to the analyst to reconstruct the module subsystem (s. figure 3) [21].

II-4. System elements flows classification and allocation

Each system element describes a process step. All the significant mass and energy inflows and outflows of this process step are being documented. The possible system element flows are shown in figure 4.

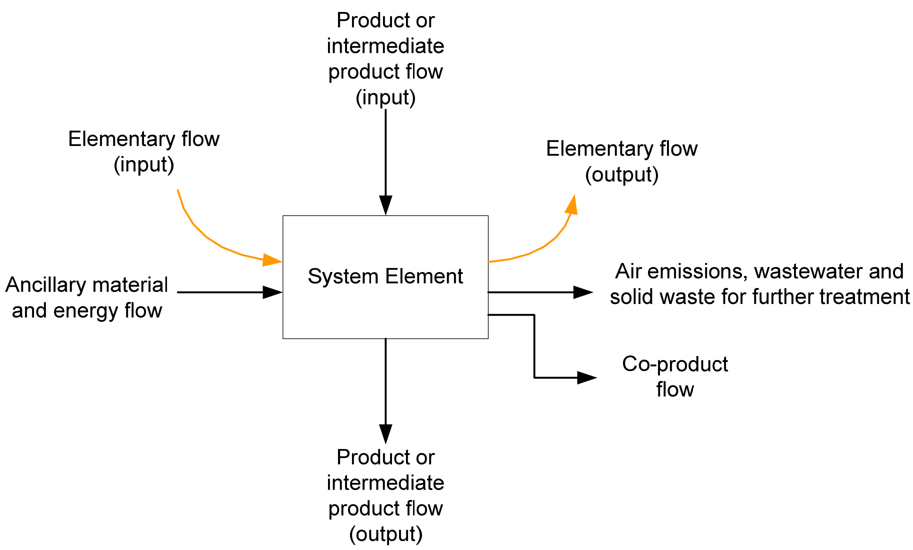


Figure 4. System element flows

The system element flows can be classified as:

i. Product or intermediate product inflow and outflow
ii. Elementary inflow and outflow
iii. Ancillary material and energy inflow
iv. Air emission, wastewater and solid waste outflow for further treatment (within the technosphere)
v. Co-product outflow

One major characteristic of a system element describing a production process step is its product outflow, while for a system element describing a disposal process step is its product inflow. Through this flow the system element is integrated into the LCI-system and the system element's mass multiplier is calculated (see also § II-7 Calculation methods for the LCI-system flows). Elementary flows are also very important. Elementary flows are defined as the mass and energy flows that either enter the LCI-system and are drawn from the environment without previous human transformation or leave the LCI-system and are released into the environment without subsequent human transformation [14].

The elementary inflows refer to the used resources while the outflows refer to the produced emissions. The elementary flow data is of major importance and is used to calculate the environmental relevance of the system element.

The identification and further classification of the flows in the above figure is in reality more complicated as *few industrial processes yield a single output or are based on linearity of raw material inflows and outflows* [14]. For instance, there are process steps with multiple product outflows (case of complementary production i.e. simultaneous production of more than one chemical product). Additionally, there are also disposal process steps with multiple product inflows (i.e. landfills).

Furthermore, the determination of a flow as a waste flow or as a co-product flow is not always clear. *Some outflows can be partly co-products and partly waste* [14]. For example, when a waste flow can be used in a recycling process step then it can be characterized instead as a co-product flow, which enters another product system. The same case may happen for an intermediate product flow entering the LCI-system under study (case of open-loop recycling).

In all cases the heart of the problem is how to allocate the environmentally relevant flows to each system element flow, system element or eventually product system. This problem was identified in the early years of LCA development and there were several proposals defining different allocation rules. There were also methodological developments in order to avoid allocation like in the case:

- the system element can be analyzed in more detail and divided into more then one system element or
- the product system is expanded with additional refinement of its function (case of complementary product production).

As far as possible the allocation should be avoided [14, 21, 43]. If this is not possible the applied allocation rules should be clearly documented and justified. Allocation rules based on physical causality rather than on economic values are preferable. The allocation thematic remains open in the LCA community and a convention solution is not foreseeable for the near future [43, 70, 85].

This thematic was out of the scope of this dissertation in which the starting point is put after the determination of the system element flows as single inflows and outflows as shown in figure 4.

II.-5 Interrelation of the system element flows

The system elements are describing physical systems and therefore their flows adhere to the laws of conservation of mass and energy [14, 43]. The inflows and outflows of a system element are also interrelated to one another because of physical causality.

However, the precise interrelation is not always known to the practitioner. In this case, the so-called black-box flow model is used, which is shown in figure 5a. In the black box flow model -so far linearity is assumed- any change of one inflow or outflow results in the proportional change of all the other flows [22, 59]. Hence, this model is strongly simplified and apparently does not correspond to how the process takes place in reality.

For example an increase in the mass of an ancillary material does not result in the proportional increase of the mass of the final product.

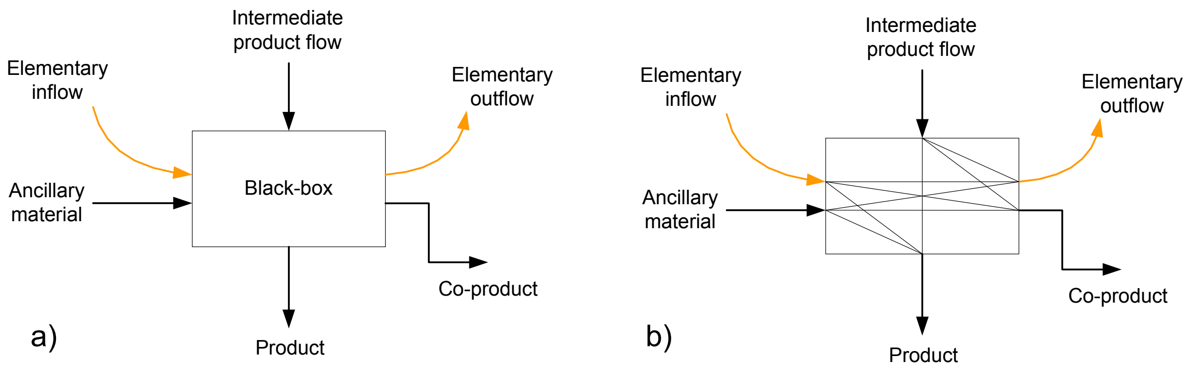


Figure 5. Black-box (a) versus functional (b) flow model

On the other hand, in the functional flow model as shown in figure 5b how each system element's inflow is interrelated to the outflows is taken into account. Hence, the functional flow model also supports non-linear modeling or modeling with the inclusion of time variables [22, 59]. The functional flow model is more precise but also more complicated. The determination of the flows' interrelations is not always feasible, especially when generic or average data is in use [43]. Theoretically, so far as possible, the application of the functional flow model is preferred compared to the black-box. However, it should be noted that the application of both flow models within the same product system investigation affects the data symmetry of the system [22]. Additionally, inconsistent modeling contravenes the ISO standard guidelines [14] and results in outcomes of low reliability. Thus, the operability of functional flow models is low at present.

At this point it is very important to highlight the difference between the aforementioned functional modeling of the system elements flows and the functional modeling of the product system (LCI-system) using modules. The development of the functional modeling of the LCI-system is within the goal of this thesis. In this case the functionality refers on the system elements (i.e. modules) and its application is independent whether the system element's flows are modeled according to the black-box flow model or the functional flow model.

II.-6. System element data

The system element data collected and handled during the LCI-system development can be divided into numerical and meta data (figure 6). The numerical data refers to the numerical values of the information about the substances, materials or energy occurred in the system element's flows. The meta data is data which gives additional information about the numerical data [8]. Numerical data is used to model the LCI-system whereas meta data is used to ensure the transparency and consistency of the study and is also needed for the data quality assessment.

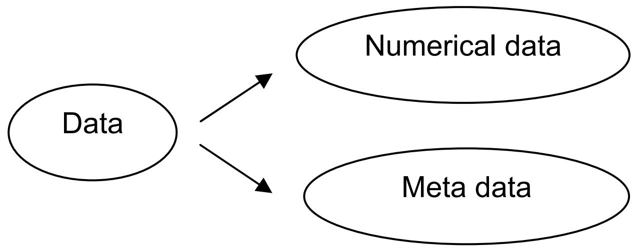


Figure 6. Data classification

Concerning the mass flows of the system element, the data can be delivered on a substance level or on a material level (figure 7). The collection of substance level data is more comprehensive and needs better knowledge of the process step; however, it is far more specific than data on the material level. Collecting data on substance level is preferable but needs knowledge and time. Knowledge of the exact chemical composition of an emission is necessary in order to quantify its environmental impact, for instance its toxicity in the LCIA phase.

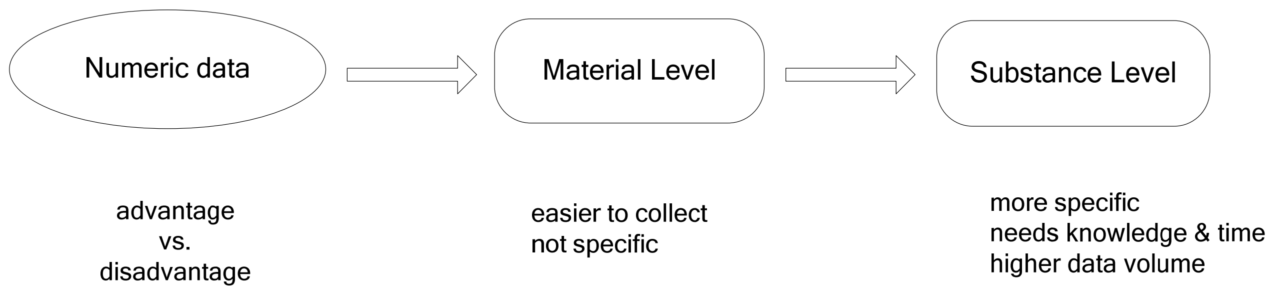


Figure 7. Numeric data forms with their plus/minus points

While the data of internal product flows of one LCA study could be kept for practical reasons on material level in order to avoid unreasoned data volume expansion the exactitude of the data for the external flows is of major importance. Substance level data of the elementary flows is very often not only preferable but also prerequisite.

The tendency in the development of life cycle impact assessment (LCIA) methods is to calculate the potential environmental impacts so far as it is possible on a substance level. Therefore in updated versions of the LCIA methods the investigated substance number is increased and materials or substance groups are separated into their components [3, 4, 12, 31, 34, 41, 63, 67, 68]. This increases the accuracy and reliability of the study but also raises the data volume.

In the division of numerical data information of non-material flows is also included, i.e. information on the production of noise, radiation level, waste heat or land use. These flows are considered as elementary flows as they can be valued in the environmental impact part [6, 44, 47, 61]. The environmental impact assessment of these impact categories is still under development [1, 69, 48, 49, 52, 53].

On the other hand, the meta data deliver information about the numerical data and the system element in general. This data is needed for conducting data quality assessment according to the set in the LCA goal and scope phase data quality requirements [14, 86]. The dimensions on which it is focused are:

- Time related coverage (the time frame the data covers and its age)
- Geographical coverage (the region for which the described process step refers)
- Technology coverage (the technology for which the process step refers)

Furthermore, it provides information about the methodological choices taken in the data collection procedure like the mean value calculation, the data precision, completeness and representativeness. Additionally, it also gives administrative information on how, when and by whom the data was being collected in order to ensure the transparency of the study [19, 39].

It is very important to outline here that in the case where the system element is a module in the meta data descriptive (s. II.-5) information about the aggregated module subsystem is also included. Frequently, statements are given about the a priori exclusion of process parts undertaken, i.e. transportation, ancillary material flows and infrastructure, while information on the module subsystem modeling like cut-off criteria or allocation rules applied is usually missing [28, 29, 54, 62, 80, 81, 82, 83]. Depending on this descriptive information about the module subsystem, it is actually impossible for the analyst to reconstruct the module subsystem [21].

The use of these kinds of modules contravenes the ISO 14040ss norm according to which *the system should be described in a sufficient detail and clarity in order to allow another practitioner to duplicate the inventory analysis* [14, 21, 43]. Nevertheless, there are some exceptional cases in some recently developed module versions where the module subsystem is given to the analyst as additional information [27].

II-7. Cut-off criteria in life cycle inventory

Cut-off criteria are criteria used to delimit the LCI-system in the technosphere part, which is relevant to the particular study. The cut-off criteria determine if a process is relevant according to the goal and scope of the LCA study and so they support limiting the product system from the environment and from other product system [5, 20, 21, 34, 43].

The cut-off criteria are used in all the LCA studies for the system boundary determination [14]. ISO 14044 gives the frame in which the cut-off criteria should be defined in order to enclose in the investigation the mass, energy and the environmental significance. However, the cut-off criteria are not strictly defined in the ISO norm 14040 series [14, 19]. The practitioner is the one who defines the cut-off criterion together with its respective cut-off criterion limit.

There are several cut-off criteria not always relying on the same principles. Applying different cut-off criteria (or the same one with different cut-off limit) on the same product tree results to the development of different LCI-systems [21, 22, 43, 45]. Thus, the final outcomes of the LCA study are also different according to the potential environmental impacts.

The cut-off criteria have a qualitative and a quantitative character. The quantitative character is enclosed in the cut-off criterion limit whereas the qualitative is in the core criterion itself (the selected investigated system element's flows and the way of the cut-off criterion score calculation). As yet there are no method-based guidelines or rules for the selection of the cut-off criterion limit [22, 45] which is set alike the cut-off criterion depended on the goal and scope of the particular study [5, 14, 21, 43].

The cut-off criteria are used in two different occasions as shown in figure 8. In the first case the analyst has to decide for which components or ingredients of the investigated product (or intermediate product) the production (or resp. disposal) chains [21] should be developed. These are the, so-called, product related cut-off criteria and are only used in the early state of the LCI-system modeling for building up the main chain.

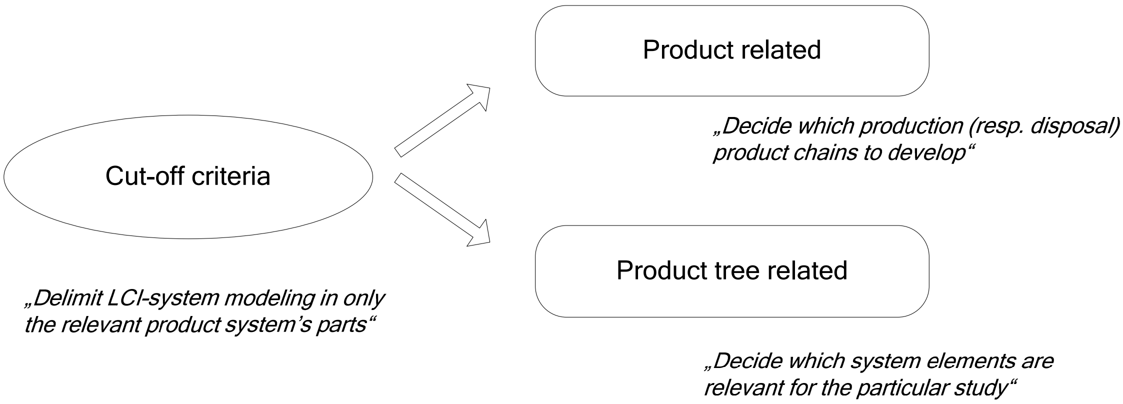


Figure 8. Cut-off criteria serve several purposes

The second occasion in which the cut-off criteria are used is during the LCI-system modeling. As already described during the development of the main and by chain network of the LCI-system the LCA analyst should decide if he should continue building up the system or stop because the system's boundaries are reached.

The product related and the product tree related cut-off criteria are used in different occasions and thus should be distinguished from each other. As the focus of this work is on the core LCI-system modeling, which takes place after the development of the main chain only the usage of the latter, the product tree related cut-off criteria will be further analyzed. From now on every reference to the cut-off criteria, if not otherwise stated, implies the product tree related ones.

II-8. Modeling the LCI-system using cut-off criteria

The development of the LCI-system is an iterative stepwise process. It starts from the system element describing the end product of the LCA understudy. Out of this initial system element the rest of the system elements are identified following the mass and energy flows upstream till the raw material acquisition and downstream till the product end of life [22].

In a first stage data is collected for the most important system elements which are involved in the several parts of the LCI-system i.e. raw material acquisition, production, end product usage, recycling and disposal life cycle parts. This initial form of the LCI-system forms the heart of the product tree and is the starting point for further development of the LCI-system.

Further development of the LCI-system is dependent on the goal and scope of the LCA study. The LCI-system, according to ISO 14044, should include all the relevant system elements needed to describe the product life cycle [19]. It is important here to highlight that the product life cycle is characterized from its function as it is defined in the LCA's goal and scope phase and not solely from the life cycle of the end product [22, 43]. Ideally, according to the ISO 14044 standards, the inflows and outflows at the boundaries of the LCI-system are elementary flows [19]. However, to model the LCI-system bordering only the natural environment means that in the investigated system the global technosphere is more or less included (see also figure 1).

By the existing means it is not possible to gather reliable data for the processes of almost the whole global technosphere. Therefore, delimitation of the LCI-system from the technosphere becomes inevitable. This LCI-system delimitation is possible using so called cut-off criteria [14, 22].

There are several proposed cut-off criteria relying on different principles [21, 45] influencing differently the way of the initial LCI-system expansion (see also § III-3 System related cut-off criteria). The LCA analyst should select and clearly define the cut-off criteria with their limits according to the goal of the particular study [19]. Additionally, the analyst should later estimate the potential effect of the cut-off criteria selection [14, 19] on the outcomes of the LCA i.e. sensitivity analysis of the omitted flows. The cut-off criterion limit as initially defined can be further refined during the development of the LCI-system based on preliminary outcomes (iterative process) [19].

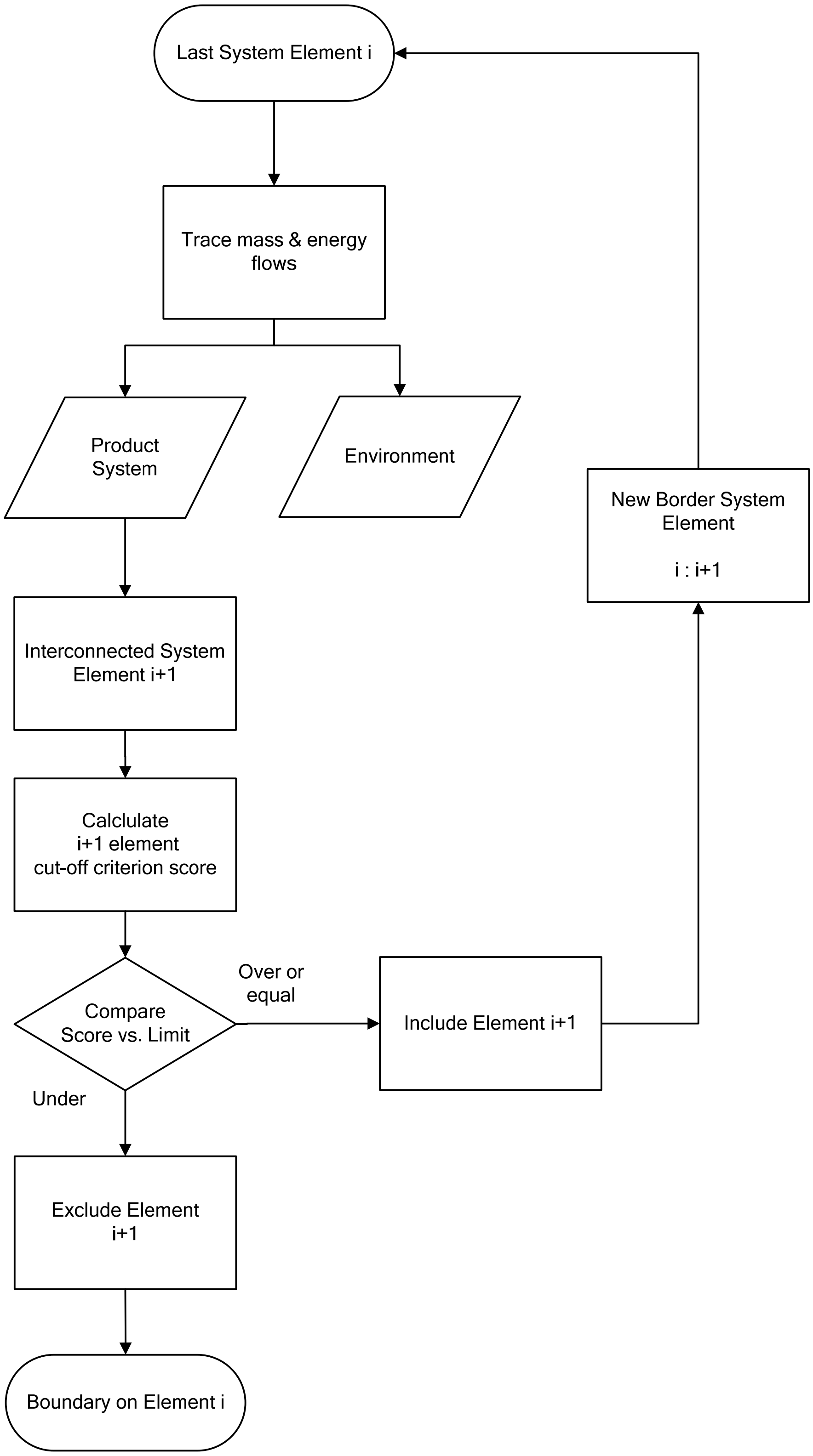


Figure 9. Decision flow chart in LCI-system modeling ("inside-outside" approach)

The decision flow chart given in figure 9 describes the sequential process of the LCI-system modeling using cut-off criteria. The system elements are sequentially justified according to the defined cut-off criterion limit whether to be included in or excluded from the LCI-system. In particular, the mass and energy flows of the last included system element i are traced back. The system element i+1 interconnected to the currently last system element i is then checked if its cut-off criterion score reaches the cut-off criterion limit. If it is reached then it is included in the LCI-system and the process starts from the beginning with last element i+1. If the limit is not reached then the boundary is set on system element i.

II-8.1 “Inside-to-outside” and “outside-to-inside” LCI-system modeling approaches

The modeling process described in figure 9 is the only process widely applicable today and implements the so called, “inside to outside” approach [21, 45]. Alternatively, if the whole product system is already known to the analyst (maybe in the future it will become possible) it is possible that the analyst could then start delimiting the LCI-system by applying the “outside to inside” approach [21].

In that case the practitioner will respectively check the system element’s cut-off criteria score one by one starting from the system element, which lays closest to the LCI-system’s border (s. also in appendix 5 the given similar to figure 9 decision flow chart for the outside-to-inside modeling approach). In the following step the system elements, which do not reach the cut-off criteria limit, will be sequentially cut-off one by one. This process goes on until the first system element that reaches the cut-off criteria limit is found. Then the limit is set on this system element.

The “outside-to-inside” modeling approach is for the present not operable therefore it would be focused on the widely used “inside-to-outside” approach. Further considerations, differences and important methodological issues concerning these two modeling approaches are given in appendix 5.

II-8.2 System elements co-equality in the application of cut-off criteria

At present it is not strictly defined whether the cut-off criterion should be applied on all of the system elements or whether there are exceptions to this [21, 45]. In practice, the cut-off criterion is not applied on the system elements of the main chain (or the foreground system), which form the heart of the LCI-system [21, 22]. The application of the cut-off criterion is usually on the outer parts of the product system upon which the system boundaries are set and afterwards refined (iterative process). At this point, the term “modeling units” is introduced. Modeling units are defined as the system elements on which are applied the cut-off criteria.

Additionally, there are also some kinds of system element, which are generally included or excluded from the investigated product system a priori and are thus not considered modeling units. These system elements are defined here as “pseudo system elements”. The pseudo system elements describe less important process steps of a larger product chain and have a rather low environmental relevance i.e. system elements referring to internal transportation processes.

In the inside-to-outside modeling shown in figure 9 if one system element does not reach the cut-off criterion limit then the LCI-system development stops there. Thus, if the pseudo system elements were subject to the cut-off criterion they would have the probable result of the exclusion of relevant system elements from the LCI-system (s. also § III-6.3.5 Hierarchy of system elements).

Hereby, it is important to highlight the issue of the system elements co-equality in reference to the cut-off criterion application or in other words, co-equality among modeling units. Ideally, all the system elements are unit processes so there is no problem, as all the modeling units are then co-equal to one another. However, in the current LCI-system development not only unit processes are used. A system element can also be a module resulting from the aggregation of several unit processes or even of unit processes and other modules (s. § II-3). In this case co-equality between unit process and module is definitely not of value as also later analyzed in §III-1.3.

However, in general the issue of co-equality among modeling units was left out of this dissertation. In this thesis apart from the modules all other system elements are handled as modeling units co-equal to each other. Moreover, these modeling units are also co-equal with the system elements, which are aggregated in the module subsystem. The determination of the system elements co-equality in general still remains open for future research.

II-9. Calculation methods for the LCI-system flows

The calculation of system elements' flows is the main objective of LCI analysis. The inventory of the LCI-system's elementary flows is the basis for the next phase of LCIA where the environmental relevance assessment of the LCI-system takes place.

The flows of the LCI-system results from the respective aggregation of the system elements flows. With this aggregation the internal flows (product and intermediate product flows see also § II-4 System elements flows) of the LCI-system are zeroed as the outflow of one system element is the inflow for the other. In order to come up to this final phase of the LCI-system's calculation the LCA analyst should (i) determine and balance each of the system element flows, (ii) interconnect the system elements to one another and (iii) set the boundaries of the LCI-system (see § II-7 Modeling the LCI-system).

The system elements are describing physical systems and therefore their flows obey the laws of conservation of mass and energy [19, 43]. This enables system reproducibility and error calculability. Moreover the hypotheses and assumptions are made identifiable [22].

The system elements are interconnected to each other thus each system element inflow and outflow is finally related to the reference flow [5, 22, 43, 73]. The present practice in LCA is to assume linearity among the system element flows and model according to the "black-box" model without time variables [13, 22]. This kind of modeling is very simplified but this becomes inevitable due to lack of appropriate data and knowledge on several specific process steps of the global technosphere [22, 43]. Additionally, the partial application (as full application is impossible) of more precise models (non-linear or with inclusion of specific process parameters) causes a vast increase of the complexity of the study [22, 23, 43, 59], despite the development of several LCA-software packages, which support such kind of models [29, 71]. However, detailed modeling of the processes is not implicit within the scope of the LCA, which is an assessment method and does not intend to simulate reality [13, 43, 73]. Besides, it is of major importance for the comparative assertions to model the system elements uniformly so far as possible [22, 43] (see also § II-5 Symmetry in modeling).

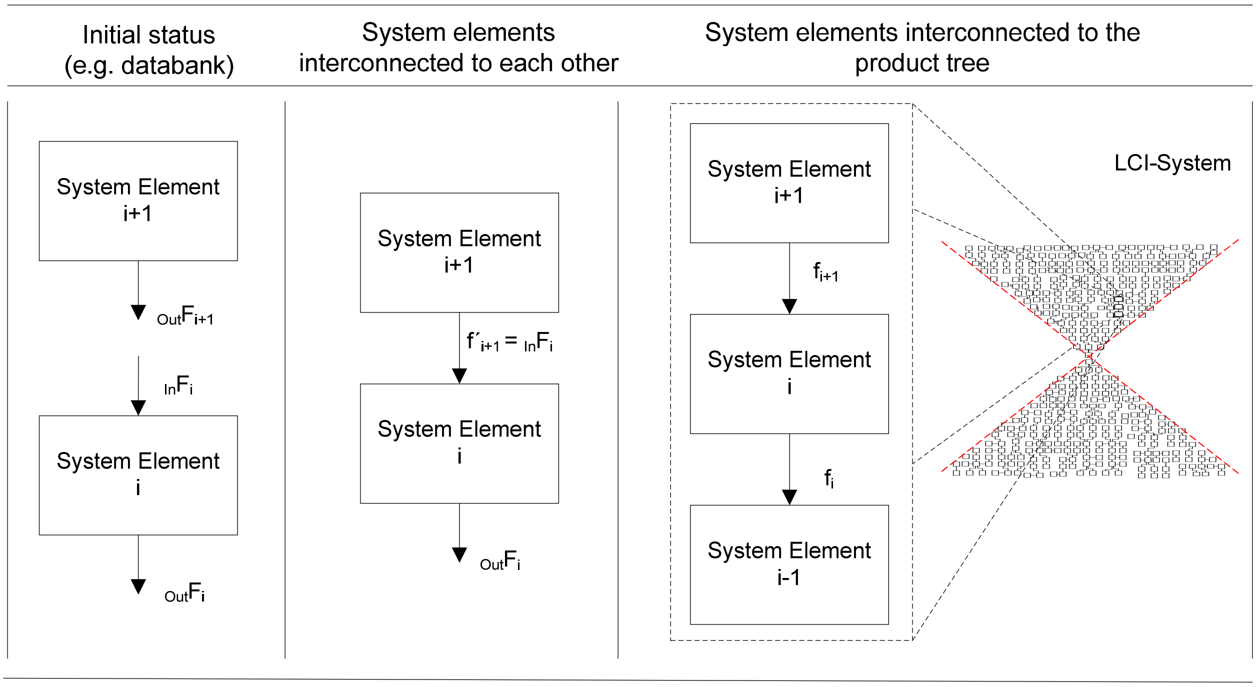


Figure 10. System element product flows: initial F, interconnected f´ and final in the LCI-system f

Figure 10 shows the possible adjustment of a system element when this is interconnected to the LCI-system in the ‘classical’, also called ‘sequential’ calculation. In the beginning, system element i+1 (which is assumed here to describe production processes) has its initial product flow $_{out}F_{i+1}$. This product flow when the system element i+1 gets interconnected to the LCI-system is finally normalized to f_{i+1}. The elementary flows (omitted in the flow chart) are always adjusted according to the applied model (i.e. linear black-box). A more detailed description of the stepwise nature of the system element interconnection in the product system is given in appendix 6.

This adjustment of the initial system element flow values to their respective values in the LCI-system can be aided by the usage of the mass-multiplier factor proposed by

Fleischer [21]. The mass multiplier (μ) is actually the factor with which the initial system element's flows are multiplied in order to be directly adjusted to the LCI-system. The adjustment is based on the system element's product outflow for the production process steps while on the respective system element's inflow for disposal process steps. For the example of system element i+1 in figure 10 the calculation is:

$$f_{i+1} = \mu_{i+1} * {}_{out}F_{i+1} \qquad (1)$$

The calculation formulas [21] of the mass multiplier are the following:

Production processes:

$$\mu_i = \frac{Input_{i-1}}{Output_i}\mu_{i-1} \Rightarrow \mu_i = \frac{{}_{In}F_{i-1}}{{}_{Out}F_i}\mu_{i-1} \qquad (2i)$$

or

$$\mu_i = \prod_{i=1}^{n}\frac{Input_{i-1}}{Output_i} \Rightarrow \mu_i = \prod_{i=1}^{n}\frac{{}_{In}F_{i-1}}{{}_{Out}F_i} \qquad (2ii)$$

Disposal processes:

$$\mu_i = \frac{Output_{i-1}}{Input_i}\mu_{i-1} \Rightarrow \mu_i = \frac{{}_{Out}F_{i-1}}{{}_{In}F_i}\mu_{i-1} \qquad (3i)$$

or

$$\mu_i = \prod_{i=1}^{n}\frac{Output_{i-1}}{Input_i} \Rightarrow \mu_i = \prod_{i=1}^{n}\frac{{}_{Out}F_{i-1}}{{}_{In}F_i} \qquad (3ii)$$

where: μ_i: Mass-multiplier of system element i

μ_{i-1}: Mass-multiplier of system element i-1 through which is system element i interconnected to the LCI-system

${}_{In}F_{i-1} = Input_{i-1}$: Product inflow of system element i-1 in its initial state (see also figure 8)

${}_{Out}F_i = Output_i$: Product outflow of system element i in its initial state (see figure 8)

${}_{Out}F_{i-1} = Output_{i-1}$: Product outflow of system element i-1 in its initial state

${}_{In}F_i = Input_i$: Product inflow of system element i in its initial state

The mass multiplier is dimensionless and expresses the direct correspondence of the initial system element's flows to the adjusted ones and, is therefore a characteristic parameter of the system element. Hence, it was also proposed to use the mass multiplier as a cut-off criterion [21, 45] (see also §III-3.2.1 System related cut-off criteria based on product flow data).

Alternatively, a much more complicated and not always feasible calculation method is the matrix calculation [36]. In the matrix method the LCI-system flows are not calculated sequentially from one system element to the next but are directly calculated using the so-called technology matrix in which all the system elements flows are integrated.

A crucial prerequisite for the calculation is for the technology matrix to be invertible [36], which is not often the case. Another great disadvantage of the matrix calculation is that it does not allow the delimitation of the LCI-system from other product systems. The implementation of cut-off criteria while modeling is not possible as for the calculation, system elements are handled regardless of their position in the LCI-system flow chart. Moreover, in the case where one system element is used more than once its flows are aggregated. Cut-off criteria can be applied only before the matrix calculation; hence, sequential modeling takes place in any case.

Nevertheless, the method is advantageous regarding the flows recursions modeling [36, 56] and is similar and compatible to the economical input-output analysis, giving ground to the development of IO-LCA and also on hybrid LCA [50, 64, 65, 66].

II.-10. Life cycle impact assessment (LCIA)

The life cycle impact assessment phase (LCIA) ascertains the potential environmental impacts caused by the elementary flows of the LCI-system determined in the LCI analysis phase. The potential environmental impacts are first assigned to environmental impact categories and for each category a category indicator is defined which quantifies the respective environmental impact. The LCI results are then classified into the impact categories (classification) and then, using the characterization factors, the analyst calculates (characterization) the indicator results for the LCIA categories (LCIA profile) [19, 22, 34, 35, 43].

The basic calculation formula [2, 22] applied to the impact categories, which determine the relevance of emissions is:

Substance impact calculation: $${}_{im.c.}I_{Sx} = {}_{im.c}c_{fx} * S_{LCIx} \qquad (4)$$

LCI-system impact calculation: $${}_{im.c.}I_{LCA} = \sum_{x}^{z} ({}_{im.c}c_{fx} * S_{LCIx}) \quad (5)$$

Where: ${}_{im.c.}I_{Sx}$: Impact indicator result (for the LCI-system) of substance x for the impact category i.c.

${}_{im.c.}I_{LCA}$: Impact indicator result of the LCI-system for impact category i.c.

${}_{im.c.}c_{fx}$: Characterization factor of substance x for impact category i.c

S_{LCIx} : Mass value of substance x in LCI-system elementary flow

x, …,z: Emissions of the LCI-system

Furthermore, there are also the optional parts of the LCIA phase where it is possible to: (a) normalize the impact indicator results to a relevance value (often country population), (b) to group the several categories together, (c) to rank the impact categories according to weighting factors, (d) apply data quality analysis. Among these optional steps the option of weighting is considered to reduce the LCA's reliability because of the subjectivity of the weighting factor determination [22, 43]. In any case, *weighting steps are based on value choices and are not scientifically based* [19].

Nowadays, there are a number of proposed LCIA methods [3, 4, 12, 25, 31, 32, 33, 35, 41, 51, 63, 67, 68], each of which define the investigated environmental impact categories and the applied models for the characterization factor determination. The development of the LCIA methods is ongoing and the similarities among them are mainly found among the established impact categories. Updated versions are improved by using more comprehensive models and by extending the investigated substance number in the characterization step [12, 41, 51].

III. Symmetric functional modeling development

III-1. Data symmetry and symmetric modeling

The term symmetry in LCA refers to data symmetry during the life cycle inventory phase. In the encyclopaedia the term symmetric is determined as:

An object is symmetric with respect to a given mathematical operation, if, when applied to the object, this operation does not change the object or its appearance [75].

In LCA the *"object"* is the product tree in the form of the LCI-system. The applied *"mathematical operation"* is enclosed in the relevant methodological decisions applied during the LCI-system's modeling. In particular, these decisions (chronologically ordered) are taken:

- while collecting the data (detail level depth),
- while determining the system elements' mass and energy flows (potential application of allocation rules),
- while setting the LCI-system boundaries (application of cut-off criteria).

Each of the aforementioned methodological decisions independently affects the data symmetry of the product system. The influence of each factor is not yet quantifiable. Each of these modeling decisions has its importance and none of them should be neglected.

This thesis focuses on the application of cut-off criteria which would be further thoroughly analyzed. The other two factors, the detail level depth and the potential allocation rule application, are not included in the scope of the thesis thus they are only briefly mentioned.

Data asymmetry may also occur when some system elements do not reach the specified in the goal and scope data quality requirements. The data requirements as specified in ISO 14044 address the: time-related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility, sources, and uncertainty of the data [19]. Nevertheless, these aspects of data asymmetry formation are not on the core modeling part of the product system therefore would also not be further investigated.

It is important to outline here that data symmetry ensures the comparability and consistency of the LCA study. In case of data asymmetry formations the final LCA environmental impact results are erratically distorted thus unreliable and finally invaluable findings are spawned [21] (s. also about the symmetric modeling importance and its role in comparative LCAs in §III-2).

III-1.1 Data symmetry with respect to data collection

A process can be investigated in greater or lesser detail. The environmental relevance of a highly detailed system element compared with the alternative of a low detailed one would probably be higher.

The detail level of a system element can be divided into the domains of detail level depth and detail level range introduced here. Data symmetry should be ensured on both detail level domains. Each detail level domain independently affects the data symmetric modeling of the LCI-system as further analyzed.

The detail level depth is the one referring to the information about the substances and materials which are documented in the input and output flows of a system element in general as shown in figure 11.

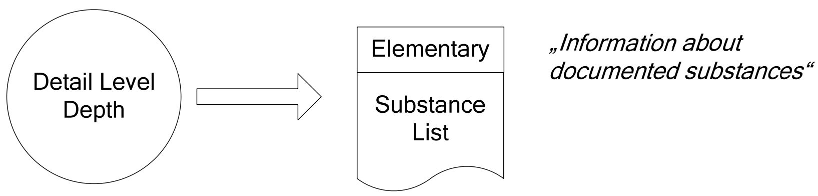


Figure 11. Detail level depth domain

The respective substances found are documented for each flow. These substances can form a substance list set per system element flow. More important for the calculation of the LCA's outcome is the system element's substance list set referring to the elementary flow. The environmental relevance is further calculated from the elementary substance list (also further referred simply as substance list).

The substance list is currently determined by the substances found. However, in order to monitor the system elements detail level depth it is better to have already pre-defined the elementary substance list set before the data collection step (LCA study substance list). Because in LCA many steps are iterative, it is possible for a LCA study substance list to be changed or refined afterwards. In this case in order to ensure symmetry, it is necessary to recheck all utilized system elements.

If there are processes in which a particular substance is not emitted then its value in the respective system element substance list will be zero. The zero value indifferently with the nonappearance indicates that the substance is not detected in the elementary flow even though it has been searched for [22].

Thus, the data collection step is more ordered, transparent, consistent and easier to perform. The person conducting the data collection has to fill in the numeric data while at the same time the analyst gets strictly ordered information. A step further for transparency and consistency in the data collection stage is possible by defining the substance limit of documentation. The substance limit of documentation is defined and analyzed in appendix 7.

Data asymmetry referring to the detail level depth can be formed in two cases. The first one is when there are substances not present in the module (or respective unit process) substance list because they have not been searched for. The second case is when a module has a longer substance list than the defined substance list of the LCA study.

The symmetric adjustment referring to the detail level depth of a module or a unit process would not be further investigated as it is not included within the scope of this thesis. Nevertheless, a symmetrical adjustment example for modules is given and analyzed in appendix 8.

III-1.2 Data symmetry with respect to the system element's flow determination

Data symmetry may also be distorted at the phase of the system element's flows determination. As mentioned previously (s. §II.-4), it becomes in many cases necessary (as it cannot be avoided) to allocate the system element's environmental relevance data among several system element's product flows, system elements or between two product systems. Thus, the practitioner has to apply allocation rules. So far, the avoidance of allocation is impossible; the selection of an allocation rule should rely on the same principles. *Allocation procedures shall be uniformly applied to similar inflows and outflows of the system* [19, 43].

There are several proposed allocation rules [5, 13, 21, 34, 42, 43]. In general, the application of different allocation rules on the same system element results in different system element flow substance lists. According to ISO 14044, the applied allocation rules shall be clearly documented and justified [19]. However, the selection of the allocation rule is finally up to the practitioner who should address the goal and scope of the particular LCA study. Until now, despite several studies on the allocation thematic, convention on the matter is not foreseeable for the near future and further research is needed [43, 85].

Thus, an unfair handling among the system elements (in respect to data symmetry) may then occur when, for example, allocation is being avoided on a number of the system elements, one allocation rule is being applied on some system elements while a different allocation rule on others. This unfair handling also becomes inevitable when data is being re-used in the form of fixed unit processes or modules supplied by the databanks. In this case, the system element flows are already allocated and the practitioner can no longer make any changes [27, 28, 30, 54, 62, 80, 81, 82, 83]. Though the justified application of different allocation rules may be eventually conformed to ISO 14044 [8, 19], the data symmetry of the product system is then inevitably distorted.

As previously mentioned, the starting point in this dissertation was set after the system elements' flow determination thus the allocation thematic was left out. The investigation on how the allocation rules affect the symmetry of the LCI-system is a challenging area for future research.

III-1.3 Data symmetry with respect to system boundaries determination

The final system boundaries of the LCI-system are set with the application of the cut-off criterion on the system elements (s. also §II.-7). According to ISO 14044 the practitioner defines the cut-off criterion and applies it consistently on the system elements of the product system [19].

Different cut-off criteria (or the same one with different cut-off limit) applied on the same product tree result in the development of different LCI-systems [21, 45, 57]. Thus, the application of the cut-off criterion on the LCI-system forms the final product system.

Hereby, the term *detail level range* is introduced. The detail level range is used as a rather qualitative attribute of a module. The detail level range refers to the number of system elements which form the module subsystem and are afterwards aggregated as shown in figure 12. Theoretically, the lowest detail level range limit is found in the case of a single unit process. The upper limit of the detail level range is not determined as the number of the aggregated system elements of a module is not restricted.

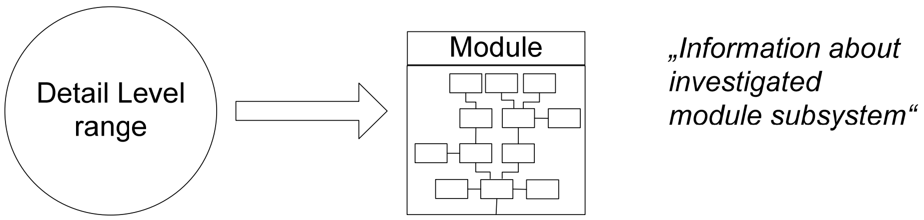


Figure 12. Detail level range domain

The module as the sum of aggregated system elements surpasses the cut-off criterion limit more easily than the individual system elements. Similarly, also a module with a high detail level range surpasses more easily the cut-off criterion limit than a module with a lower detail level range. Thus, it is inaccurate to apply the cut-off criterion on the module level without any data-symmetric adjustment. The symmetric adjustment of the module in the LCI-system requires the implementation of the defined cut-off criterion on the module subsystem level.

At present the available modules are in a fixed form not enabling any symmetric adjustment [21, 45, 26, 30, 54, 62]. Thus, the erratic formation of data asymmetries is unavoidable and results in the distortion of the final LCA outcomes [21, 22].

The development of the module functionality which enables module symmetric adjustment and further integration into the LCI-system would be thoroughly analyzed in the following § III-6 Multifunctional modules development. Beforehand, several available cut-off criteria are analyzed (s. § III-3) in order to evolve the module functionality in a way which would handle the different criteria as uniformly as possible.

III-2 Symmetric modeling importance and its role in comparative LCAs

Data symmetry ensures the comparability and consistency of the LCA study thus it ensures high reliability of the final LCA outcomes [21, 22]. In case of data asymmetry, some data of the modeled product system are eventually either detailed differently (case of detail level depth s. §III-1.1) or modeled differently from the rest of the LCI-system (application of allocation rules or cut-off criteria, s. §III-1.2 & III-1.3).

Hence, the environmental relevance values of the LCA study, which will later be calculated, are erratically distorted. This results in a significant decrease in reliability of the final LCA results. The extent to which the results are distorted is not yet known [21]. The formation of data asymmetries and their influence on the final environmental relevance value of the LCI-system is case specific (s. also § IV-5).

Additionally, symmetric modeling of the LCI-system is important in the case of comparative LCAs. A comparison in a LCA study of different products or alternative product varieties is only feasible when these products fulfill the same function (as this is defined in the goal and scope phase) [5, 13, 21, 22, 43]. As quoted above, the modeled product systems are characterized by their function and not by their end-products [14].

Furthermore, alternative product systems should be developed symmetrically. At present symmetric modeling was solely set in the context of single product systems. In comparative assertions the symmetric modeling of the product trees should not be limited to every developed LCI-system itself but should be extended to the alternative LCI-systems themselves as further analyzed in § III-5.2 Symmetric modeling of the LCI-system in the context of more than one LCI-system.

Each investigated LCI-system should be modeled as equivalent to the other LCI-systems. In particular, referring to the system boundaries the different LCI-systems should be delimited from the rest of the technosphere in a way which would ensure their comparability. Therefore the same cut-off criterion and cut-off criterion limit is currently applied on all the modeled product systems [5, 22, 34, 43].

However, investigations on how the several cut-off criteria affect the comparability of the different LCI-systems are not yet made. Although consistent application of the same cut-off criterion limit ensures symmetric development of the single product system, it is still not certain if it is also sufficient to ensure the comparability among different LCI-systems. This issue is analyzed in §III-5.2.

III-3 System related cut-off criteria

At this point a thorough analysis on the cut-off criteria state-of-the-art will be given. The analysis is focused on the most reliable and practicable criteria. The investigation includes all the widely used and proposed kinds of cut-off criteria (i.e. based on mass, energy and environmental relevance data).

New cut-off criteria were also developed based on the most reliable of the current cut-off criteria. The new ones contain slight modifications on some calculation steps of current available cut-off criteria in order to restrict potential drawbacks. The influence of the modifications carried out is also investigated. A comparison of the cut-off criteria in terms of reliability in a symmetric modeled LCI-system follows in §III-4.

The cut-off criteria are based either on the mass, the energy or the environmental relevance of the system element as stated in ISO 14044 [19]. Throughout the LCA development, there are several kinds of system related cut-off criteria coined [5, 21, 22, 45].

The classification of the cut-off criteria is possible from various perspectives. Essential for the symmetric LCI-system modeling is the introduction of the classification of the “process” dependent and the “system” dependent cut-off criteria as shown in figure 13.

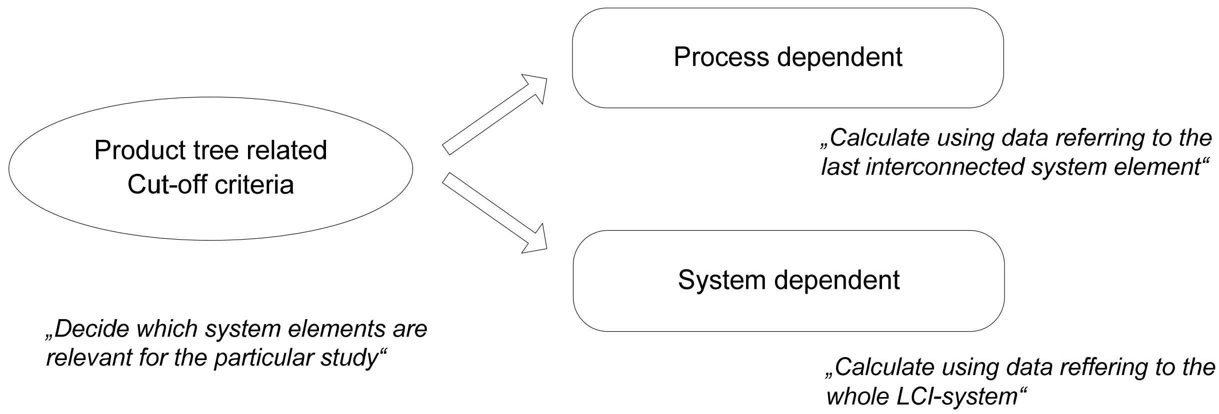


Figure 13. Cut-off criteria classification in system and process dependent criteria

In the process related cut-off criterion the inclusion of the system elements is judged depending on the process product outflow (for production steps) or inflow (for disposal steps) of the last system element interconnected to the LCI-system. On the contrary, the system related cut-off criteria judges on respective data of the whole LCI-system.

III-3.1 Process related cut-off criterion

The difference between process related and system related cut-off criteria is easier to identify when considering the following flow chart in figure 14. The system element i is the last one included in the LCI-system system element describing a production process step of the product life cycle. Interconnected to the system element i are its main chain system elements i+1, i+2 and i-1 and its by-chain system elements i´-1 and i´+1 respectively. The system elements are interconnected to each other and are adjusted to the system elements elementary flows respectively.

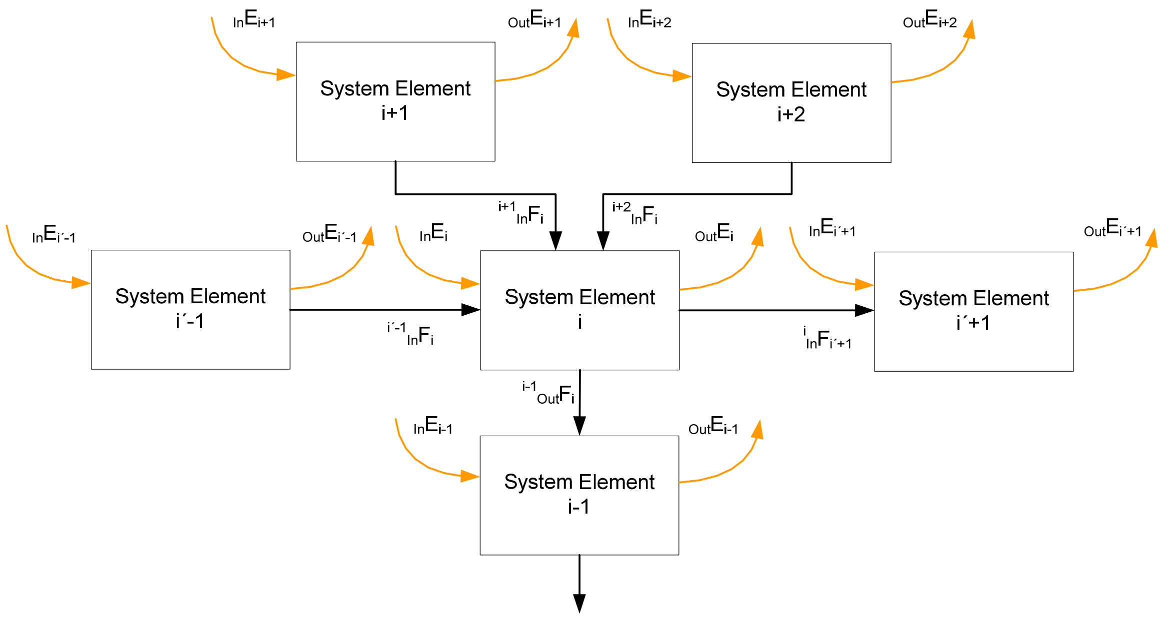


Figure 14. System elements interconnected to each other shown in a flow chart.

Acronyms clarification

F: product flow

E: adjusted elementary flow from initial status to the interconnected flow chart

i´: refers to the by-chain of system element i, i.e. i´-1: the first system element interconnected with system element's i by-chain referring to production processes

Indexes

- right down: system element of the flow
- left up: system element from which the flow comes from or goes to
- left down: In = Input and Out = Output

i.e. ${}^{i+2}{}_{In}F_i$: Input (In) product flow (F) of system element i, coming from system element i+2

${}_{Out}E_{i+2}$: Output (Out) of the adjusted elementary flow (E) of system element 1+2

The process related cut-off criterion as defined by several researchers [21, 20, 38, 39, 45, 57] is:

Cut-off criterion 1

Mass (or respectively energy) value of the last interconnected system element product inflow (for production steps) referred to the mass (or respectively to the energy) of its product outflow (often given as a percentage (%)). Respectively, for disposal steps the system element's product outflow referred to its product inflow is studied.

In particular for figure 14 and the four system elements i, i+1, i+2, i´-1, and i´+1, its respective cut-off criterion score is calculated by the following ratios:

system element i: $$Sc_i = {}^{i}_{In}F_{i-1} \Big/ {}^{i-2}_{Out}F_{i-1} \quad (6i)$$

system element i+1: $$Sc_{i+1} = {}^{i+1}_{In}F_{i} \Big/ {}^{i-1}_{Out}F_{i} \quad (6ii)$$

system element i+2: $$Sc_{i+2} = {}^{i+2}_{In}F_{i} \Big/ {}^{i-1}_{Out}F_{i} \quad (6iii)$$

system element i´-1: $$Sc_{i'-1} = {}^{i'-1}_{In}F_{i} \Big/ {}^{i-1}_{Out}F_{i} \quad (6iv)$$

system element i´+1: $$Sc_{i'+1} = {}^{i}_{In}F_{i'+1} \Big/ {}^{i-1}_{Out}F_{i} \quad (6v)$$

in which Sc_i : the cut-off criterion score for system element i

It is important to highlight here, that the calculation of formula (6) is not meaningful when one involved flow refers to energy values whereas the other to mass values [22, 57]. For instance, in figure 14, if system element i´-1 delivers the required energy for the production of the intermediate product in system element i, then system element i´-1 cannot be subject to cut-off criterion 1. Hence, the application range of cut-off criterion 1 is strongly limited (s. also §III-5.1). The same problem is also found in cut-off criterion 2, which will be next analyzed.

III-3.2. System related cut-off criteria

Contrary to the “process” related cut-off criteria, the “system” related cut-off criteria study the correlation of the product or the elementary flow of the system element under study with the respective flow of the LCI-system. The following figure 15 is representative for the system related cut-off criteria. The [system element] – [LCI-system] interrelation is visualized here in a hierarchical structured system perspective [58, 59]. On the top left corner in figure 15 is given a closer view of the integrated system element i in the product tree. In this hierarchical perspective, the LCI-system

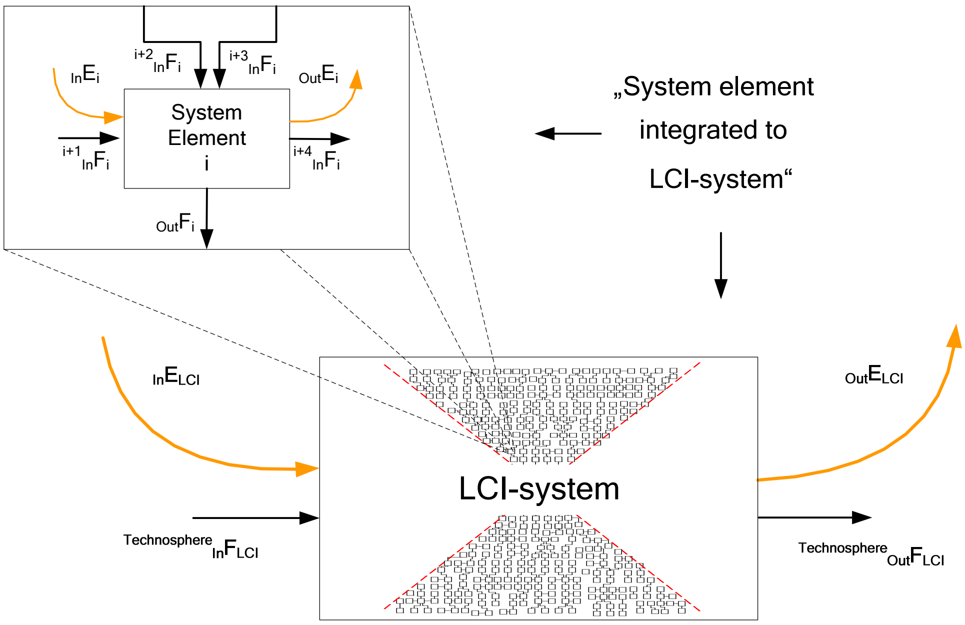


Figure 15. System element and LCI-system flows associated in system related cut-offs

could be observed as a sole system element of the technosphere system. Thus, it is easier to identify the relationship several product systems have to each other through the input and output product flows, marked here as $^{Technosphere}{}_{In}F_{LCI}$ and $^{Technosphere}{}_{Out}F_{LCI}$.

III-3.2.1. System related cut-off criteria based on product flow data

The proposed system related cut-off criteria correlate with either the system element's product flow or the system element's elementary flow with the respective ones of the LCI-system. In particular, the system cut-off criteria using the product flows are defined as:

<u>Cut-off criterion 2</u>

> Mass (or respective energy) value of the integrated system element's product outflow (for production processes) or inflow (for disposal processes) related to the mass (or energy) value of the end product's inflow or respective outflow (LCI-system's reference flow as defined in the goal and scope phase) [21, 72, 45, 46, 55].

It is important to highlight here that like cut-off criterion 1, the application range of cut-off criterion 2 is also limited. If the reference flow is defined in mass units, cut-off criterion 2 is not applicable to system elements which are interconnected to the product with flows expressed only in energy units and vise versa (s. § III-3.1 and §III-5.1).

<u>Cut-off criterion 3</u>

System element's mass multiplier (μ) value calculated using the system element's product outflow (for production process steps) with formula (1) or inflow (for disposal process steps) with formula (2) [21, 45].

III-3.2.2. System related cut-off criteria based on elementary flow data

Contrary to the aforementioned system cut-off criteria, there are also the ones that compare the system element's elementary flow with the LCI-system's elementary flow. Referring to figure 12 for system element i, the following comparison takes place for this kind of cut-off criteria. The system element i elementary outflows, ${}_{Out}E_i$ are compared with the respective LCI-system elementary outflows ${}_{Out}E_{LCI}$, and correspondingly the elementary inflows of system element i, ${}_{In}E_i$ with the elementary inflows, ${}_{In}E_{LCI}$ of the LCI-system.

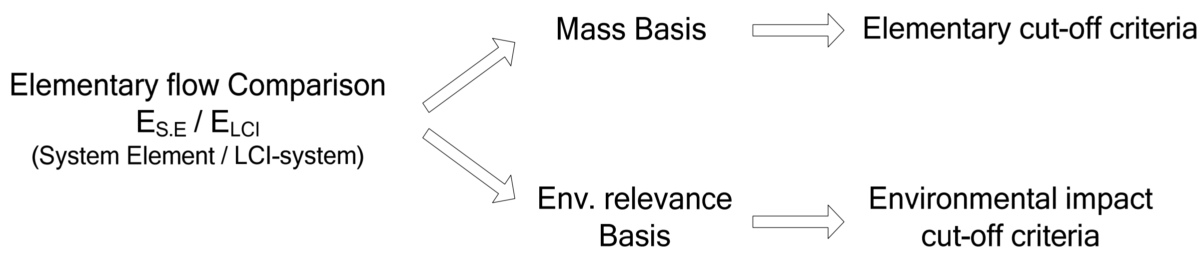


Figure 16. Classification of system related cut-off criteria based on elementary flow data comparison of (System element) vs. (LCI-system)

The comparison of the elementary flows could be based on either mass or on environmental relevance values. For each kind of comparison, a type of cut-off criterion is defined called here simply the "elementary cut-off criterion" and the "environmental impact cut-off criterion" respectively, as shown in figure 16.

III-3.2.2.1 Elementary cut-off criterion (cut-off criterion 4a and 4b)

An important difference between the product and the elementary flows is that in the latter more than one substance (and/or material) are documented. Thus, the elementary flow is not a single flow but is split up for each substance. Consequently, the calculation of the elementary cut-off criterion score is not as simple as for other cut-off criteria, which are based on the product flows. It is only meaningful to compare flows of the same substances (or materials), which results in an initial per-substance cut-off criterion score. In a later step the per substance cut-off criterion score is converted to one final cut-off criterion score.

Moreover, the final LCI-system elementary flows are, in contrast to the product flows, not known at the time of modeling; actually, their determination is the objective of the LCI. Hence, like in other LCA phases [19, 43] the analyst has to work iteratively. Therefore, for the primary calculation, estimated data values are used which are calculated based on data of either the LCI-system's main chain [21] or the foreground system. These estimated values should afterwards be evaluated and, if needed, further refined.

Thus, in order to avoid an extensive time and effort-consuming calculation in the proposed elementary cut-off criterion (here 4a) as originally presented by Fleischer [21], the comparison is limited to a manageable number of representative substances (used as indicators). Additionally, the final system element's cut-off criterion score is defined by the respective highest substance cut-off criterion score. In figure 17, the stepwise application of the proposed elementary cut-off criterion 4a is presented.

In step 1 and 2 the relevant substances documented in the elementary flow are firstly selected and then their respective data for the system element and the LCI-system are collected. In step 3 the initial per-substance cut-off criterion scores are calculated. Step 4 converts the per-substance cut-off criterion scores in one final cut-off criterion score. Finally, in step 5 the final system element cut-off criterion score is compared with the defined cut-off criterion limit score.

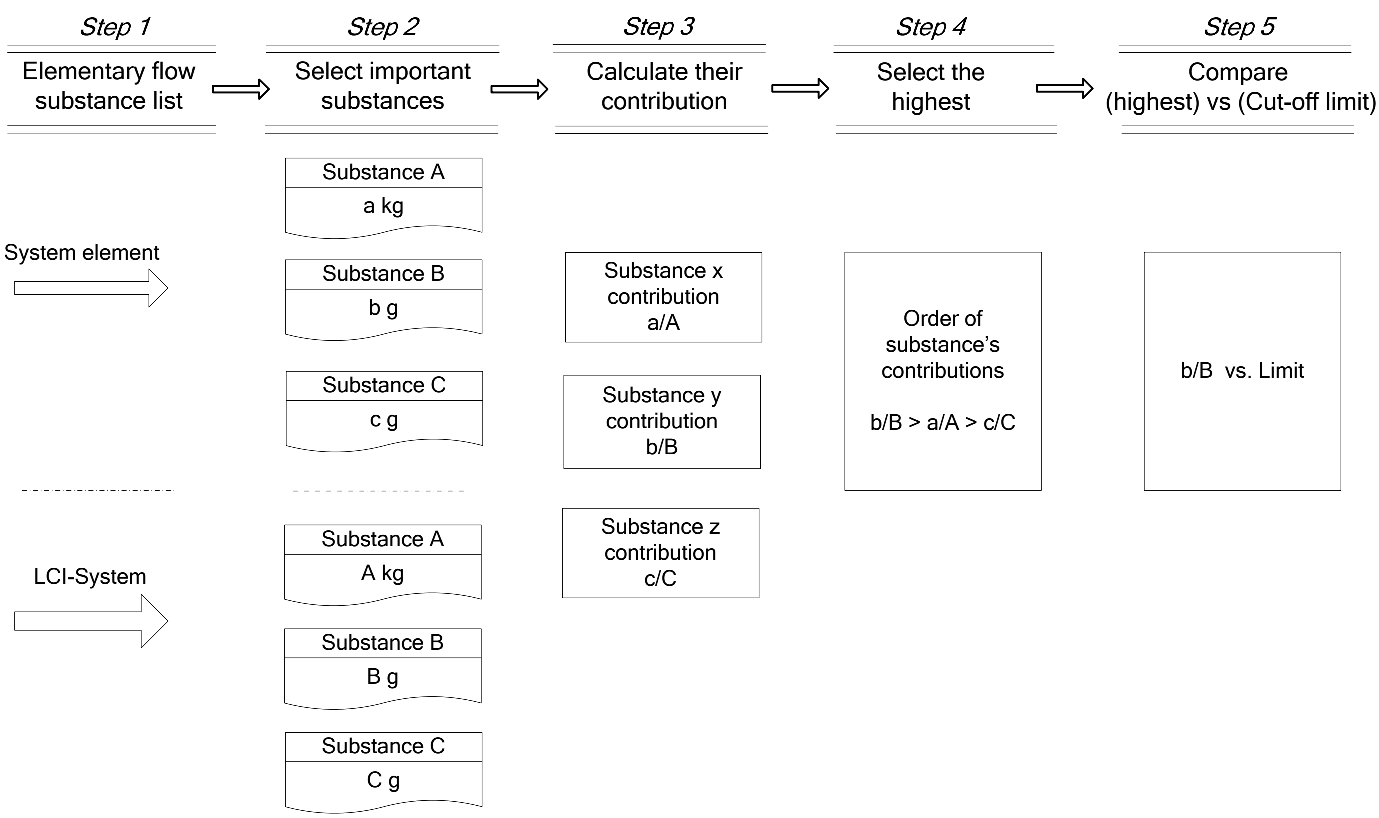


Figure 17. Stepwise application of elementary cut-off criterion 4a (Fleischer's B3 [21])

In the current work, the elementary cut-off criterion 4b was developed which is a modified version of criterion 4a. In particular, a different way of determining the final cut-off criterion score from the initial per-substance cut-off criterion scores is proposed, as given in figure 18. In this case in step 4 the final cut-off criterion score is then not equal to the highest substance cut-off criterion score but to the sum of all the substances' cut-off criterion scores. In this way each relevant substance has its portion in the final score and the cut-off criterion score is more representative of the system element's relevance.

It is important to note here that the cut-off criterion limit between the two cut-off criteria (4a and 4b) cannot remain the same and the limits are also not comparable to each other. In the initial version the limit refers to one relevant substance score while in the second version, it refers to the whole number of relevant substances investigated and their related scores. In the next figure 17 the stepwise application of these two cut-off criteria versions is given. A comparison of the two versions is given later in §III-3.2.2.2 together with a comparison of cut-off criterion 5a and 5b whose analysis follows.

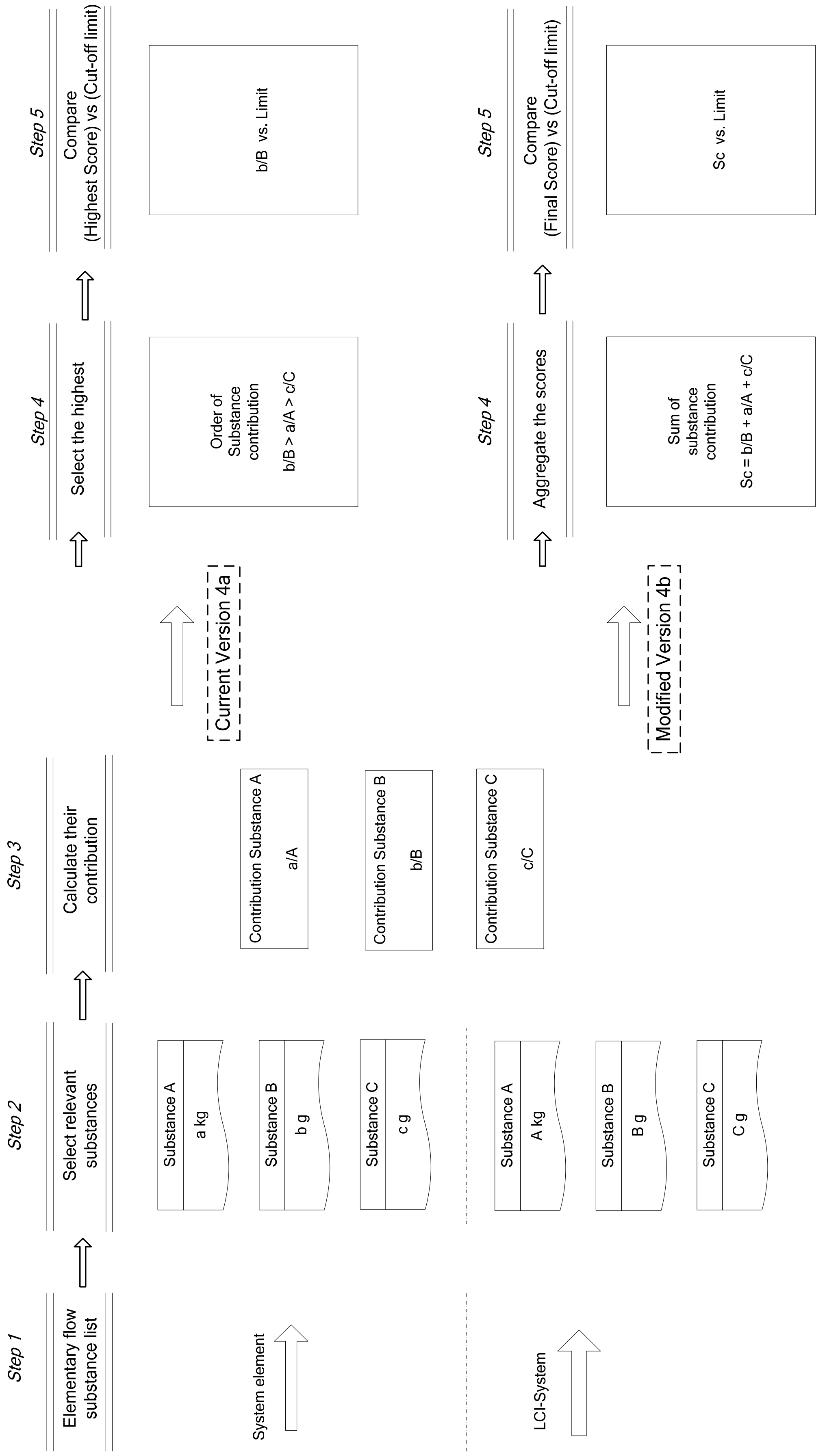


Figure 18. Stepwise application of elementary cut-off criterion. Current [21] and introduced modified version.

III-3.2.2.2 Environmental impact cut-off criteria (cut-off criteria 5, 6 and 7)

Environmental impact cut-off criterion 5

Contrary to the elementary cut-off criterion, in the environmental impact cut-off criteria the comparison of the elementary inflows and outflows of the system element and the LCI-system is based on environmental impact values.

Similar to the elementary cut-off criteria and in order to avoid a calculation requiring extensive time and effort, it is again proposed [21] to limit the comparison to a manageable number of representative relevant substances. The environmental relevance is calculated using the respective adopted LCIA method [19] (s. also § II-10).

The environmental impact cut-off criterion score calculation is more comprehensive and complicated than the elementary cut-off criterion as the scores are now split twice; per substance and per environmental category. Initially, for each investigated environmental impact category there is a per-substance cut-off criterion score. These substance cut-off criterion scores can then be converted to one final score similar to the elementary cut-off criterion.

In the version proposed by Fleischer [21], here cut-off criterion 5a, the final cut-off criterion score of the environmental impact category is equal to the highest substance cut-off criterion score for the respective category. Like in the case of the elementary cut-off criterion a modified version of the environmental impact cut-off criterion 5 is introduced. In this modified version, cut-off criterion 5b, the final environmental impact category cut-off criterion score is calculated by adding together the respective substance cut-off criterion scores.

It should be highlighted that the cut-off criterion limit between these two versions of environmental impact cut-off criterion cannot be the same as they are not directly comparable to one another.

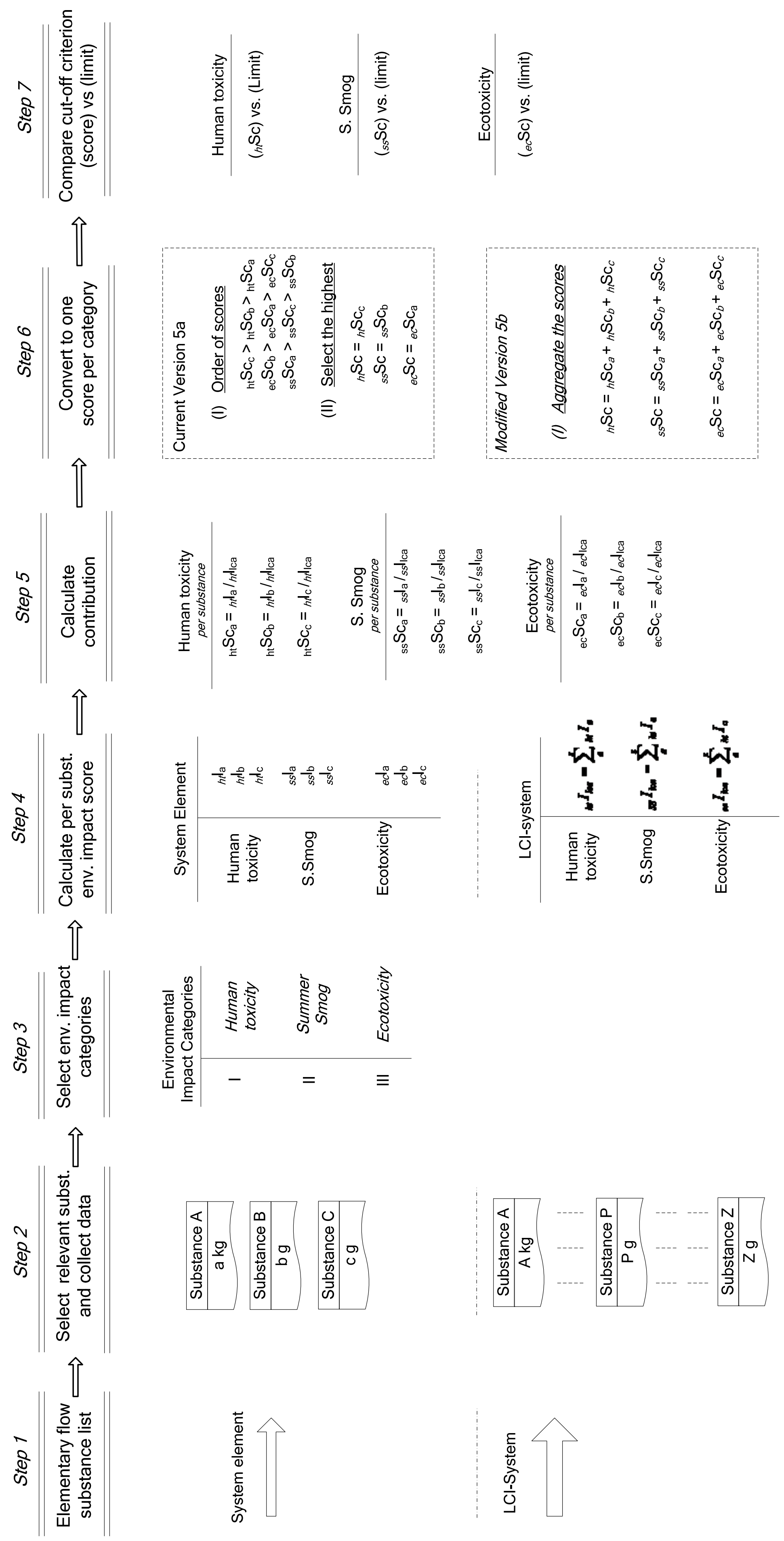


Figure 19. Stepwise application of environmental impact cut-off criteria 5a and 5b.

In figure 19, the stepwise application of the environmental impact cut-off criterion (2 versions 5a & 5b) is given. Steps 1 and 2 are similar to elementary cut-off criterion with the major difference that the required data from the LCI-system is not limited to the selected substances but includes all documented substances.

In step 3, the investigated environmental impact categories are selected. In steps 4 and 5, the per-substance contribution to the LCI-system final environmental impact category score is calculated. In step 6, the per-substance environmental impact cut-off criterion scores are converted to one final score per category (note difference between 5a and 5b versions). Finally, step 7 compares the system element's environmental impact cut-off criterion score per impact category with the set limit.

Comparison of final score determination in cut-off criterion 4 and 5

The difference between versions a and b in both cut-off criteria 4 and 5 is implied in the determination of the final system element cut-off criterion score (s. step 4 in figure 18 and step 6 in figure 19).

In the first case, the system element score is determined by the highest system element's substance score (version a) whereas in the latter it is determined by the aggregation of the entire system element's relevant substances' scores (version b). Therefore, in version a, the distribution of the initial system element substances scores is crucial in the final score calculation. In particular, the final criterion score actually depends on the substance cut-off criterion score, which dominates the system element, whereas this is not the case for version b.

In version b every investigated substance has its share in the final cut-off criterion system element score. Thus, in version b, "the correspondence of the system element's cut-off criterion score to its environmental relevance score is more fully ensured". Based on this statement it can be argued that version b of these cut-off criteria are superior to version a. A proof of this is given in appendix 9 by referring to a case study of two different system elements A and B, which reach the same environmental impact score.

Environmental impact cut-off criteria 6 and 7

In the current work, alternatives to the environmental impact cut-off criterion 5 described above, were developed namely the environmental impact cut-off criteria 6 and 7 which are operable at the time of LCI-system modeling. These cut-off criteria are primarily based on elementary cut-off criterion 4b.

Their main difference from cut-off criterion 5 is the requirement for data of the LCI-system (step 1 on figure 19). While cut-off criterion 5 requires the data of all the documented substances, these new cut-off criteria 6 and 7 only require the LCI-system data for a limited, manageable number of selected relevant substances. This data is not known at the time of modeling but as in the case of cut-off criterion 4 can be estimated based on the data values of the main-chain or the foreground system. This initial estimate should be later evaluated and if needed refined working iteratively. Thus, cut-off criteria 6 and 7 are operable at the time of modeling as opposed to cut-off criterion 5 (s. also § III-4).

As previously mentioned, cut-off criteria 6 and 7 are based on cut-off criterion 4. In the figures 20 and 21, the stepwise calculation of cut-off criterion 6 and 7 (versions a and b) is given. The first three steps of these cut-off criteria are identical to cut-off criterion 4. Afterwards, the per-substance results of the elementary cut-off criterion 4 scores (step 3 in figure 18) are weighted based on environmental relevance data.

In the case of cut-off criterion 6, the characterization factor of each investigated substance is used as a weighting factor (s. step 5 in figure 20). Just as in the other environmental cut-off criteria, the final results are again split per environmental impact category. In step 7 the substance cut-off criterion score is converted to one final cut-off criterion score by aggregation of the substances cut-off criterion scores like cut-off criterion 4b. Finally, in the last step 8 the cut-off criterion score is compared with the defined limit.

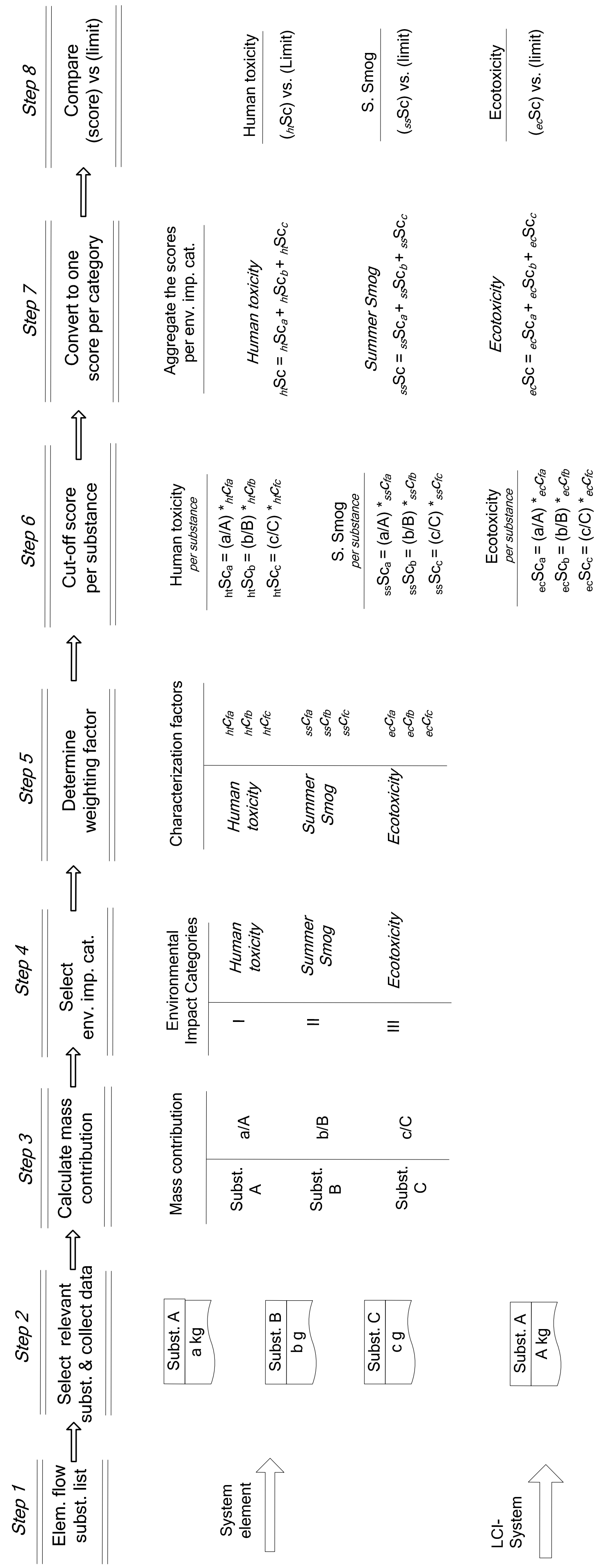


Figure 20. Stepwise application of environmental impact cut-off criterion 6.

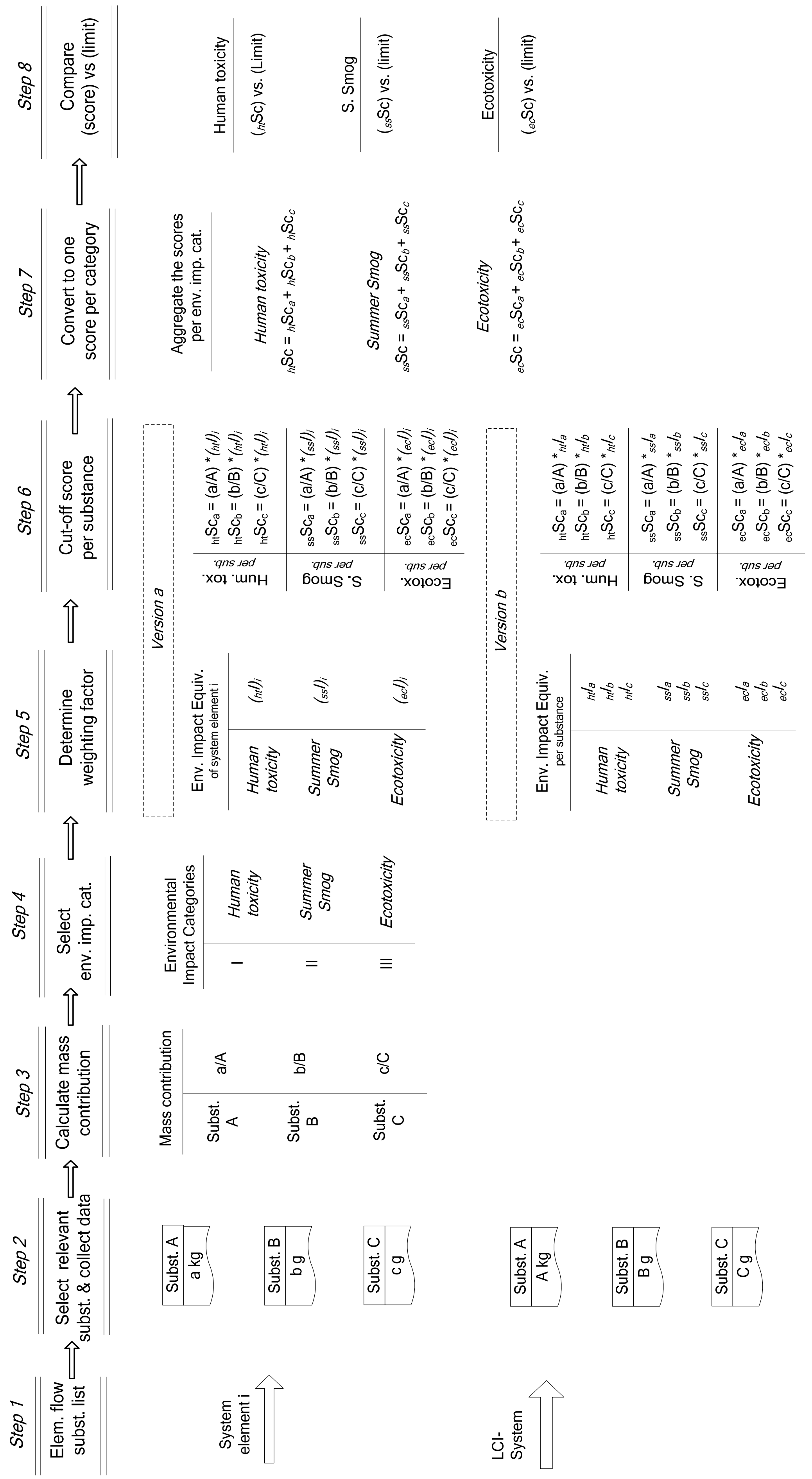


Figure 21. Stepwise application of environmental impact cut-off criterion 7a and 7b.

On the other hand, in cut-off criterion 7, the environmental impact indicator equivalents values are used in step 5 for the weighting (figures 20 and 21), instead of the characterization factors. In particular, in the first version 7a the overall environmental impact equivalent indicator result of the system element is used. Similarly, on version 7b the environmental impact equivalent indicator result of each investigated substance is used (s. figure 21 step 5). Again, for both versions the substances cut-off criterion scores are converted in the next step, step 7 (figure 21), into one score by aggregation. In the end, in step 8, the final system element cut-off criterion score per environmental category is compared with the respective defined cut-off criterion limit.

III-4 Cut-off criteria comparison in terms of reliability

The aim of the LCI analysis is to determine the product and elementary flows of the product life cycle and further deliver the latter ones to the environmental impact assessment. The cut-off criteria, as already mentioned, are used in order to systematically delimit the product tree to only those parts of the life cycle relevant to the assessment.

Therefore, the reliability of a cut-off criterion refers to the extent to which the cut-off criterion goal of *excluding from the LCI-system those parts of the product life cycle which have a lesser environmental relevance for the particular LCA being carried out* [19] is fulfilled.

Cut-off criterion 1

The cut-off criterion 1 is one of the most widely applied cut-off criteria [21, 57] mainly due to its comprehensiveness and simplicity of application. Despite the fact that the process related cut-off criterion 1 is often being used, it is considered insufficient because it does not study a system element attribute in reference to the respective attribute of the LCI-system. There is only a symmetry hold between the last system element and the new integrated system element and not between the system element and the LCI-system. Alternatively, there is no holistic thinking concerning the system element's final interconnection to the LCI-system.

In particular, the investigated ratio of the system element's product flows in formula 6 has no correspondence or correlation with the relation between the system element and the LCI-system environmental relevance values. Hence, by implementing this cut-off criterion despite the systematic development of the LCI-system the desired goal to ensure data symmetry and to exclude from the LCI-system only the system elements with a lesser environmental relevance cannot be achieved (or neared). Moreover, system elements interconnected with flows expressed only in energy units are out of the cut-off criterion's application range as they are not compatible [57] (s. also § III-3.1 Process related cut-off criterion). In conclusion the application of cut-off criterion 1 is not recommended.

Cut-off criterion 2

In cut-off criterion 2 "life cycle" thinking is implemented thus it delivers results of an acceptable reliability level. Nevertheless, the reliability is not high as the criterion's investigation is limited to "absolute" determined mass values of product flows, which don't correlate directly with the elementary flows, not to mention with the environmental relevance of the elementary flows. In addition, caution is needed in the determination of the cut-off criterion limit as, especially in the case of complex products, it can be easily set too high [21] i.e. in a LCA study with reference flow mineral water in 1l glass bottles the percentage contribution of the used glue on the bottle label to the total weight of the full bottle is extremely low. Furthermore, as mentioned previously, system elements interconnected through flows expressed solely in energy units are out of the criterion's application range, like cut-off criterion 1, which counts as one of its strongest disadvantages. On the other hand, the application and comprehension of the criterion is easy and simple, which is its greatest advantage.

Cut-off criterion 3 (mass multiplier)

From the current work, it was found that the mass multiplier values (as they are presently determined through the calculation formula (2) and (3)) cannot serve as a cut-off criterion because the denominator in both formulas (2) and (3) is not strictly defined. In particular, it was found that when using data values from different databanks referring to identical process steps the calculated mass multiplier values can differ up to 6 orders of magnitude which is not acceptable (see appendix 10). Hence, given that there is no generally applicable way to determine the initial system element product flow ${}_{Out}F_i$ (for production processes) in formula (2), or ${}_{In}F_i$ (for disposal processes) in formula (3), the mass multiplier should not be used as a cut-off criterion.

Cut-off criterion 4 (elementary cut-off criterion)

Cut-off criterion 4 is for investigating the system element's contribution to the LCI-system elementary flow. Even though the elementary flow contribution differs from the environmental relevance contribution, the correspondence to it is still direct (see also formulas (4) & (5)). The reliability of the elementary cut-off criterion's outcomes is very high. More reliable results can only be delivered by the environmental impact cut-off criteria.

Contrary to the environmental impact cut-off criterion, which has a cut-off criterion score per impact category, the elementary cut-off criterion is expressed with a single score which is advantageous. Furthermore, it is the best available criterion for stand-alone LCI studies.

Cut-off criterion 5

Cut-off criterion 5 investigates the system element's environmental relevance with reference to the environmental relevance of the whole LCI-system, which is actually the goal of every cut-off criterion (s. beginning of §III-4). Therefore, its results are the most reliable among all the other cut-off criteria.

Here the only simplification step is that the investigation is limited to a manageable number of relevant substances. The environmental relevance of these selected substances should be representative of the LCI-system environmental relevance.

Unfortunately, this criterion which delivers the most reliable results is not operable at the time of LCI-system modeling because the computation of its score needs environmental relevance data for the whole LCI-system (step 2 and 4 figure 19). This data cannot be available before the LCI-system is modeled at full scale. Actually, the objective of the LCI analysis is to ascertain this data so it is also not meaningful to use estimated values. Nevertheless, this cut-off criterion can be used in an additional step after modeling the product tree for evaluating the environmental relevance of the excluded system elements.

Cut-off criteria 6 and 7

The cut-off criteria 6 and 7 are (after cut-off criterion 5) the ones which deliver the most reliable results. The sole simplification undertaken here is identical to that taken when using cut-off criteria 4 and 5 where the investigation is limited to a manageable number of selected relevant substances.

Contrary to cut-off criterion 5, these criteria do not require the environmental relevance calculation of the whole LCI-system. The environmental relevance here is integrated into the criterion's score by weighting the preliminary elementary substance's mass contributions.

In conclusion, cut-off criteria 6 and 7 are the most reliable and operable criteria during the LCI-system modeling stage. The environmental relevance of the system element is investigated with reference to the one of the LCI-system utilizing a, calculation operation which is as simple as possible. The slight difference between cut-off criterion 6 and 7 will be further analyzed in § III-5.1 as there are cases in which this difference becomes important concerning the symmetric modeling of the product tree.

The following figure 22 illustrates the cut-off criteria classification here undertaken.

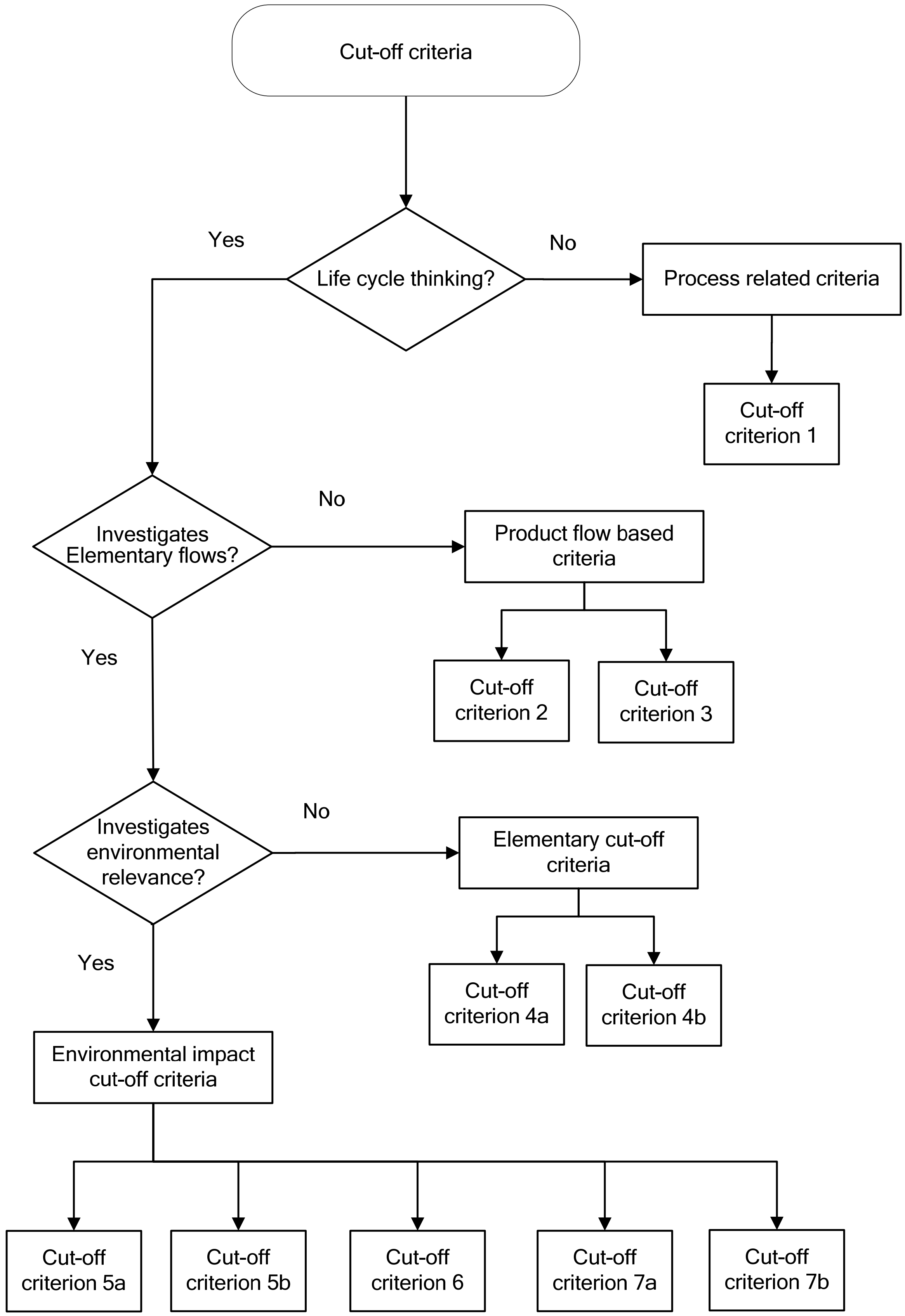


Figure 22. Cut-off criteria classification overview

III-5 Symmetric modeling of the LCI-system

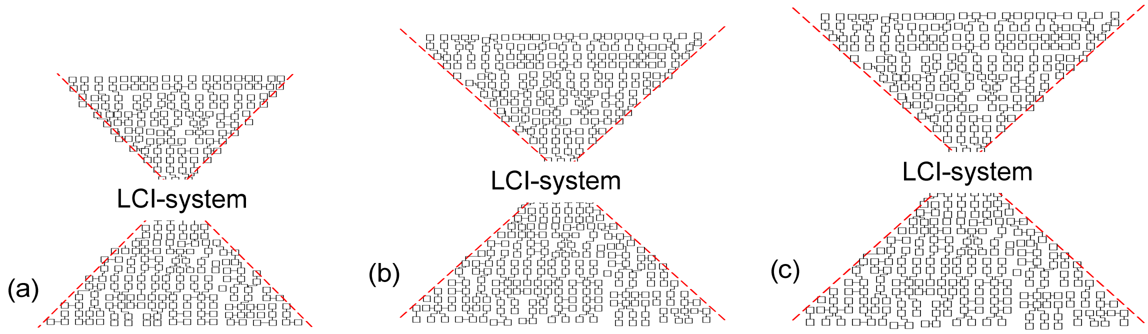
III-5.1 Symmetric modeling of single LCI-systems

An LCI-system is modeled gradually by adding one by one the system elements of the product tree. As quoted before, the system elements of the main chain are a priori in the product tree whereas the system elements of the by-chain are subject to the cut-off criterion (see also the decision flow chart in figure 9). So far, if a system element is considered relevant for the particular LCI-system it is added [19].

Assuming that the cut-off criterion is investigating the environmental relevance then the system element is actually excluded from the product tree not because of its low number of environmental impact indicator equivalents but due to its rather low contribution to the overall environmental impact indicator equivalents of the LCI-system. The symmetric modeling of the product tree is based upon this relativity. The inclusion of a system element is not based on absolute terms which are calculated independently from the LCI-system but on a relative value which depends on LCI-system data.

When considering a product system in which the cut-off criterion limit is gradually reduced, more and more system elements are then integrated in the LCI-system. This is presented in figure 23. It should be noted that the clepsydra form is used pragmatically and is not realistic to the shape of the flow chart.

Though the different LCI-systems (a), (b) and (c) are not equal to each other -especially considering their environmental impact relevance scores in absolute terms- the form and the heart of the product tree is the same in all of them.



With : $(\ell_{LCA})_a > (\ell_{LCA})_b > (\ell_{LCA})_c$

Figure 23. Different growths of the same symmetric modeled LCI-system visualized in a clepsydra form when the cut-off criterion limit, ℓ_{LCA} is gradually reduced from (a) to (c).

Among the several cut-off criteria previously analyzed, the ones which allow symmetric development of the product tree are the system related criteria which are: the cut-off criterion 2, the elementary cut-off criterion 4, and the environmental impact cut-off criteria 5, 6 and 7. Cut-off criterion 5, despite its high reliability, will not be further investigated since it is not operable at the time of product system modeling.

Cut-off criterion 2 is the only one based on process flow data and has the drawback that it is not applicable to system elements which are interconnected to the product tree through energy flows (s. § III-3.2.1 and § III-4.). Thus, the LCI-system's symmetric development inevitably stops each time such a system element is crossed (s. also the decision flow chart in figure 9).

Furthermore, all the system elements which are afterwards interconnected to this system element can also not be subject to cut-off criterion 2. Consequently data asymmetries are formed erratically in the product tree so long as the application range of cut-off criterion 2 is not extended in order to cover all the system elements. Thus, this criterion cannot ensure the symmetric development of the LCI-system.

Moreover, the score determination of the elementary cut-off criterion 4 is based on the initial per relevant-substance contribution. In particular, in figure 18 on step 4, the primary substances' cut-off criterion scores are expressed by the following ratios:

for relevant substance a: $S_{ia}/S_{LCIa} = a/A$, (7i)

for relevant substance b: $S_{ib}/S_{LCIb} = b/B$ (7ii)

and for relevant substance c: $S_{ic}/S_{LCIc} = c/C$ (7iii)

where: S_{ia}: the mass of substance a documented on the elementary flow of system element I

S_{LCIa}: the total mass of substance a in the LCI-system

Additionally, figure 24 shows which data are obtained from the flow chart in order to calculate the initial substances' elementary cut-off criterion scores.

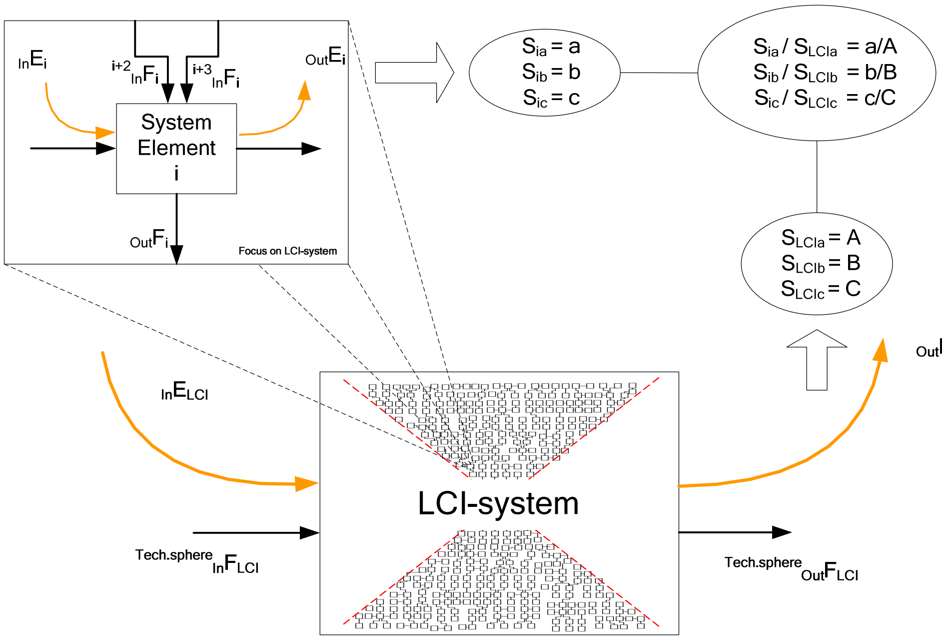


Figure 24. Elementary cut-off criterion score determination

It is important to point out here that the final scores calculated through formula 7 are relative values (no units), as they present the percentages of the substances' contribution to the product system. Thus, the substance cut-off criterion score actually investigates the distribution of the emitted substance x among several system elements in the product system. The ratio S_{ix}/S_{LCIx} depends not only on the mass of the emitted substance x in the system element i but also on the total emitted mass value of substance x in the LCI-system.

Hence, in some cases it is possible for some system elements to have a relatively high substance cut-off criterion score, whereas its respective environmental relevance is rather low. In particular, this happens under the following conditions:

- the emitted mass of substance x in system element i, S_{xi}, is relatively high compared with the emitted mass of other system elements.
- and the total emitted mass of substance x in the LCI-system is, in absolute values S_{LCIx}, relatively low.

The first condition results in a relatively high substance cut-off criterion score. On the contrary, based on the second condition, the overall contribution of substance x to the LCI-system's environmental relevance compared to the respective contribution of other substances would be rather low. This is due to the proportional relationship between the substance mass in the LCI-system, S_{LCIx}, and its environmental relevance $_{im.c.}I_{LCIx}$ (s. formulas 5 and 6). Furthermore, the environmental impact of system element i -caused by substance x- $_{im.c.}I_{ix}$ would also be inevitably relatively low, as S_{ix} is lower than S_{iLCI} (s. also end of § III-5.1).

Hence, in some cases the system element's environmental relevance contribution to the LCI-system does not correspond with its substance cut-off criterion score. This finally results in the formation of inherent transaction errors in the application of the elementary cut-off criterion. The developed symmetry of the LCI-system is then also biased.

Compensation for this error propagation is possible with modification of the criterion through the additional integration of absolute values of the product system into the calculation. A modified version of the elementary cut-off criterion is therefore proposed in appendix 11.

Similarly, in the score calculation of the environmental impact cut-off criteria 6 and 7, the ratio S_{ix}/S_{LCIx} is also integrated, as shown in step 6 of figures 20 and 21 respectively. In cut-off criterion 6 the substance cut-off criterion results from the multiplication of the ratio S_{ix}/S_{LCIx} with the characterization factor of substance x for the respective impact category $_{im.c.}c_{fx}$. However, the characterization factor is a constant thus the abovementioned error propagation is not prevented in cut-off criterion 6.

This is not the case for cut-off criterion 7. The substance cut-off criterion score in this case is multiplied with the environmental impact indicator equivalent (see step 7 on figure 21), which is not a constant value but depends on the mass absolute value of substance x, S_{ix}. In the particular example described above in figure 24 we will have the following calculations for cut-off criteria 4, 6 and 7:

Case study conditions

- S_{ix} (low in absolute terms but relative high in system element i)
- S_{LCIx} (relative low) $\Rightarrow$ ${}_{im..c..}I_{ix}$ (relative low)

Cut-off criterion 4	Cut-off criterion 6	Cut-off criterion 7
$Sc_{ix}= S_{ix}/S_{LCIx}$ (high)	$Sc_{xi}= S_{ix}/S_{LCIx}{*}_{im.c.}c_{fx}$ (high)	$Sc_{xi}= (S_{ix}/S_{LCIx}){*}_{im.c.}I_{ix}$ (quite low)
	As ${}_{im.c.}c_{fx}$ independent from S_{ix}	as ${}_{im.c.}I_{ix}$ is low because it is proportional to S_{ix}

With:$_i$

Sc_{ix} : substance's x cut-off criterion score in system element i

S_{ix} :mass of substance x in system element i elementary flow

S_{LCIx} :total mass of substance x in the LCI-system

${}_{im.c.}c_{fx}$: characterization factor of substance x (for specified impact category)

${}_{im.c.}I_{ix}$: environmental impact score (for specified impact category) of system element i caused by substance x

In conclusion, if the substance cut-off criterion score is only dependent on the distribution of the investigated substance among the system elements of the product system, then the system element's environmental relevance contribution to the LCI-system may not correspond with its substance cut-off criterion score and transaction errors are generated (case of cut-off criterion 4 and 6).

Compensation of this transaction error is possible through the integration of an absolute value of the system element into the calculation steps. Otherwise, the transaction error is only prevented in the case where the selected relevant substances (step 2 figures 18, 20 and 21) are among the ones which contribute the most to the LCI-system environmental relevance. In this case the first condition described in the above case study, is no longer true.

III-5.2 Symmetric modeling of the LCI-system in the context of more than one LCI-system

The symmetry of the product tree is currently under the single perspective. In the case of a comparative LCAs in the analysis, more than one LCI-system is developed. These are then further compared in regard to their environmental relevance. The development of the product tree and its delimitation from the rest of the technosphere, as analyzed before is based on the significance of each system element to the LCI-system. Ideally, the system element significance refers to its environmental relevance.

An analysis of the comparability of two LCI-systems investigated in a comparative assertion follows. The analysis focuses on the product trees' modeling comparability and not on comparability concerning the determination of the product system functions (s. also §II-8). Additionally, all the following theoretical considerations are per principle in value in all the system related cut-off criteria (cut-off criterion 4, 5, 6 and 7), because the cut-off criterion score correlates in all of them with the environmental relevance. Therefore, any specific previously described cut-off criterion will not primarily be focused on.

In the ideal case, two LCI-systems 1 and 2, as given in the following figure 25, are modeled with the cut-off criterion correlating the system elements environmental relevance to the overall environmental relevance of the respective LCI-system.

In the case where one specific system element i is used in both LCI-systems, its cut-off criterion score per impact category would then be calculated by the following formulas:

$${}_1Sc_i = ({}_{im.c.}I_i)_1 \,/\, ({}_{im.c.}I_{LCI})_1 \qquad {}_2Sc_i = ({}_{im.c.}I_i)_2 \,/\, ({}_{im.c.}I_{LCI})_2 \qquad \text{(8i) and (8ii)}$$

With:
${}_1Sc_i$: Cut-off criterion score of system element i in LCI-system 1
$({}_{im.c.}I_i)_1$: environmental impact indicator equivalents of system element i in the LCI-system 1
$({}_{im.c.}I_{LCI})_1$: overall environmental impact indicator equivalents of the LCI-system 1

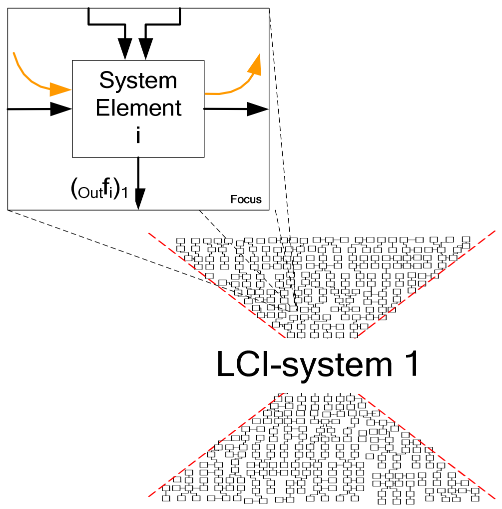


Figure 25. The same system element i in two alternative product life cycles 1 and 2 of a comparative assertion

Assuming that the system element i product flows in both LCI-systems are equal to each other $({}_{Out.}f_i)_1 = ({}_{Out.}f_i)_2$ in the two positions of figure 25, then its environmental impact indicator equivalents used in the formula 8, $({}_{im.c.}I_i)_1$ and $({}_{im.c.}I_i)_2$ would also be equal. Note that ${}_{im.c.}I_i$ refers to the environmental impact of system element i in the specific positions in the LCI-systems and not to the overall environmental impact of system element i in the LCI-system.

Therefore, if the overall environmental impact of system 1 is higher than the respective environmental impact of system 2, then the score of system element i in these two positions would be:

$${}_1Sc_i < {}_2Sc_i$$

$$\text{because: } ({}_{im.c.}I_i)_1 = ({}_{im.c.}I_i)_2 \text{ and } ({}_{im.c.}I_{LCI})_1 > ({}_{im.c.}I_{LCI})_2$$

At present, in the case of comparative assertions, the practitioner defines and applies the same cut-off criterion with its respective cut-off criterion limit for all the developed LCI-systems [5, 21, 34, 43, 45]. However ISO 14044 is not strict on this point and states that the different *systems shall be compared using equivalent methodological considerations such as system boundary* [19].

Considering that the cut-off criterion limit, ℓ_{LCA}, is the same for both LCI-systems, it is possible for the cut-off criterion score of system element i in the first LCI-system 1, ${}_1Sc_i$, to be lower than the set limit, whereas the respective criterion's score for the LCI-system 2, ${}_2Sc_i$ is higher. The following inequality holds:

$$ {}_1Sc_i < \ell_{LCA} < {}_2Sc_i \qquad (9)$$

With:

ℓ_{LCA}: Cut-off criterion limit in LCI-system 1 and LCI-system 2

Consequently, the system element i would be excluded from the LCI-system 1 while it would be included in the LCI-system-2.

The reason for this is the relativity in the cut-off criterion score determination. In the cut-off criterion, system elements values are compared with the ones of the investigated LCI-system. Thus, the reference point of the cut-off criterion is always a value of the LCI-system; hence every calculated cut-off criterion score is always depending on the particular product system investigated.

It is argued that the comparability of the assertion is strongly biased when an identical system element, with the same determined environmental impact score, is taken into account in one system, while excluded from the other system. The LCI-systems are comparable when a system element with a defined environmental relevance is handled identically among the several systems. Thus, product systems in comparative LCAs should be modeled in a symmetrical way, which should ensure their comparability.

The product system is actually a part of the technosphere. The LCI-system in the form of a flow chart gives a picture of one part of the technosphere. Although the product system is defined from its function, its final system boundaries are set by the application of the cut-off criterion. Hence, the cut-off criterion also determines the detail level of the investigation.

In comparative LCAs, more than one LCI-system is investigated. The fulfillment of the defined in the goal and scope phase function is prerequisite for the comparison of these product systems [5, 14, 22, 34, 43]. Moreover, the comparability of the systems is dependent on the detail level of the modeled LCI-systems.

The cut-off criteria as analyzed are determined in such a way that a value of the LCI-system is always used for reference, i.e. the overall environmental impact score ${}_{im.c.}I_{LCI}$ or the total emitted mass of a substance x, S_{LCIx}.

However, in the case where more than one LCI-system is investigated, the reference of the cut-off criterion should be the same in all the LCI-systems. This would ensure the same detail level for all the modeled product systems. Thus, particular system elements with the same determined environmental impact score in both LCI-systems as in the case of system element i in figure 25, which would be either included or excluded from both LCI-systems.

Thus, referring practically to the application of cut-off criteria in the case of comparative assertions, it is proposed to have the same cut-off criterion limit but to define one reference value upon which the several system elements would be compared. In particular, if the practitioner defines the values of the LCI-system 1 as the reference values, then formula 8ii would change and the cut-off criterion score for the second LCI-system would be calculated by formula 10:

$$ {}_2Sc_i = ({}_{im.c.}I_i)_2 \,/\, ({}_{im.c.}I_{LCI})_1 \qquad (10) $$
$$ \text{when: } \ell_1 = \ell_2 = \ell_{LCA} $$

In the case of the previously analyzed cut-off criteria 4, 6 and 7, the calculation changes are similar. In the elementary cut-off criterion 4 and the environmental impact cut-off criteria 6 and 7, the overall substance x mass value in LCI-system 2 $(S_{LCIx})_2$ is replaced with the overall mass substance x mass value in LCI-system 1 $(S_{LCIx})_1$. In the case of the environmental impact cut-off criterion 5, the change undertaken is identical to that described in formula 10.

Another way to ensure the same detail level in comparative assertions is to apply the calculation through formula 8 as it was, but to define the cut-off criterion limit differently among the several LCI-systems. Again one LCI-system would be set as the reference system i.e. LCI-system 1. Assuming that the limit for the LCI-system 1 is set as $\ell_1 = \ell_{LCA}$ then the limit for LCI-system 2 would be:

$$ \ell_2 = \ell_1 * ({}_{im.c.}I_{LCI})_1 \,/\, ({}_{im.c.}I_{LCI})_2 \qquad (11i) $$

with:

ℓ_2 : cut-off criterion limit for LCI-system 2

ℓ_1 : cut-off criterion limit for LCI-system 2

$({}_{im.c.}I_{LCI})_1$: environmental impact indicator equivalents for LCI-system 1 (per category)

$({}_{im.c.}I_{LCI})_2$: environmental impact indicator equivalents for LCI-system 2 (per category)

Respectively, for the case of cut-off criterion 4, 6 and 7 the calculation changes are analogous as follows:

$$\ell_2 = \ell_1 * (S_{LCIx})_1 / (S_{LCIx})_2 \qquad (11ii)$$

with:

ℓ_2 : cut-off criterion limit for LCI-system 2

ℓ_1 : cut-off criterion limit for LCI-system 1

$(S_{LCIx})_2$: the overall mass substance x mass value in LCI-system 2

$(S_{LCIx})_1$: the overall mass substance x mass value in LCI-system 2

In the case of the environmental impact cut-off criterion 5, the undertaken change is identical to the one described in formula 11i.

The result of the cut-off criterion application when using in the first case the same cut-off criterion limits and formula 10 and in the second case different limits with formula 11i and formula 8ii is the same. A proof on this follows (the proof for the case of cut-off criteria 4, 6 and 7 is analogous).

<u>Option 1</u>

Formula 10: ${}_2Sc_i = ({}_{im.c.}I_i)_2 / ({}_{im.c.}I_{LCI})_1$

And $\ell_2 = \ell_1$

A system element remains in the system so far as :

$${}_2Sc_i \geq \ell_2$$

$$\Rightarrow ({}_{im.c.}I_i)_2 / ({}_{im.c.}I_{LCI})_1 \geq \ell_1$$

<u>Option 2</u>

Formula 8ii: ${}_2Sc_i = ({}_{im.c.}I_i)_2 / ({}_{im.c.}I_{LCI})_2$

Formula 11i: $\ell_2 = \ell_1 * ({}_{im.c.}I_{LCI})_1 / ({}_{im.c.}I_{LCI})_2$

a system element remains in the system so far as :

$${}_2Sc_i \geq \ell_2$$

$$\Rightarrow ({}_{im.c.}I_i)_2 / ({}_{im.c.}I_{LCI})_2 \geq \ell_1 * ({}_{im.c.}I_{LCI})_1 / ({}_{im.c.}I_{LCI})_2$$

$$\Rightarrow ({}_{im.c.}I_i)_2 / ({}_{im.c.}I_{LCI})_1 \geq \ell_1$$

In conclusion, it is important to highlight that by adopting the above proposal in the cut-off criteria application, the difference between the several LCI-systems in terms of environmental impact equivalents rises. In the specific example of figure 25, system element i was initially excluded from LCI-system 1. The difference in the environmental impact scores (calculation 1), ${}^{1}\Delta I$ of the two systems would then be:

$$ {}^{1}\Delta_{\,im.c.}I_{LCI} = \left| ({}_{im.c.}I_{LCI})_1 - ({}_{im.c.}I_{LCI})_2 \right| \qquad (12i) $$

In the case where the two systems are modeled with the same detail level, then system element i would be either included in LCI-system 1 or excluded from LCI-system 2. Therefore, the difference in the environmental impact scores (calculation 2), ${}^{2}\Delta_{\,im.c.}I_{LCI}$ of the two systems would increase and change to:

$$ {}^{2}\Delta_{\,im.c.}I_{LCI} = \left| ({}_{im.c.}I_{LCI})_1 - ({}_{im.c.}I_{LCI})_2 + {}_{im.c.}I_i \right| \qquad (12ii) $$

Furthermore, for the precise calculation of the above difference, should be taken care all the rest system elements which like system element i after the readjustment of the system boundaries are included in LCI-system 1 (or respectively excluded from LCI-system 2). Thus, all the environmental impact equivalents caused by these system elements should be added in the ${}^{2}\Delta_{\,im.c.}I_{LCI}$ calculation. Consequently, the difference ${}^{2}\Delta_{im.c.}I_{LCI}$ would increase even more.

Hereby, it should be highlighted that the greater the difference between the environmental impacts scores of the investigated LCI-systems, the more reliable the support LCA offers in decision making.

III-6 Multifunctional modules development

As mentioned previously, at the positions of the LCI-system where modules are used data symmetry can be ensured only when the cut-off criterion is applied on the module subsystem (s. §III-1.3).

The cut-off criteria values are dependant on the module's flows, which vary according to the module's position in the product tree. Hence, in order to avoid data asymmetries the module detail level range should be adjusted each time according to its position in the product tree. Thus, the development of the modules functionality is necessary.

In the current work, the so-called relevance unit normalization (RUN) modeling is evolved, which aids the development of the module functionality. Based on the RUN models a five step algorithm is established which enables the symmetric adjustment of the module in the product tree through the effective interrelation between the practitioner and the databank as further analyzed in § III-6.3.8.

In RUN modeling the term “relevance” is introduced and used. This term is until this juncture considered ambiguous. Therefore the specification of the term and its relation to the cut-off criteria would first be analyzed. Afterwards the stepwise development of the RUN models, which are based on the cut-off criteria scores is given. The symmetric adjustment algorithm is thereafter developed.

III-6.1 Defining Relevance

Direct interrelation between the relevance of a system element and its cut-off criterion score is not yet specified. Initially, it is necessary to denote the exact meaning of the term *system element relevance* as there is no generally adopted definition yet.

*Relevanc*e is a general term defined in the encyclopaedia [74] as:

> *The term relevance represents the proximity of information to what is desired.*

Starting from this definition, it should be highlighted that *relevance* always refers to proximity of information. This proximity refers to the desired information. The problem of definition is now shifted to what is desired.

Actually, in LCI-system modeling the desired information is stated through the set cut-off criterion. Not all of the cut-off criteria determine which information is desired identically. Figure 26 illustrates this difference.

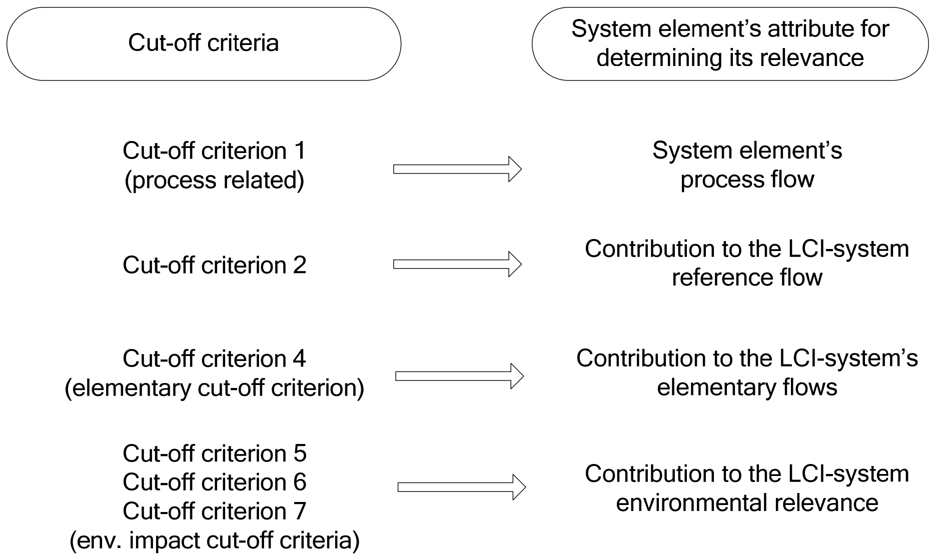


Figure 26. Cut-off criteria correspondence to relevance determination

As analyzed before, in the process related cut-off criterion 1 the system element's process flow through which the system element is integrated in the product tree is investigated while in cut-off criterion 2 the contribution of the system element to the reference flow is investigated. Conversely, in the elementary cut-off criterion 4, the contribution to the elementary flow is investigated whereas in the environmental impact cut-off criteria 5, 6 and 7 the contribution to the overall environmental relevance is investigated. Thus, the aforementioned desired information is different among the several cut-off criteria as in one case it refers to the process flow data while in another to the elementary flow or environmental relevance data.

III-6.2 Relevance measurement

Despite the fact that there is no direct relevance measurement there is a non-relevance measurement in LCA methodology. Non-relevant system elements are determined by the use of the cut-off criterion. In particular the following way of reasoning is followed:

$$\text{(cut-off criterion score)} < \text{(cut-off criterion limit)} \Rightarrow \text{non-relevant system element}$$

Hence, an irrelevant system element is an element with low relevance. Thus, it can be considered that the cut-off criterion limit determines the lowest level of relevance accepted for the specific study. Specifically, system elements are of low relevance when their cut-off criterion score is low. Low is defined as the score under the cut-off criterion limit.

Therefore, the cut-off criterion not only determines the relevance in an indirect way but can also be used in its quantification the cut-off criterion score. This quantification is yet per definition applicable to the low relevance level as this is determined through the cut-off criterion limit. The relevance quantification can be extended so far the following requirements are in value:

- the calculation of the cut-off criterion score is independent from the set cut-off criterion limit
- a positive continuality could be assumed

cut-off criterion score $\Rightarrow$ relevance score

Hence, the cut-off criterion score can also be used for the system element's relevance measurement. It is important to note here that in general, the principle of linearity is not necessary in value when the relevance score is determined by its cut-off criterion score. Consequently, if the cut-off criterion score of a system element i is twice as much as that of another system element q then it apparently does not mean that the system element i is twice as relevant and important for the study than system element q.

III-6.2.1 System element relevance and cut-off criterion function

The cut-off criterion is used in order to check the system elements if their relevance surpasses the set cut-off criterion limit [19]. Each time a new system element is integrated into the product tree it is then checked as already shown in the decision flow chart of LCI-modeling figure 9. Considering that the cut-off criterion score serves as the relevance measurement then the cut-off criterion function in the LCI-system modeling can be defined as:

The cut-off criterion score ranks the system elements according to their relevance to the LCA study.

As quoted above, the quantitative character of the cut-off criterion is enclosed in the cut-off criterion limit (s. §II-7). The cut-off criterion limit is then the means by which the detail level of a modeled product system becomes quantifiable (s. § III-5.2).

In each modeled LCI-system, a cut-off criterion limit is defined. Although the cut-off criterion limit is defined in relative terms (as analyzed in § III-5.1), in the end, these relative terms can be inverted back to absolute terms. An example of this follows. If the cut-off criterion limit, ℓ_{LCA} is defined as 3% of the total environmental impact of the LCI-system per category, $_{im.c..}I_{LCI}$ then this means that the cut-off criterion limit can be finally expressed in absolute terms as 0,03*($_{im.c..}I_{LCI}$) environmental impact indicator equivalents. Thus, the cut-off criterion limit function can be defined as:

The cut-off criterion limit grades the detail level range of the modeled LCI-system.

III-6.3 Relevance unit normalization modeling

III-6.3.1 Relevance unit normalization modeling and module relevance

Relevance unit normalization modeling is based on the cut-off criterion score. As analyzed in the cut-off criteria score determination (s. figures 18 to 21) the substance's cut-off criterion scores are initially calculated and upon these values the system element cut-off criterion score can be further calculated.

In the proposed RUN modeling the calculated substance and the system element cut-off criterion scores are adopted as later analyzed in §III-6.3.2. These are referred to here respectively as substance relevance score, r_{iSx} and as system element relevance, r_i.

Additionally, in the case of modules in a further step, a module score called module relevance, R_M is also calculated. The module relevance score should serve in quantifying the detail level range of the module.

It is important that the module relevance is determined in a way that every system element of the module subsystem has its share. Then the more system elements are in the module subsystem, the higher its module relevance score, R_M. Consequently, the higher the detail level range of a module, the higher would be its relevance score and vise versa.

Another important factor to be considered when calculating the module relevance is co-equality among system elements. Additionally because the system elements of the module subsystem are handled as co-equal with respect to their cut-off criterion score determination then in the module relevance calculation, the relevance of the system elements should also be handled co-equally.

The system elements of the module subsystem are integrated into the module relevance calculation using their respective system element relevance values hence the co-equality refers now to the system element relevance, r_i.

Following the above considerations, the module relevance (R_M) is defined to be equal to the sum of the respective relevance values (r_i) of the system elements (i,..,j) which are aggregated in the module subsystem.

$$R_M = \sum_{i}^{j} r_i \qquad (13)$$

R_M: Module relevance
r_i: System element i relevance
i…j: The aggregated system elements in the module subsystem

Using pure addition of the system elements relevance score to the module relevance calculation, each system element has its share in the final module score and the system elements are handled co-equally.

It should be noted here that by definition the relevance value is always positive and cannot be lost (*constantly preserved*). The relevance as shown later is basically considered an attribute of the documented in the elementary substance list substances. Thus module relevance, like system element relevance, eventually relies on the relevance of the documented substances on the elementary substance list.

The module relevance, the system element relevance and the substance relevance are uniformly measured in relevance units. However, it should be highlighted that the same module has a different number of relevance units when different cut-off criteria are applied (see also the further analyzed formulas 17 to 21).

III-6.3.2 System element relevance and substance relevance models

Considering the system element relevance its determination as quoted above depends on the selection of the cut-off criterion. The relevance of a system element (r_i) can be generally defined as a function of the relevance substances' system element scores investigated in the cut-off criterion.

In the case of cut-off criterion 4b, 5b, 6 and 7 the cut-off criterion score is determined by the addition of the respective substances cut-off criterion scores (see also step 4 of figure 18, step 6 of figure 19, step 7 of figures 20 and 21). Substance system element's scores are handled co-equally to another in these cut-off criteria. The system element relevance is then calculated using the following formula 14i:

$$r_i = \sum_x^z r_{iS_x} \qquad (14i)$$

r_i: Relevance of system element i
r_{iSx}: Relevance of the substance x found in the system element i
x,…,z: investigated in System-Element i relevant substances

On the contrary, in the case of cut-off criterion 4a and 5a the cut-off criterion score is determined by the highest substance cut-off criterion score (see. also step 4 of figure 18 and step 6 of figure 19), thus the system element relevance is given here using formula 14ii:

$$r_i = \{r_{iSx}, r_{iSy}, \ldots, r_{iSz}\}_{\max} \qquad (14ii)$$

r_i: Relevance of system element i
r_{iSx}: Relevance of the substance x found in the system element i
x,…,z: investigated in System-Element i relevant substances

Similar to the system element relevance, r_i, the substance system element relevance r_{iSx} is also dependant on the cut-off criterion selection. In general, the substance relevance is proportional to the mass of the relevant substance investigated and to the overall used normalization factor N_x, as shown in formula 15.

$$r_{iSx} = S_{ix} * N_x \qquad (15)$$

r_{iSx}: Relevance of the substance x found in system element i
x,…,z: investigated in System-Element i relevant substances
S_{ix}: Mass of the relevant substance x found in system element i
N_x: overall normalization factor for substance x

The overall normalization factor N_x is determined according to the selected cut-off criterion and always depends on specific data of the overall LCI-system. In general the normalization factor can be expressed as the product of two normalization coefficients, namely the mass normalization coefficient n_{mSx} and the environmental impact normalization coefficient $_{im.c}n_{ISx}$. Thus the normalization factor N_x is given by formula 16:

$$N_x = n_{mSx} *_{im.c.} n_{ISx} \qquad (16)$$

N_x: overall normalization factor
n_{mSx}: mass normalization coefficient of substance x
$_{im.c.}n_{ISx}$: env. impact normalization coefficient of substance x per env. impact category

Particularly, in elementary cut-off criterion 4 the normalization is based on pure mass data. Thus, the environmental impact normalization coefficient is defined in this case equal to 1. The mass normalization coefficient of substance x, n_{mSx} is then defined using the overall found mass of substance x in the LCI-system, S_{LCIx} as given by formula 17:

Elementary cut-off criterion 4: $$n_{mSx} = \frac{1}{S_{LCIx}} \quad [m]^{-1} \text{ Rel.Un.} \qquad (17)$$

S_{LCIx}: Overall mass of the relevant substance x found in the LCI-system
n_{mSx}: mass normalization coefficient of substance x

Conversely, in the environmental impact cut-off criterion 5 the normalization is based on pure environmental impact data. Thus, in this case, the mass normalization coefficient is defined as being equal to 1. The environmental impact normalization coefficient of substance x for the respective impact category, $_{im.c.}n_{ISx}$ is then defined using the characterization factor of substance x (for the specific category), $_{im.c.}c_{fx}$ and the overall environmental impact of the LCI-system, $_{im.c.}I_{LCI}$ as given by formula 18:

Env. impact cut-off criterion 5:
$$_{im.c.}n_{ISx} = \frac{_{im.c}c_{fx}}{_{im.c.}I_{LCI}} \quad (18)$$

$_{im.c.}n_{ISx}$: environmental impact normalization coefficient of substance x for impact category im.c.

$_{im.c.}c_{fx}$: characterization factor of substance x in respective env. impact normalization coefficient of substance

$_{Im.c.}I_{LCI}$: overall environmental impact score of LCI-system in the defined environmental impact category

In the case of the environmental impact cut-off criteria 6 and 7 the normalization relies on both mass and environmental impact data. The mass normalization coefficient is the same in both cut-off criteria 6 and 7 and similarly to elementary cut-off criterion 4 as given by formula 17. The environmental impact normalization coefficient varies among the criteria but in all cases, it expresses the weighting factor used in step 5 of figures 20 and 21.

In particular, in cut-off criterion 6, the environmental impact normalization coefficient is equal to the characterization factor of substance x as given in formula 19. On the other hand, in cut-off criterion 7 in its first version, it is equal to the overall environmental impact of the system element i (formula 20) whereas in its second version it is equal to the environmental impact of system element i caused by substance x (formula 21).

Env. impact cut-off criterion 6: $_{im.c.}n_{ISx} = {}_{im.c.}c_{fx}$ (19)

Env. impact cut-off criterion 7a: $_{im.c.}n_{ISx} = {}_{im.c.}I_{i}$ (20)

Env. impact cut-off criterion 7b: $_{im.c.}n_{ISx} = {}_{im.c.}I_{iSx}$ (21)

$_{im.c.}c_{fx}$: characterization factor of substance x in respective env. impact normalization coefficient of substance

$_{Im.c.}I_{i}$: overall environmental impact score of system element i in the defined environmental impact category.

$_{Im.c.}I_{iSx}$: overall environmental impact score of system element caused by substance x in the defined environmental impact category.

Correspondingly, the units of the impact normalization coefficients are those of the characterization factor and of the environmental impact indicator equivalents of the investigated impact category.

In conclusion in the RUN models of the system element relevance and the substance relevance are uniformly integrated the respective system element and substance cut-off criterion scores. The normalization coefficients used are defined according to the definition of the cut-off criterion. Therefore, when different cut-off criteria are used, the calculated relevance units of the system elements are also different.

Hereby, the determination of the normalization coefficients was given for the most reliable system related cut-off criteria 4, 5, 6 and 7 (s. figure 22). In the case of other system related cut-off criteria in which the respective calculation is similarly based on elementary flow data the determination of the normalization coefficients is then analogous.

Moreover, it is important to clarify the dependence of the system element relevance score determination. In first place the substance relevance score is proportional to its mass and to its normalization factor as given in formula 15. Thus, the relevance of the system element changes according to its position in the LCI-system as in different positions its substances' mass flows are also different. Moreover, the normalization factor also changes when the module or respectively, the system element, is integrated into different LCI-systems because in different LCI-systems the normalization coefficients are different.

Therefore the relevance computation eventually depends on the LCI-system in which the system element or module is used and on the particular position where it is employed. Hence, the RUN models are conformed to the fact that different cut-off criteria, or the same one in different LCI-systems, rank the system elements differently. Furthermore, the RUN models are also conformed to the current state-of-the-art of LCI-system modeling where different cut-off criteria are selected, each time according to the particular goal and scope of the study [19].

III-6.3.3 Relevance unit normalization application on a system element

Figure 27 shows the stepwise application of the RUN model on a system element i. In this example it is assumed that the elementary cut-off criterion 4b is selected for the LCA study.

In the first step the relevant substances selected are identified from the elementary flow. Then the respective mass-normalization coefficient is determined for each relevant substance (formula 17). In the next step, 4, each substance relevance value is calculated (formula 16 and 15). In case of the environmental impact cut-off criterion 5, 6 and 7, the impact normalization coefficient would have been additionally determined in step 3 (see also formulas 18, 19, 20 and 21 respectively). Finally, as the relevance of the substances is measured uniformly in relevance units, their aggregation is enabled utilizing formula 9 (step 5).

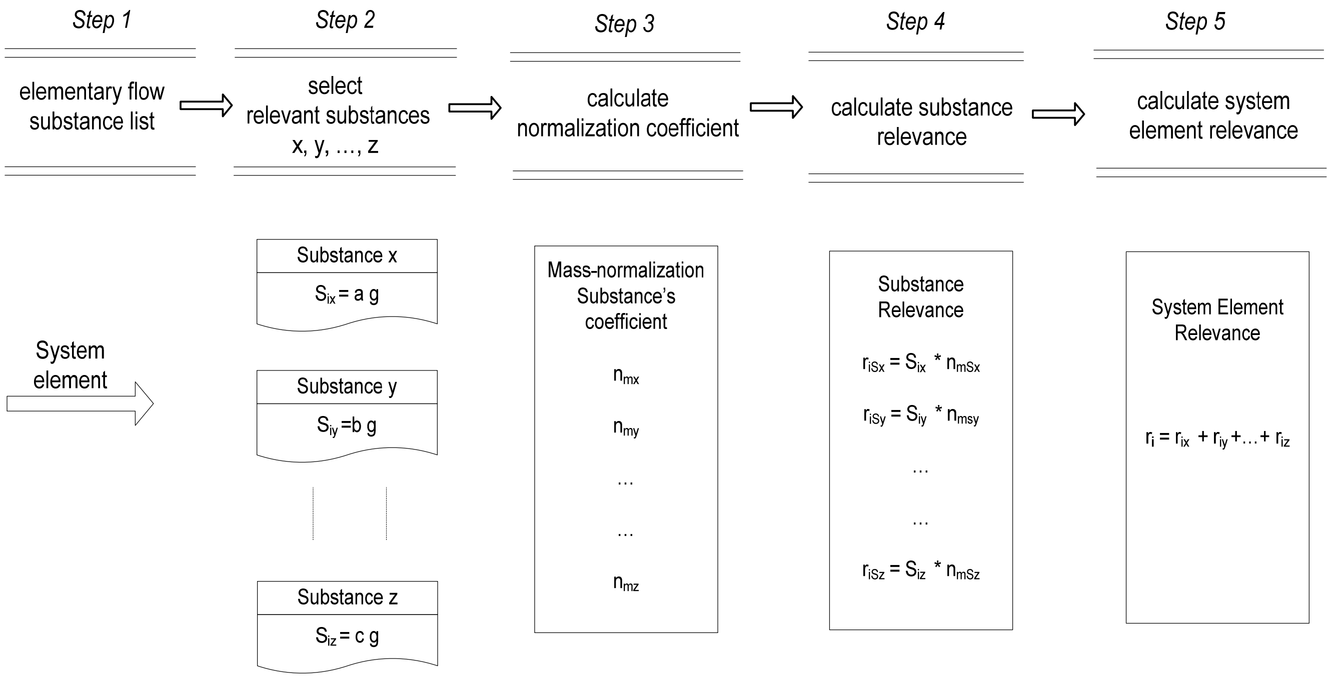
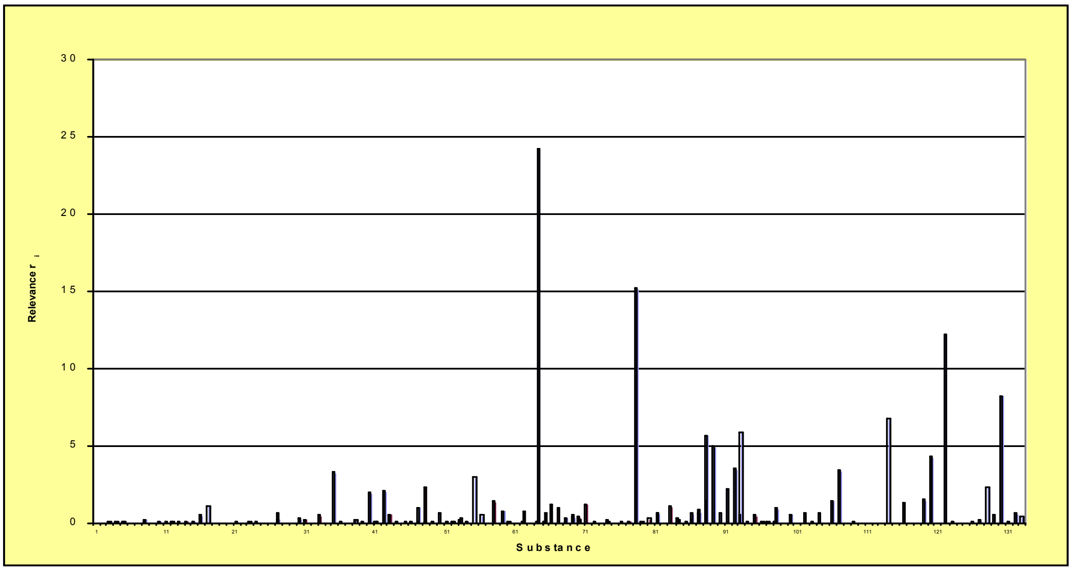


Figure 27. Stepwise application of relevance unit normalization (RUN) methodology for one system element

The substances' relevance can be shown graphically in the following graph 1. In graph 1 are used the results of the case study of an energy production module for Austria. On the x axis, the investigated relevant substances are in alphabetical order, while their respective relevance values r_{iSx} are on y axis. From this graph the extent to which a substance contributes to the system element relevance r_i can be identified and compared to the other substances.



Graph 1. Relevance of substances of a system element
(Exemplary result of an energy system element of Austria performed in the case study)

The kind of graph above (relevance values to substances) supports the dominance analysis on a relevance level as it directly identifies the dominant substances in a system element. Similarly, respective graphs can be drawn referring to the module relevance R_M on the y axis, or even to the overall LCI-system relevance. Thus, it is feasible that by integrating the RUN models in LCA software tools to perform a simultaneous dominance analysis on relevance unit level while modeling.

III-6.3.4 System element relevance and cut-off criterion limit

The correspondence of the system elements relevance, r_i to the respective system element cut-off criterion score is direct. The calculation of the system element relevance score using formulas 14 to 21 (according to the cut-off criterion selection) is finally identical with the cut-off criterion score determination, thus the LCI-system modeling can be shifted unhindered from cut-off criterion score to relevance score determination.

In this case the cut-off criterion limit is expressed in relevance units. Then the decision flow chart in LCI-system modeling presented previously (figure 9) remains the same, while the system elements relevance values, which substitute the cut-off criterion scores are now investigated. Moreover, the change from cut-off criterion score to relevance score makes the communication between the analyst and the interested parties easier as it is more comprehensive and simple to refer to relevance units.

III-6.3.5 Hierarchy of system elements

A system element’s hierarchy concerning their order in modeling can be determined based on the decision flow chart in LCI-system modeling (figure 9). The system element’s position in this hierarchy order is determined in first place by:

- the sequence in which the system element is checked whether to be included in the LCI-system or not during the described LCI-system modeling decision flow chart of figure 9.

and later in a second place by:

- the system element relevance score.

Particularly, on the top of the hierarchy pyramid, the initial system element is set which will be the starting point for the connection to the LCI-system for the rest system elements. This system element is more important than the others because if it does not reach the cut-off limit and is thereby excluded from the LCI-system, all the forthcoming system elements interconnected to it would also be excluded (even if they have not been checked).

Tracing the mass and energy flows of the initial system element the rest of the interconnected system elements are being sequentially identified. The system element, which is checked next follows in the hierarchy order and this procedure repeats. If there is more than one system element checked at the same time then the one with the higher relevance score comes first because this one reaches the cut-off limit more easily.

Hence, “every system element has a lower rank from its upper directly connected link to the LCI-system system element regardless of its relevance score” (hierarchy rule). As a result, system elements which are closer to the main chain and are checked out first, have a higher hierarchical order.

It is important to highlight here that according to current modeling practice as described in §II-8.2, not all system elements become always subject to the cut-off criterion [22, 45]. As previously mentioned it is common practice, for instance, not to check system elements describing less important process steps of a larger product chain i.e. system elements referring to internal transportation processes [45]. These kinds of system element are characterized here as pseudo system elements (see also II-8.2).

In particular, a pseudo system element is usually included in the LCI-system when the interconnected system element next to it reaches the cut-off limit. This actually contravenes the strict modeling rules where all system elements ought to be handled uniformly. Nevertheless, the LCI-system is a model which should represent reality so it is reasoned to include the pseudo-system elements which are part of an investigated larger product chain a priori.

The position of the pseudo system element in the aforementioned hierarchy is the same as the position of the next system element directly interconnected to it which encloses it in the investigated larger product chain.

Figure 28 visualizes the determination of the system elements hierarchy for a simple product chain referring to a post usage life cycle part. A pseudo system element is also included and is marked as ps.-j.

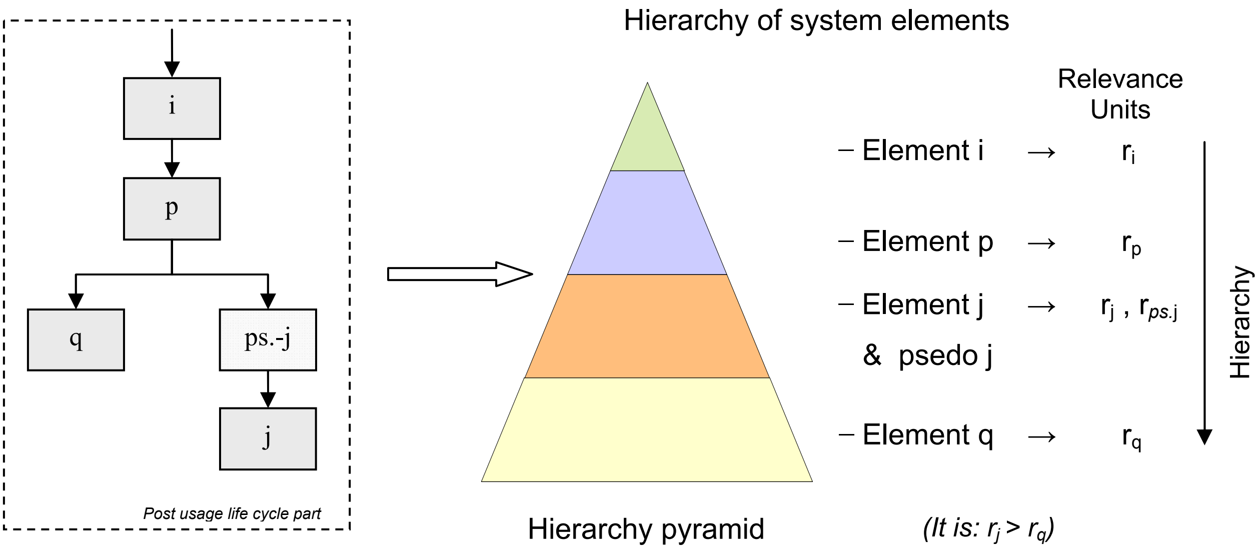


Figure 28. System elements hierarchical order in modeling the LCI-System

On top of the hierarchy order is the initial checked system element i followed by the next checked system element p (see also decision flow chart of figure 9). Because the pseudo system element ps.-j is not checked, its position is determined by system element j. Thus, in the next sequence system element q and j are checked at the same time.

The relevance of system element j is assumed to be higher than that of system element q therefore system element j comes next in the hierarchical order. The pseudo system element ps.-j has the same hierarchical position with system element j hence system element q gets the last position in the hierarchical order.

This hierarchy makes it feasible to identify the system elements which should be excluded when the cut-off limit varies. In this case, it is necessary to start from the top of the pyramid and go down until the first system element not reaching the cut-off limit score is identified. Then this system element and all the other system elements ordered lower than this in the hierarchy should be excluded.

In comparison to the up-to-date state of modeling, the analyst should have needed to start remodeling the whole system and apply again for each system element the decision flow chart until the boundary would be found.

III-6.3.6 Module relevance and cut-off limit

The module subsystem is modeled like the LCI-system so its system elements modeling hierarchy can be determined as described in §II-6.3.5. Similarly, using the hierarchy order which of the system elements should be excluded when the cut-off limit varies can be identified.

Additionally, the module relevance is calculated through the aggregation of the system elements, which are included in the module subsystem (formula 8). Thus, the module relevance score also changes when the cut-off limit varies causing to the exclusion or inclusion of system elements. The lower the cut-off limit score, the larger the module subsystem.

Thus, the module relevance score gradually raises as the cut-off limit decreases and more system elements are included in the module subsystem. The order in which the system elements are one after the other included in the module subsystem is the one of the modeling hierarchy.

In particular, the cut-off limit can be correlated with the module relevance score. Figure 29 visualizes how the hierarchy, the module relevance value and the cut-off limit correlate to each other for the example of the post usage life cycle module described in figure 28.

The module relevance value starts from the value of the first system element ordered in the hierarchy, i. When the cut-off limit decreases, then the system element coming next in the hierarchy order, p, reaches the cut-off limit and is then included in the module subsystem. As a result, the module relevance R_M increases and is then equal to the sum of the relevance values of system element i and p. This procedure is repeated until all the system elements under the hierarchical order reach the cut-off limit. Thus, the module relevance increases gradually with the addition of the relevance value of the next system element.

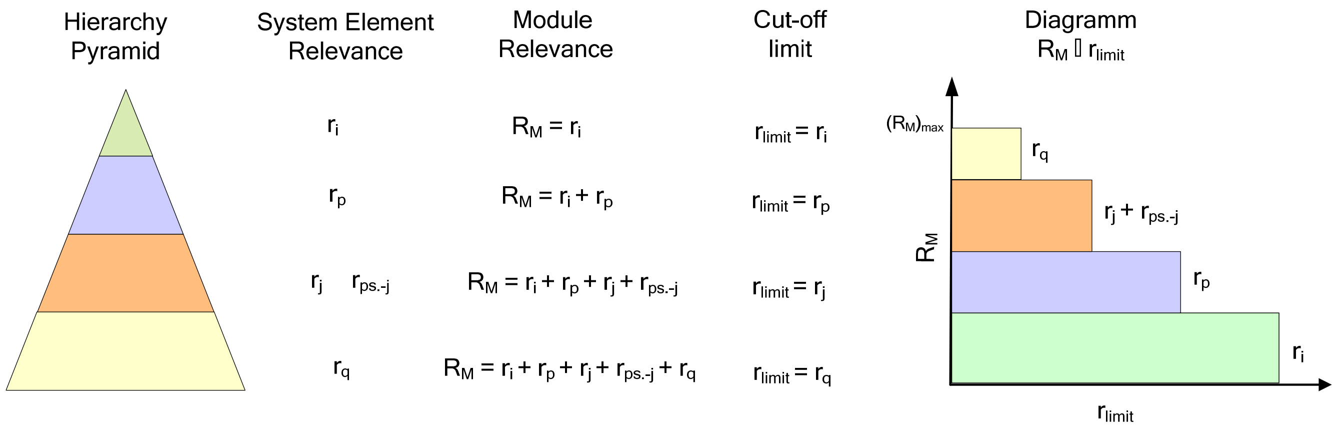


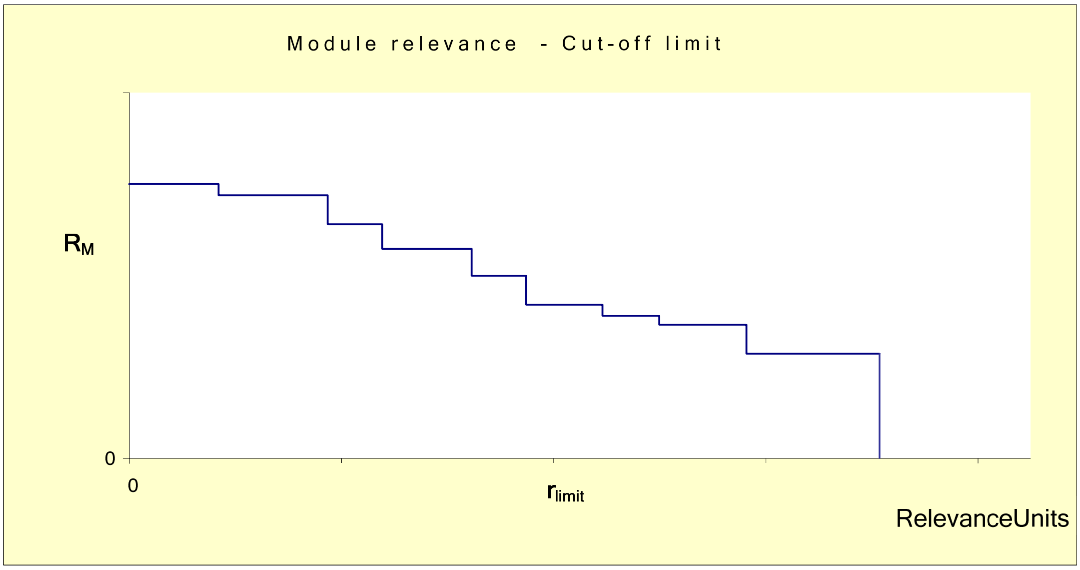
Figure 29. Hierarchy pyramid, module relevance and cut-off limit correlation

Similar to the qualitative R_M-r_{limit} diagram in figure 29 is graph 2. Graph 2 shows how the module relevance R_M value increases in relation to the respective decrease of the cut-off limit r_{limit} in a case study on an energy production module of Austria. Noteworthy from this graph is the step–like form the R_m – r_{limit} diagram takes.

The curve meets the x axis when the first system element in the hierarchy reaches the cut-off limit. When the cut-off limit value is zeroed (curve intersects the y axis) the module is at its highest detail level state including all possible system elements. Modeling with zero cut-off limit is, in general, not practically possible as then almost the whole technosphere should be modeled (see also § II-8.). However, the curve can be drawn until the y axis if it is assumed that the last system element borders only with nature.

Another important finding is that the step-like form of the R_m-r_{limit} curve proves that the mathematical function between module relevance and the cut-off limit is discontinuous (though for simplicity reasons the discontinuity points were omitted on figure 29 and graph 2). The module relevance only increases when a further system element enters in the system. At this point a step on the curve is formed and the curve has a discontinuity point.

Moreover, as the correspondence of the relevance values with the environmental impact values is direct, then the diagram of the module environmental impact value in correlation to the cut-off limit has the step like form of graph 2. Thus, it is considered that the mathematical function between the module environmental impact and generalizing between the LCI-system environmental impact value and the applied cut-off limit is also discontinuous. When the cut-off limit value decreases the environmental impact of the LCI-system remains stable until the first discontinuity point is found. At this point the environmental impact rises suddenly forming a step and then remains stable at this higher rate until the next discontinuity point is found.



Graph 2. Module Relevance and cut-off limit
(Exemplary result of an energy module for Austria performed in the case study)

In addition, it is important to remark that in the R_m-r_{limit} diagram, all the relevance values are eventually calculated using:

- the mass values S_{ix} (formula 15) of each relevant substance x in each system element i and
- using the particular LCI-system data respectively in the determination of the normalization factor N_x (formulas 16-21).

Therefore the substance relevance values used and through them the system element relevance and module relevance values eventually depend on the substance mass values used which rely on the initial module (intermediate) product flow F and on the respective data values of the LCI-system.

Thus, the relevance module to cut-off limit, R_M-r_{limit} diagram refers to the LCI-system investigated and to a module position in which the module product flow F is equal to the one used in the establishment of the diagram. An analysis and a derivation of an analogy formula which enables the use of one R_M-r_{limit} diagram per LCI-system for several module product flows follows.

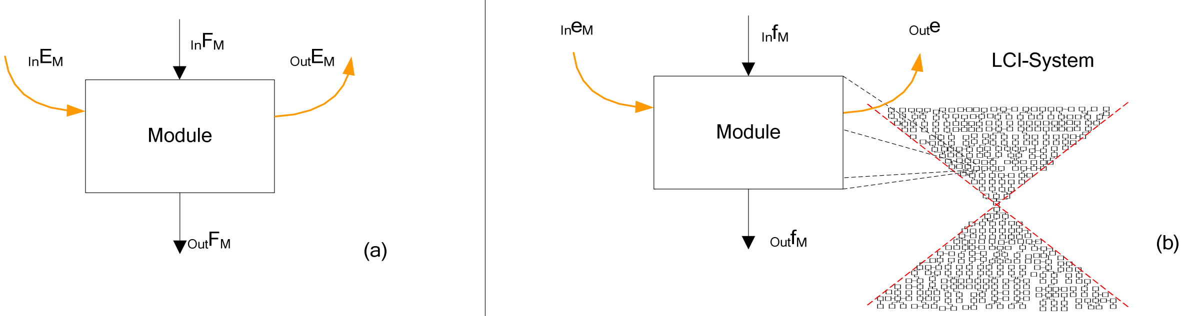
III-6.3.7 Analogy formula derivation

Hereby, it would be investigated how several calculated parameters of the module change when a module from its initial state (e.g. as found in its generic form in the databank) changes in order to get integrated in a LCI-system. The investigated parameters are the module relevance (R_M), the relevance of the several system elements (r_i, r_p,…, r_q) which form the module subsystem, the respective emitted mass values of the substances per system element S_{ix} and the cut-off limit of the module, r_{limit}.

The module of figure 30 is used as an example. In its initial form figure 30a the module is as found in the databank while in figure 30b the module is within the LCI-system.

Module Initial status

Module in the product tree



<u>Parameters</u>

R_M : Module relevance

r_i, r_p,… r_q : Relevance of system elements

S_{ix}, …, S_{iz}: Substances mass values

r_{limit} :cut-off limit on the subsystem

<u>Parameters</u>

R'_M : Module relevance

r'_i, r'_p,… r'_q: Relevance of system elements

S'_{ix}, …, S'_{iz}: Substances mass values

r'_{limit} : Cut-off limit on the module subsystem

r_{LCA} : Cut-off limit on the LCI-system

Figure 30. Module phases: (1) module initial status (databank), (2) module in the product tree.

The module subsystem is formed by the aggregation of several system elements i, p, …,q (though not visualized in figure 30). When the module enters the LCI-system it is assumed that the module subsystem does not change. The defined cut-off limit for the given LCI-system of figure 30b is given as $r_{LCA.}$ In the module's initial state capital letters are used for denoting the module product and elementary flows. Whereas the several parameters investigated when the module is in the product tree are marked with a prime (figure 30b).

The module is interconnected to the product tree through its product flow. If the module refers to production processes it is interconnected to the LCI-system with its product outflow ${}_{Out}f_M$ whereas in the case of disposal processes with its product ${}_{In}f_M$ inflow.

In particular, if the module refers to production processes then the module product outflow ${}_{Out}F_M$ should be changed in ${}_{Out}f_M$ therefore it is multiplied with the portion (${}_{Out}f_M/{}_{Out}F_M$). As a result when black box modeling is applied, all the other module flows are also multiplied proportionally with the portion (${}_{Out}f_M\,/{}_{Out}F_M$). Conversely, if the module refers to disposal processes then the module product inflow ${}_{In}F_M$ should be changed in ${}_{In}f_M$. Thus, in this case all the module flows are respectively multiplied with the portion (${}_{In}f_M/\,{}_{In}F_M$).

In addition, the several system elements flows in the module subsystem are then also multiplied with the respective portion (${}_{Out}f_M\,/{}_{Out}F_M$) or respectively (${}_{In}f_M/{}_nF_M$). Therefore, when comparing the two phases of the module in figure 30 the substances' mass values found in the elementary flows of the system elements are correlated with the following formula 22:

$$S'_{ix} = ({}_{\mathrm{Out}}\mathrm{f_M} \big/ {}_{\mathrm{Out}}\mathrm{F_M}) * S_{ix} \qquad (22i)$$

or $$S'_{ix} = ({}_{\mathrm{In}}\mathrm{f_M} \big/ {}_{\mathrm{In}}\mathrm{F_M}) * S_{ix} \qquad (22ii)$$

Formulae 22i and 22ii stands for all the investigated substances x to z and for all the system elements i to j

In the case of the module referring to production processes formula 22i is employed whereas respectively formula 22ii is used for disposal processes.

III-6.3.7.1 Interrelation of system element relevance values r_i and r'_i when module is in the databank and in the LCI-system

The relevance value of a system element i r_i is calculated as previously mentioned through formula 14i or 14ii according to the selected cut-off criterion. This system element relevance value r_i relies on the value of the substances' relevance values r_{iSx}, r_{iSy}, to r_{iSz} which is calculated using formula 15. Thus, a system element i which is in the module subsystem when the module is integrated in the product tree (figure 30b) has relevance score equal to:

$$r'_{iSx} = S'_{ix} * N'_x \qquad (23)$$

The normalization factor N_x is calculated using formula 16:

$$N_x = n_{mSx} *_{im.c.} n_{ISx} \qquad (16)$$

The mass normalization coefficient n_{mSx} is determined with formula 17:

$$n_{mSx} = 1 / S_{LCIx} \qquad (17)$$

Hereby, the overall mass of the substance in the LCI-system expressed in formula 17 as S_{LCIx} refers to the fully modeled LCI-system. If the module is included in the full LCI-system and through it the system element i then in the S_{LCIx} value is also included the substance mass value, S'_{ix}.

It should be clarified here that although the overall mass of the substance in the LCI-system actually changes during the modeling because new system elements are added, the S_{LCIx} value used here is stable because it refers to the final overall substance mass value of the LCI-system. When the LCI-system reaches its final form no more system elements are added or excluded.

As a result the mass normalization coefficient does not change if the system element i relevance score is determined in the initial state or when the module is integrated into the LCI-system.

On the contrary, the impact normalization coefficient ${}_{im.c.}n'_{Sx}$ is in some cases dependent on the particular substance mass value S'_{ix}. In general the impact normalization coefficient ${}_{im.c.}n_{ISx}$ is determined using one of the formulas 18, 19, 20 or 21 according to the selected cut-off criterion.

$$ {}_{im.c.}n_{ISx} = {}_{im.c.}c_{fx} / {}_{im.c.}I_{LCI} \quad (18) \qquad {}_{im.c.}n_{ISx} = {}_{im.c.}c_{fx} \quad (19) $$

$$ {}_{im.c.}n_{ISx} = {}_{im.c.}I_{i} \quad (20) \qquad {}_{im.c.}n_{ISx} = {}_{im.c.}I_{iSx} \quad (21) $$

In the case of cut-off criterion 5 and 6 where the formulae 18 and 19 are used respectively the impact normalization coefficient is not dependent on the substance mass value S'_{ix}.

In particular, the characterization factor of a substance x per impact category used in both formulas 18 and 19 is a constant. Additionally, the value of the overall impact of the LCI-system ${}_{im.c.}I_{LCI}$ used in formula 18 refers (like in the case of the S_{LCIx} value) to the final LCI-system therefore it is also stable. Thus, the impact of system element i is also included in the value of the overall impact of the LCI-system ${}_{im.c.}I_{LCI}$.

However, it can be proven that in the case of cut-off criterion 7 (s. also formula 20 and 21) the impact normalization coefficient ${}_{im.c.}n'_{iSx}$ is dependent on the substance mass value S'_{ix}. Furthermore, the impact normalization coefficient ${}_{im.c.}n'_{iSx}$ of system element i when the module is integrated into the LCI-system is proportional to its respective value ${}_{im.c.}n_{iSx}$ when the module is in its initial state. The proof of this is given in the derivation of the following formulas 27, 28, 32 and 33.

Derivation of formula 27, 28, 32 and 33

When the module is integrated in the LCI-system formula 20 takes the form of:

$$_{im.c.}n'_{ISx} = {}_{im.c.}I'_i \qquad (24)$$

Using formula (4) and (5) for system element i:

$$_{im.c.}I'_i = \sum_x^z c_{fx} * S'_{ix} \qquad (25)$$

(24) and (25) is then:

$$_{im.c.}n'_{ISx} = \sum_x^z c_{fx} * S'_{ix} \qquad (26)$$

Out of formula 22 we have:

$$S'_{ix} = ({}^{\mathrm{Out}}\mathrm{f_M} / {}_{\mathrm{Out}}\mathrm{F_M}) * S_{ix} \qquad (22i) \qquad \text{or} \qquad S'_{ix} = ({}^{\mathrm{In}}\mathrm{f_M} / {}_{\mathrm{In}}\mathrm{F_M}) * S_{ix} \qquad (22ii)$$

then using (22i) in (26): $_{im.c.}n'_{ISx} = \sum_x^z c_{fx} * S'_{ix}$

$$\Leftrightarrow \; _{im.c.}n'_{ISx} = \sum_x^z (c_{fx} * ({}^{\mathrm{Out}}\mathrm{f_M} / {}_{\mathrm{Out}}\mathrm{F_M}) * S_{ix})$$

$$\Leftrightarrow \; _{im.c.}n'_{ISx} = ({}^{\mathrm{Out}}\mathrm{f_M} / {}_{\mathrm{Out}}\mathrm{F_M}) * \sum_x^z (c_{fx} * S_{ix})$$

$$\Leftrightarrow \; _{im.c.}n'_{ISx} = ({}^{\mathrm{Out}}\mathrm{f_M} / {}_{\mathrm{Out}}\mathrm{F_M}) * {}_{im.c.}n_{ISx} \qquad (27)$$

And respectively for (22ii) in (26) we have:

$$_{im.c.}n'_{ISx} = ({}^{\mathrm{In}}\mathrm{f_M} / {}_{\mathrm{In}}\mathrm{F_M}) * {}_{im.c.}n_{ISx} \qquad (28)$$

Similarly, when the module is integrated in the LCI-system formula 21 becomes:

$$_{im.c.}n'_{ISx} = {}_{im.c.}I'_{iSx} \qquad (29)$$

Using formula (4) for system element i:

$$_{im.c.}I'_{iSx} = {}_{im.c.}c_{fx} * S'_{ix} \qquad (30)$$

and (29) is then:

$$_{im.c.}n'_{ISx} = {}_{im.c.}c_{fx} * S'_{ix} \qquad (31)$$

then using (22i) in (31) we have:

$$_{im.c.}n'_{ISx} = {}_{im.c.}c_{fx} * S'_{ix} \Leftrightarrow {}_{im.c.}n'_{ISx} = {}_{im.c.}c_{fx} * \left({}_{Out}f_M \big/ {}_{Out}F_M \right) * S_{ix}$$

$$\Leftrightarrow {}_{im.c.}n'_{ISx} = \left({}_{Out}f_M \big/ {}_{Out}F_M \right) * {}_{im.c.}n_{ISx} \qquad (32)$$

And respectively for (22ii) in (31) we have:

$$_{im.c.}n'_{ISx} = {}_{im.c.}c_{fx} * \left({}_{In}f_M \big/ {}_{In}F_M \right) * S_{ix}$$

$$\Leftrightarrow {}_{im.c.}n'_{ISx} = \left({}_{In}f_M \big/ {}_{In}F_M \right) * {}_{im.c.}n_{ISx} \qquad (33)$$

It should be noted here that formula 32 is identical to 27 and similarly formula 28 is identical to formula 32.

Conversely, in the case of cut-off criterion 5 and 6 as long as the impact normalization coefficient is not dependent on the substance mass value S'_{ix} (s. formula 18 and 19) we have:

$$_{im.c.}n'_{ISx} = {}_{im.c.}n_{ISx} \qquad (34)$$

<u>Interrelation of substance relevance r_{iSx} and r'_{iSx}</u>

The interrelation of the substance relevance of a system element i when the module is integrated into the LCI-system and when the module is in its initial state is then calculated using the following formulas:

- $r'_{iSx} = S'_{ix} * N'_x$ (23)
- $N'_x = n_{mSx} * {}_{im.c.}n'_{ISx}$ (16)

- $S'_{ix} = ({}^{\mathrm{Out}}f_M / {}_{\mathrm{Out}}F_M) * S_{ix}$ (22i) or $S'_{ix} = ({}^{\mathrm{In}}f_M / {}_{\mathrm{In}}F_M) * S_{ix}$ (22ii)

  - when cut-off criterion 4, 5 and 6 is valid:

    $_{im.c.}n'_{ISx} = {}_{im.c.}n_{ISx}$ (34)

  - when cut-off criterion 7 is valid:

    $_{im.c.}n'_{ISx} = ({}^{\mathrm{Out}}f_M / {}_{\mathrm{Out}}F_M) * {}_{im.c.}n_{ISx}$ (27)

    or $_{im.c.}n'_{ISx} = ({}^{\mathrm{In}}f_M / {}_{\mathrm{In}}F_M) * {}_{im.c.}n_{ISx}$ (28)

Applying formula 16 in formula 23 we have:

$$r'_{iSx} = S'_{ix} * N'_x$$

$$\Rightarrow r'_{iSx} = S'_{ix} * n_{mSx} * {}_{im.c.}n'_{ISx} \qquad (35)$$

Applying formula 22i in 35 we have:

$$(35) \Rightarrow r'_{iSx} = ({}^{\mathrm{Out}}f_M / {}_{\mathrm{Out}}F_M) * S_{ix} * n_{mSx} * {}_{im.c.}n'_{ISx} \qquad (36)$$

If cut-off criterion 4, 5 and 6 is selected then formula 34 is in value:

$$_{im.c.}n'_{ISx} = {}_{im.c.}n_{ISx} \qquad (34)$$

and with (34) in (36):

$$(36) \Rightarrow r'_{iSx} = ({}^{\mathrm{Out}}f_M / {}_{\mathrm{Out}}F_M) * S_{ix} * n_{mSx} * {}_{im.c.}n_{ISx}$$

$$\Leftrightarrow r'_{iSx} = ({}^{\mathrm{Out}}f_M / {}_{\mathrm{Out}}F_M) * r_{iSx} \qquad (37)$$

Correspondingly if formula 22ii is applied instead of 22i we have:

$$r'_{iSx} = ({}^{\mathrm{In}}f_M / {}_{\mathrm{In}}F_M) * r_{iSx} \qquad (38)$$

Conversely in the case of cut-off criterion 7 in formula 36 formula 27 is used instead of formula 34. Thus we have:

$$r'_{iSx} = S'_{ix} * N'_{x} \qquad \Rightarrow \; r'_{iSx} = S'_{ix} * n_{mSx} *_{im.c.} n'_{ISx}$$

$$\Rightarrow \; r'_{iSx} = ({}^{\text{Out}}\text{f}_{\text{M}} / {}_{\text{Out}}\text{F}_{\text{M}}) * S_{ix} * n_{mSx} * ({}^{\text{Out}}\text{f}_{\text{M}} / {}_{\text{Out}}\text{F}_{\text{M}}) *_{im.c.} n_{ISx}$$

$$\Rightarrow \; r'_{iSx} = ({}^{\text{Out}}\text{f}_{\text{M}} / {}_{\text{Out}}\text{F}_{\text{M}})^2 * S_{ix} * n_{mSx} *_{im.c.} n_{ISx}$$

$$\Rightarrow \; r'_{iSx} = ({}^{\text{Out}}\text{f}_{\text{M}} / {}_{\text{Out}}\text{F}_{\text{M}})^2 * r_{iSx} \qquad (39)$$

Correspondingly if formula 22ii is applied instead of 22i we have:

$$\Rightarrow \; r'_{iSx} = ({}^{\text{In}}\text{f}_{\text{M}} / {}_{\text{In}}\text{F}_{\text{M}})^2 * r_{iSx} \qquad (40)$$

Interrelation of system element relevance r_i and r'_i

The calculation of the system element relevance r_i is enabled using formula 14i and 14ii. If the above derived formulas 37, 38, 39 and 40 are used we have:

- In cut-off criterion 4a and 5a it is applied: $r'_i = \{r'_{iSx}, r'_{iSy}, \ldots, r'_{iSz}\}_{\max}$ (14ii)

  and with application of formula 37 in formula 14ii:

$$\Rightarrow \; r'_i = \{({}_{\text{Out}}\text{f}_{\text{M}} / {}_{\text{Out}}\text{F}_{\text{M}}) * r_{iSx}, ({}_{\text{Out}}\text{f}_{\text{M}} / {}_{\text{Out}}\text{F}_{\text{M}}) * r'_{iSy}, \ldots, ({}_{\text{Out}}\text{f}_{\text{M}} / {}_{\text{Out}}\text{F}_{\text{M}}) * r'_{iSz}\}_{\max}$$

$$\Rightarrow \; r'_i = ({}_{\text{Out}}\text{f}_{\text{M}} / {}_{\text{Out}}\text{F}_{\text{M}}) * r_i \qquad (41)$$

  and respectively when in formula14ii formula 38 is applied instead of formula 37 there is:

$$r'_i = ({}_{\text{In}}\text{f}_{\text{M}} / {}_{\text{In}}\text{F}_{\text{M}}) * r_i \qquad (42)$$

- In cut-off criterion 4b, 5b and 6 it is applied: $r'_i = \sum_{x}^{z} r'_{iSx}$ (14i)

  and with application of formula 37 in formula 14i there is:

$$r_i' = \sum_x^z ((_{\mathrm{Out}}\mathrm{f_M} / _{\mathrm{Out}}\mathrm{F_M}) * r_{iSx})$$

$$\Rightarrow \ r_i' = (_{\mathrm{Out}}\mathrm{f_M} / _{\mathrm{Out}}\mathrm{F_M}) * \sum_x^z r_{iSx}$$

$$\Rightarrow \ r_i' = (_{\mathrm{Out}}\mathrm{f_M} / _{\mathrm{Out}}\mathrm{F_M}) * r_i \qquad (43)$$

and respectively when in formula 14ii formula 38 is applied instead of formula 37 we have:

$$r_i' = (_{\mathrm{In}}\mathrm{f_M} / _{\mathrm{In}}\mathrm{F_M}) * r_i \qquad (44)$$

Hereby, it is very important to note that the above equations 43 and 44 as derived are identical to formulas 41 and 42 respectively.

- In cut-off criterion 7 the following is applied: $r_i' = \sum_x^z r_{iSx}'$ (14i)

  and with application of formula 39 in formula 14i we have:

$$r_i' = \sum_x^z (_{\mathrm{Out}}\mathrm{f_M} / _{\mathrm{Out}}\mathrm{F_M})^2 * r_{iSx})$$

$$\Rightarrow \ r_i' = (_{\mathrm{Out}}\mathrm{f_M} / _{\mathrm{Out}}\mathrm{F_M})^2 * r_i \qquad (45)$$

  and respectively when in formula 14ii formula 40 is applied instead of formula 39 we have:

$$r_i' = (_{\mathrm{In}}\mathrm{f_M} / _{\mathrm{In}}\mathrm{F_M})^2 * r_i \qquad (46)$$

Hereby, is defined as analogy α, the portion which is needed to multiply the relevance r'_i of a system element i when it is in the LCI-system, in order to be equal to the system element relevance r_i value when the module is in its initial state.

Analogy definition: $$\alpha = \frac{r_i}{r'_i} \qquad (47)$$

Thus, analogy α is determined differently according to which of the above formulae 41 to 46 are valid.

In case of application of formula 41 or formula 43 analogy α is:

$$\alpha = \frac{{}_{Out}F_M}{{}_{Out}f_M} \qquad (48)$$

In case of application of formula 42 or formula 44 analogy α is:

$$\alpha = \frac{{}_{In}F_M}{{}_{In}f_M} \qquad (49)$$

In case of application of formula 45 analogy α is:

$$\alpha = \left(\frac{{}_{Out}F_M}{{}_{Out}f_M}\right)^2 \qquad (50)$$

In case of application of formula 46 analogy α is:

$$\alpha = \left(\frac{{}_{In}F_M}{{}_{In}f_M}\right)^2 \qquad (51)$$

III-6.3.7.2 Cut-off limit and derivation of analogy equation

Based on the correlation of the system element values r_i and r'_i as given by the above derived formulas 41 to 46 it is possible to correlate the cut-off limit r_{limit} of the module subsystem and the defined cut-off limit of the LCI-system r_{LCA} (s. also figure 30a and 30b).

As mentioned above in the example given of figure 30, when the module enters in the

LCI-system its subsystem does not change. If the cut-off limit r_{LCA} which is selected in the LCI-system is applied on the module subsystem then the calculated relevance values of all the system elements i to j, r'_i to r'_j are compared with the cut-off limit value r_{LCA}. In particular, the system elements are compared one after the other following the modeling hierarchy order (s. §III.6.3.5).

Hereby, it is important to highlight that the defined cut-off limit r_{LCA} is applied to the system elements' relevance values r'_i to r'_j which are calculated when the module is already integrated into the product tree and not on the respective relevance values r_i to r_j when the module is in its initial state. The system element relevance values r'_i to r'_j change according to the module position in the LCI-system.

In black-box modeling the system element relevance values r'_i and r_i are interrelated to each other as given in formulas 41 to 46 (s. §III-6.3.7.1). Thus, in this case the modeling hierarchy order does not change when the module enters into the LCI-system because all the system element relevance values are then changed proportionally (s. also analogy definition and formula 47).

In addition, the module relevance values calculated before and after the module entering in the product tree, R_M and R'_M respectively, are then also proportional to each other as proven below:

Formula 13: $$R_M = \sum_i^j r_i$$

with formula 47 : $$(13) \Rightarrow R_M = \sum_i^j (\alpha * r'_i) \Rightarrow R_M = \alpha * \sum_i^j r'_i$$

$$\Rightarrow R_M = \alpha * R'_M \qquad (52)$$

Thus, it is possible to calculate the cut-off limit r_{limit} score which should be applied on the module's initial form in order for the module cut-off limit value r'_{limit} to be equal to r_{LCA} when the module is afterwards integrated into the LCI-system (s. also figure 30).

Therefore it is used as an example one system element p, which is in the subsystem of a module integrated into the LCI-system and has relevance score r'_p equal to the relevance score of the applied in the subsystem cut-off limit r'_{limit}.

$$r'_p = r'_{limit} \qquad (53)$$

Consequently, the relevance score of the system element p, r_p, which refers to the initial status of the module would be then equal to the respectively applied cut-off limit r_{limit}.

$$r_p = r_{limit} \qquad (54)$$

If this cut-off limit r'_{limit} applied on the module is equal to the cut-off limit r_{LCA} defined for the LCI-system then the module is symmetrically integrated in the product tree.

$$r'_{limit} = r_{LCA} \qquad (55)$$

Now combining formulae 54, 53, 55 and 47 gives us:

$$r'_p = r'_{limit} \quad \Leftrightarrow \quad r'_p = r_{LCA} \quad \Leftrightarrow \quad \frac{r_p}{\alpha} = r_{LCA} \quad \Leftrightarrow \quad \frac{r_{limit}}{\alpha} = r_{LCA}$$

$$\Leftrightarrow \quad r_{limit} = \alpha * r_{LCA} \qquad (56) \quad \text{Analogy formula}$$

Hence, using the analogy formula 56 with the defined cut-off limit of the LCI-system r_{LCA} known, the cut-off limit r_{limit} value which should be applied in order to afterwards have the module symmetrically adjusted in the product tree can be determined.

III-6.3.7.3 Analogy formula validity range

It is important to outline here that the analogy formula 56 as derived before is valid regardless of the numerical value of the analogy α. As given in formulae 48 to 51 the analogy α depends on the module product flow values before and after its integration in the product tree.

If the initial module product flow ${}_{Out}F_M$ (or ${}_{In}F_M$) is larger than the respective one ${}_{Out}f_M$ (or ${}_{In}f_M$) of the integrated module then the initial relevance limit r_{limit} in the module would be higher than the respective limit applied in the product tree r_{LCA} and vice versa:

If ${}_{Out}F_M > {}_{Out}f_M$ or ${}_{In}F_M > {}_{In}f_M$

then analogy (s. formula 48, 49, 50 and 51): $a>1$

Thus, formula 56: $r_{limit} > r_{LCA}$ (57)

Therefore there is no restriction on the value of the module product flow ${}_{Out}F_M$ (or ${}_{In}F_M$) , which is first used to calculate the relevance scores and later to draw the diagram R_M-r_{limit} (as described in figure 29 and in graph 2). The analogy formula 56 is always valid regardless of the module product flow ${}_{Out}F_M$ (or ${}_{In}F_M$) value.

However, the analogy formula as derived in the form of formula 56 is only valid when several system elements are modeled according to the black-box model. In case of functional modeling in formulae 22i and 22ii initially derived parameters of the particular functional model are additionally integrated. Consequently, parameters of the functional model are also integrated then in formulae 27, 28, 32 and 33.

In addition, although in black-box modeling the formulae 22i, 22ii, 27, 28, 32 and 33 are valid for all the system elements of the subsystem this is apparently not the case in functional modeling as different functional models can be applicable for each system element. Furthermore, the modeling hierarchy order may also differ if the relevance values are calculated when the module is first in its initial state (databank) and later in the target state (product tree). Hence, in the case of functional modeling the analogy formula is more complicated then formula 56 which refers to black-box modeling.

III-6.3.8 Module symmetric adjustment algorithm

Here, an algorithm is presented which enables the symmetric adjustment of the module in the product tree. The symmetric adjustment algorithm is built up in 5 steps as presented in the following figure 31 and is based on the relevance models described above (s. §III-6.3.1 to III-6.3.6) and on the analogy formula 56.

Before adjusting the module in the product tree, the practitioner provides to the databank the specific information of the case study. This information concerns the selection of the cut-off criterion, the defined cut-off limit, r_{LCA} and the data of the LCI-system needed for the determination of the normalization factor(s) i.e. S_{LCIx}. Afterwards the relevance models are applied in the databank (formulas 13 to 15), the hierarchical order of the system elements is set, the module relevance values R_M is calculated and the diagram R_M-r_{limit} for a module reference flow ${}_{Out}F_M$ (or ${}_{In}F_M$) is drawn.

These calculations are made once and are used for all positions in which the module is used in one LCI-system. Moreover, these calculations also hold for the alternative LCI-systems investigated in the case of comparative LCAs when the different LCI-systems are modeled symmetrically to one another as described in §III-5.2 (s. also formula 9).

As shown in figure 31, in the first step of the adjustment algorithm, the relevance limit for the module's initial state, r_{limit} is calculated in the databank. Therefore the module product flow through which the module is integrated into the specific position in the LCI-system, ${}_{Out}f_M$ or ${}_{In}f_M$ (s. also figure 30) is given from the practitioner.

Then first the analogy α value is calculated using one of the formulae 48, 49, 50 or 51 according to which cut-off criterion is applied in the LCI-system and through which flow the module is integrated in the product tree. Afterwards, the r_{limit} value is determined implementing the analogy formula 56. The cut-off limit of the LCI-system r_{LCA} value needed in formula 56 is already known to the databank.

1

Calculation of the relevance limit r_{limit} in the module subsystem

$$r_{limit} = \alpha * r_{LCA}$$

r_{limit} :the limit in the module initial status

r_{LCA}: the limit in the LCI-system

analogy: $\alpha = \frac{F_M}{f_M} = \frac{product\ flow\ initial\ status}{product\ flow\ in\ LCI-system}$ or $\alpha = \left(\frac{F_M}{f_M}\right)^2$ according to cut-off limit

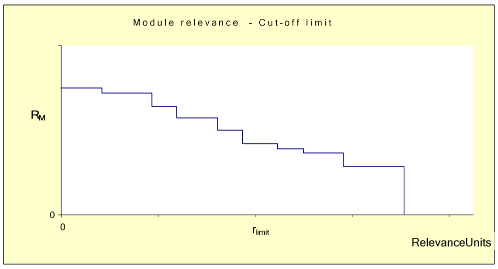
(s. Formulas 48-51)

2

Determination of the module relevance R_M

R_M is specified through the $R_M - r_{limit}$ diagram

r_{limit} value was in step 1 calculated



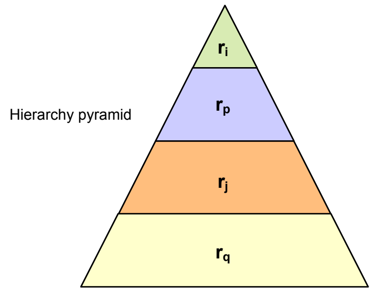
3

Determination of the last included system element

Start aggregate in hierarchical order the system Elements' relevance values until R_M is reached

$$r_i + r_p + ... + r_j = \sum_i^j r_i = R_M$$

identify last included system element j



4

Exclude from the module subsystem the asymmetric data

System elements hierarchically under the last identified system element j are excluded from the module subsystem

5

Module is in ready-to-use form delivered to the practitioner

Figure 31. Module detail level range symmetric adjustment algorithm

In the second step the module relevance score R_M, which should have the module in its initial state in order to afterwards be symmetrically adjusted in the databank is determined. The module relevance value R_M is specified through the R_M – r_{limit} diagram using the r_{limit} value determined in step 1. The r_{limit} value, which was already calculated in step 1 corresponds to the terminus R_M value in the R_M – r_{limit} diagram.

Thereafter, the last included system element of the module subsystem is determined in step 3. Following the system elements hierarchical order, the system elements relevance values r_i are aggregated one after the other until the module relevance R_M score of step 2 is reached. The last system element, which is included in the aggregation is also the last included in the subsystem system element i.e. in figure 31, system element j.

In step 4 asymmetric data of the module is excluded. All the system elements that are under the last included system element j hierarchically are those which form the data asymmetry in the specific position in the product tree. Therefore, these system elements are excluded from the module subsystem. Finally, in step 5, the module is in a ready-to-use state thus it is delivered to the practitioner.

The overall information exchange described between the databank and the practitioner is shown in the next figure 32. Initially, the module is in its generic form. Thereafter the practitioner delivers the general information concerning the modeling of the LCI-system to the databank (i.e. cut-off criterion, cut-off limit and normalization factor data) allowing for the application of the relevance models. In the next phase, the specific information of the module position in the product tree is revealed by the practitioner and the symmetric adjustment algorithm is applied. Finally, the symmetric adjusted module is delivered to the practitioner. In a case of the module being applied in more than one position the last two phases are repeated.

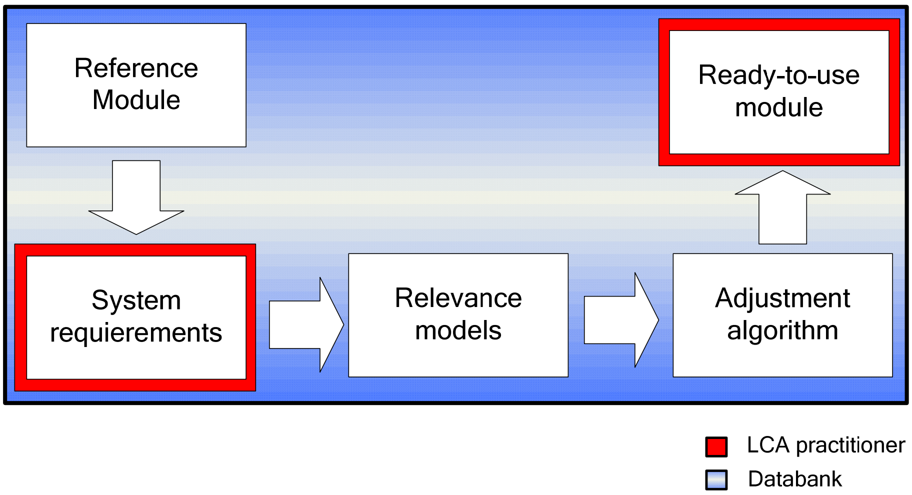


Figure 32. Databank – practitioner interrelation in the multifunctional module application

As a result, using multifunctional modules the practitioner does not need to manually delimit the module subsystem according to the defined cut-off limit as this is now shifted to the databank. The effort of the practitioner is hereby limited in providing the general information concerning the modeling of the LCI-system (i.e. cut-off criterion, cut-off limit and normalization factor data) and the module product flow value of the particular module position. Additionally, using multifunctional modules, the practitioner only acquires data from the databank in an aggregated form. Thus, it is feasible to restrict the public access of the core system element data. Therefore complications caused by reasons of confidentiality could be more easily overcome allowing a potential increase of the data quality handled in the databank.

IV. Multifunctional module performance in a case-study

IV-1. Case-study selection

The symmetric adjustment of modules as evolved in chapter III is performed in the case study of energy production modules. These modules refer in their full detailed version to the cradle-to-gate life cycle inventory of energy production starting from the primary resource exploration and ending in the supply of energy to the national network.

Hereby, the multifunctional energy production modules (also simply referred as e-modules) are evolved and performed in a plethora of positions in a cradle-to-grave modeled product life cycle. The investigation is extended by including the e-module's symmetric adjustment when the LCI-system is modeled using different cut-off criteria. Finally, the e-modules' performance is compared in respect to the environmental relevance result with the performance of the currently applied fixed-modules.

The selection of energy production modules was considered as an appropriate example since these modules are some of the most used system elements in the product system because energy is needed in several life cycle process stages. In addition, the use of generic data in the case of energy production modules is very common [43, 25, 76, 77, 78].

The LCI-system under investigation is drawn out of the LCA phase of the research project Disassembly Factories (Environmental systems engineering department Sonderforschungsbereich (sfb281)) recently carried out by the Technical University of Berlin [79]. In the selected LCI-system, the whole product life cycle of a washing machine was modeled from cradle-to-grave with respect to the ISO 14040 norm series [14, 19]. It should be noted here that though the e-modules adjustments are tested on the application of different cut-off criteria, these cut-off criteria were not further applied to the rest of the LCI-system. The core scope of the case study is to perform the evolved modules functionality. Application of the cut-off criteria on the whole LCI-system does not apparently serve this. Conclusions associated with the comparative assertion taken place in the specific LCA project should be avoided as due to confidentiality reasons the data was converted to anonymous data.

IV-2 Developing the multifunctional energy production modules

The development of the multifunctional energy production modules takes place in two phases. Firstly, the data is collected and the module subsystem modeled while in the next step RUN models are employed in respect to the LCI-system.

IV-2.1 Development of the e-module subsystem

The generic data used is derived from the ETH databank [76, 25, 81, 82]. ETH databank modules were selected because of their wide geographical and technological coverage, their good, transparent documentation protocols and the module subsystem availability.

In addition, the fixed energy production ETH databank's modules were widely used in the modeled LCI-system enabling a direct comparison of the performance of the multifunctional modules (where data asymmetry is prevented) and by the fixed modules (where data asymmetry is generated).

The e-module subsystem is based on the subsystem supplied by the databank for the fixed-modules. The databank module's subsystem is high detailed investigating more than 1500 unit processes and modeled as stated including all possible relevant unit processes [25, 76, 82] without a consistent application of any cut-off criterion. Though the methodological correctness of the subsystem setup could be argued (s. §II-8 Modeling the LCI-system using cut-off criteria), as far as this remains irrelevant for the core e-module operability, the undertaken modeling was not rechecked.

The e-modules subsystem is based on the aforementioned unit process network and consists of system elements which correspond (as far it is adequate) to the life cycle phase of exploration, production, transportation and energy power plant. Thus, the functionality of the e-modules is evolved on a life cycle stage (LCS) level rather than on a unit process level.

It is considered easier to ensure co-equality among life cycle stages than among unit processes. The reason for this is the inherent problem in defining a unit process (as given in §II-3) which also hinders the co-equality determination among unit processes. However, this is not the case for the widely accepted life cycle stages like exploration, primary production, transportation and energy production.

The following figure 33 describes how the system elements for the example of energy production out of oil are formed. The inventory of the subsystem as supplied by the ETH databank [82] is obtained in the first step. Afterwards, analyzing the inventory of the processes contribution unit processes which refer to the different life cycle stages of exploration, production, transportation and energy production are selected and classified (steps 2 to 4). Finally, the e-module system elements are formed by modeling the processes and unifying the data for each of the aforementioned life cycle stages.

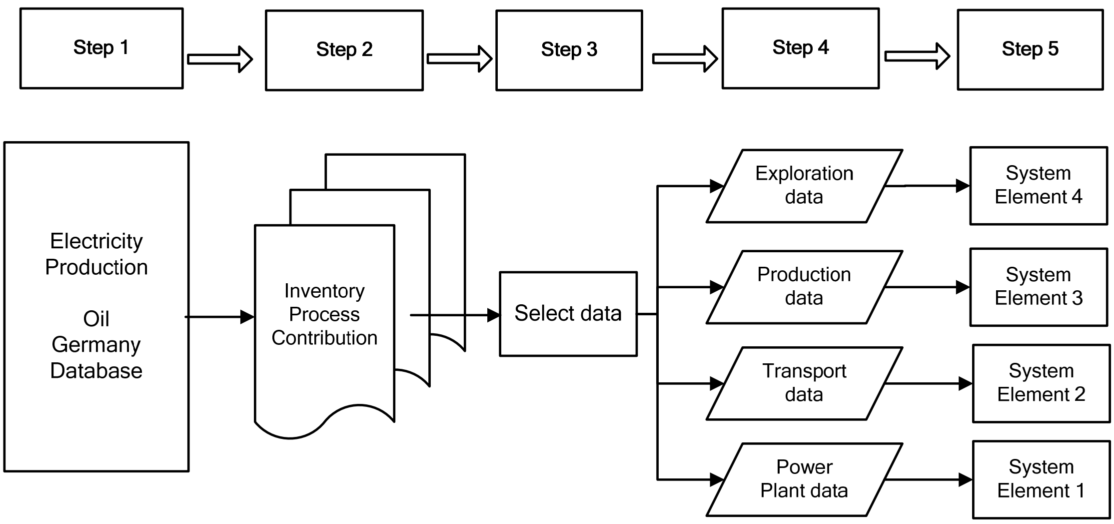


Figure 33. Stepwise system elements development out of fix module data (example of Germany's electricity production out of oil).

The evolved e-module with the highest developed detail level range is the one referring to the European energy mix production (UCPTE mix) investigating the energy mix production of the following 12 countries: Austria, Belgium, Germany, France, Greece, Spain, Switzerland, Portugal, The Netherlands, Ex-Yugoslavia republic, Italy and Luxemburg (figure 34).

Aside from the geographical dimension (figure 33, phase 1) the technological dimension is also investigated (figure 33, phase 2). The investigation covers energy

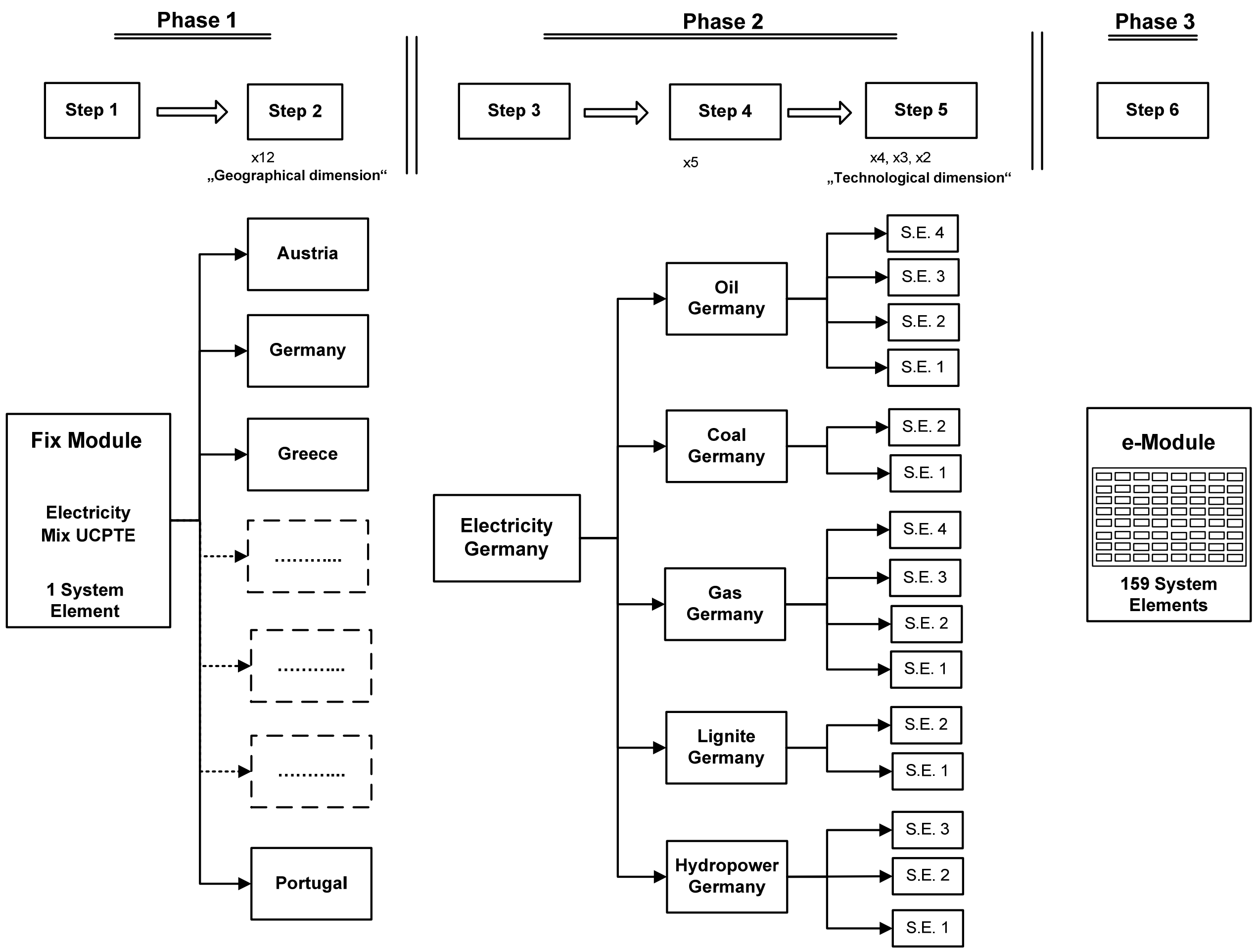


Figure 34. Stepwise e-module subsystem development out of fix module

production from oil, coal, gas, lignite and hydropower. For oil and coal the subsystem can be divided, as shown in figure 33, into four system elements each referring to the life cycle stage of exploration, production, transportation and power plant. For energy production from coal and lignite it is appropriate to separate the LCI network into two parts. The first includes mining and production and the second refers to the energy power plant. Similarly, for hydropower distinguishing the energy production gained from a flowing water hydropower plant, pumping storage hydropower plant and reservoir hydropower plants is appropriate.

It is important to highlight here that at this phase the system elements which refer to transportation processes are characterized as *pseudo system elements* since they are not involved in the modeling decision flow chart (figure 9) as analyzed in §III-6.3.5.

The final high-detail e-module subsystem consists of 159 system elements. The other similarly modeled e-modules differ from the high-detail one in phase 1 (figure 34) in which geographical coverage is restricted to one or two countries. In all developed e-modules the modeled process data additionally went through a consistency control and validation algorithm with the respective databank data (s. also appendix 12).

IV-2.2 Employment of RUN models

At this phase the relevance score of the selected relevant substances r_{iSx} per system element is calculated (formula 15), as well as the relevance score of the module system elements r_i (formula 14) and the e-module relevance score R_M (formula 13).

The selected and applied cut-off criteria are:

- the elementary cut-off criterion 4 in the b version and
- the environmental impact cut-off criterion 7 in the a version.

The environmental impact categories investigated in cut-off criterion 7 are:

- the human toxicity,
- the summer smog
- the ecotoxicity.

The environmental impact assessment (LCIA) method applied in the case-study project [79] was the CML 2000 [12] investigating the following environmental impact categories:

- Human toxicity
- Ecotoxicity
- Eutrophication
- Global warming
- Ozone depletion
- Summer smog
- Acidification

The relevance substance list investigated in the cut-off criteria is given in table 1 and covers up to 100 substances which were determined from the detail level depth substance list. The detail level depth substance list was set through the applied environmental impact method (s. figure Ap.8-1 in appendix 8). The determination of the relevant substance list was primarily based on the substance environmental relevance.

Furthermore, the selection was aided by the rate of reoccurrence among the system elements and the data reliability.

Table 1. Relevant substance list set

Nr.	Medium	Substance	Nr.	Medium	Substance	Nr.	Medium	Substance
1	Air	1,2-dichloroethane	35	Air	H_2S	69	Water	Cd
2	Air	acetaldehyde	36	Air	HALON-1301	70	Water	chlorobenzenes
3	Air	acetone	37	Air	HCl	71	Water	Co
4	Air	acrolein	38	Air	heptane	72	Water	COD
5	Air	aldehydes	39	Air	HF	73	Water	Cr (VI)
6	Air	alkanes	40	Air	Hg	74	Water	Cu
7	Air	ammonia	41	Air	methane	75	Water	C_xH_y
8	Air	As	42	Air	methanol	76	Water	C_xH_y aromatic
9	Air	Ba	43	Air	Mn	77	Water	cyanide
10	Air	benzaldehyde	44	Air	Mo	78	Water	dichloroethane
11	Air	benzene	45	Air	N_2O	79	Water	ethyl benzene
12	Air	benzo(a)pyrene	46	Air	Ni	80	Water	Fe
13	Air	Br	47	Air	non methane VOC	81	Water	fluoride ions
14	Air	butane	48	Air	NO_x (as NO_2)	82	Water	Hg
15	Air	butene	49	Air	P	83	Water	Kjeldahl-N
16	Air	Cd	50	Air	PAH's	84	Water	Ni
17	Air	CFC-11	51	Air	Pb	85	Water	nitrate
18	Air	CFC-116	52	Air	pentane	86	Water	N-tot
19	Air	CFC-12	53	Air	phenol	87	Water	PAH's
20	Air	CFC-14	54	Air	propane	88	Water	Pb
21	Air	CO	55	Air	propene	89	Water	phenols
22	Air	CO2	56	Air	propionic acid	90	Water	phosphate
23	Air	cobalt	57	Air	Sn	91	Water	P-tot
24	Air	Cr	58	Air	SO_x (as SO_2)	92	Water	Sb
25	Air	Cu	59	Air	toluene	93	Water	Sn
26	Air	C_xH_y aromatic	60	Air	V	94	Water	SO_3
27	Air	cyanides	61	Air	vinyl chloride	95	Water	sulphates
28	Air	dioxin (TEQ)	62	Air	xylene	96	Water	toluene
29	Air	ethane	63	Air	Zn	97	Water	tributyltin
30	Air	ethanol	64	Water	alkenes	98	Water	trichloroethene
31	Air	ethene	65	Water	AOX	99	Water	xylene
32	Air	ethylbenzene	66	Water	As	100	Water	Zn
33	Air	ethyne	67	Water	Ba			
34	Air	formaldehyde	68	Water	benzene			

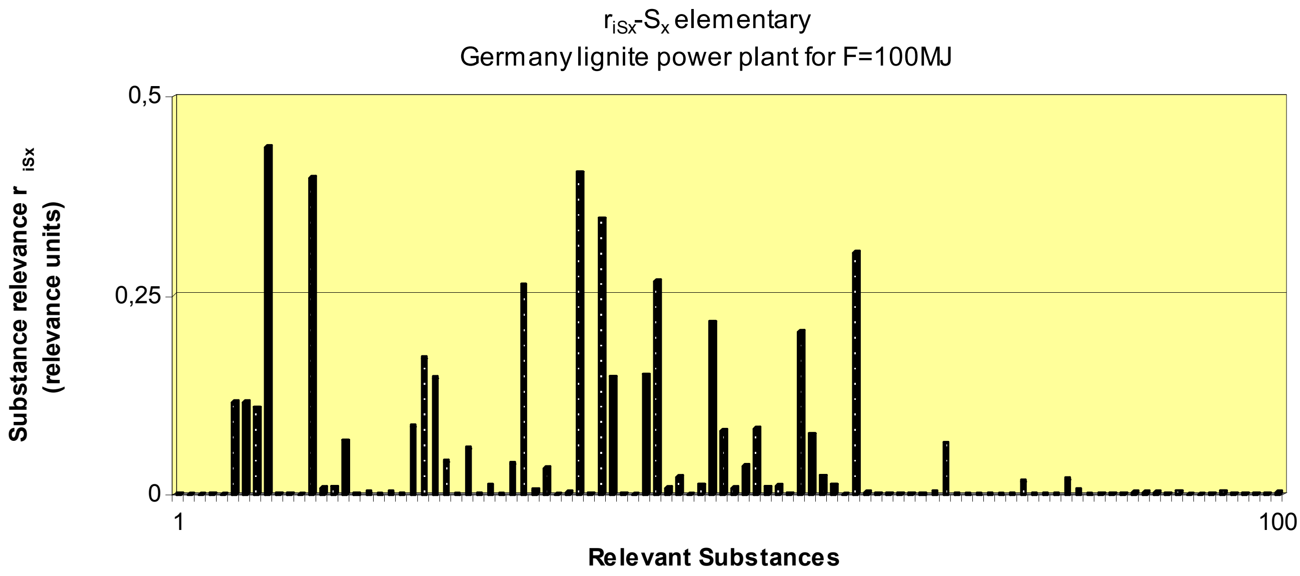
Following the application of the RUN models as described in figure 27 (s. §III.-6.3.3) the respective normalization coefficients are determined. The mass-normalization coefficient, $_{m}n_{Sx}$ is calculated using formula 17. The substances mass values (S_{LCIx}) referring to the LCI-system in particular were taken from the initial modeled in the project data [79]. Here, it should be noted that these values should normally be evaluated after implementation of the modules and recalculated if necessary (s.§ III-3.2.2.1 and III-6.3.2). However, for the needs of the operability verification of the developed multifunctional modules, this was not considered a necessity.

On the other hand, the environmental impact normalization coefficients for each impact category investigated, $_{ht}n_{ISx}$, $_{ssm}n_{ISx}$, and $_{ec}n_{ISx}$ are calculated utilizing formula 14. The calculations of the substance mass values, S_x are based on a reference module output product flow, $_{Out}F_M$, equal to 100 MJ of electricity.

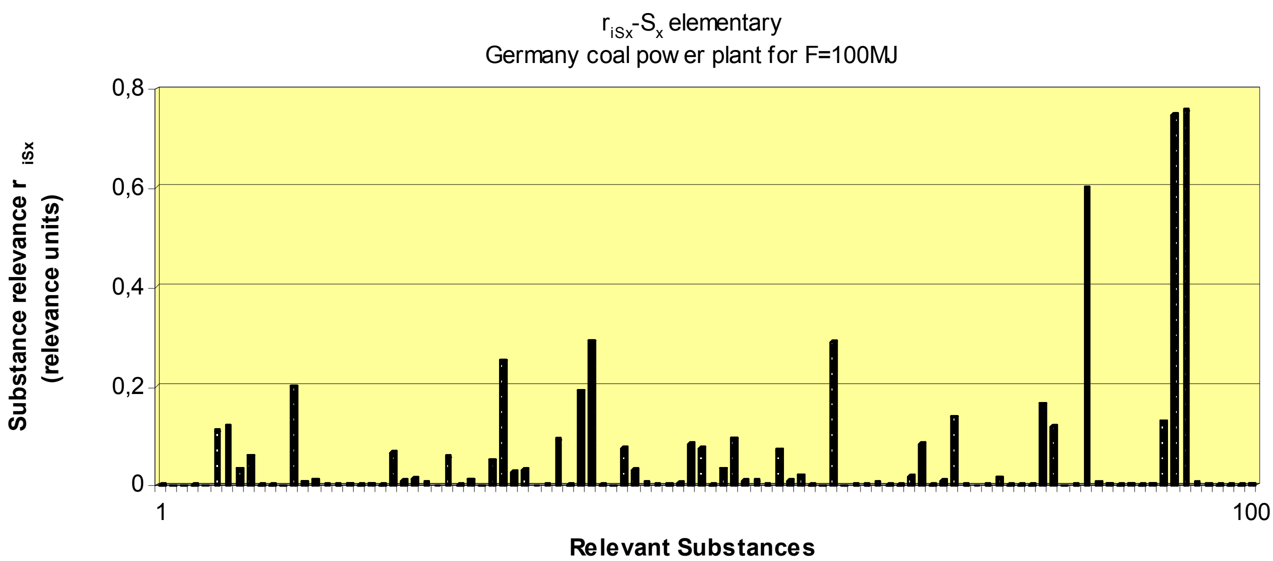
Thereafter the normalization factor N_x for both the elementary cut-off criterion and the environmental impact cut-off criterion is calculated using formula 16. In a next step the substance relevance value r_{iSx} implementing formula 15 is calculated for each system element. r_{iSx} – S_x graphs are then drawn based on the substance relevance values.

Examples are given here in the graphs 3, 4 and 5. On the x axis of these graphs the relevant substances are marked (see relevant substance list on table 1) while the y axis shows their respective relevance values. The relevance units are calculated referring to the elementary cut-off criterion. Graph 3 refers to the system element describing the lignite electricity power plants in Germany while graphs 4 and 5 refer respectively to the coal electricity power plants in Germany and Austria. Investigating the graphs 3, 4 and 5 major differences among the substance relevant scores can be observed. This is normal as the emission of each substance differs in each system element.

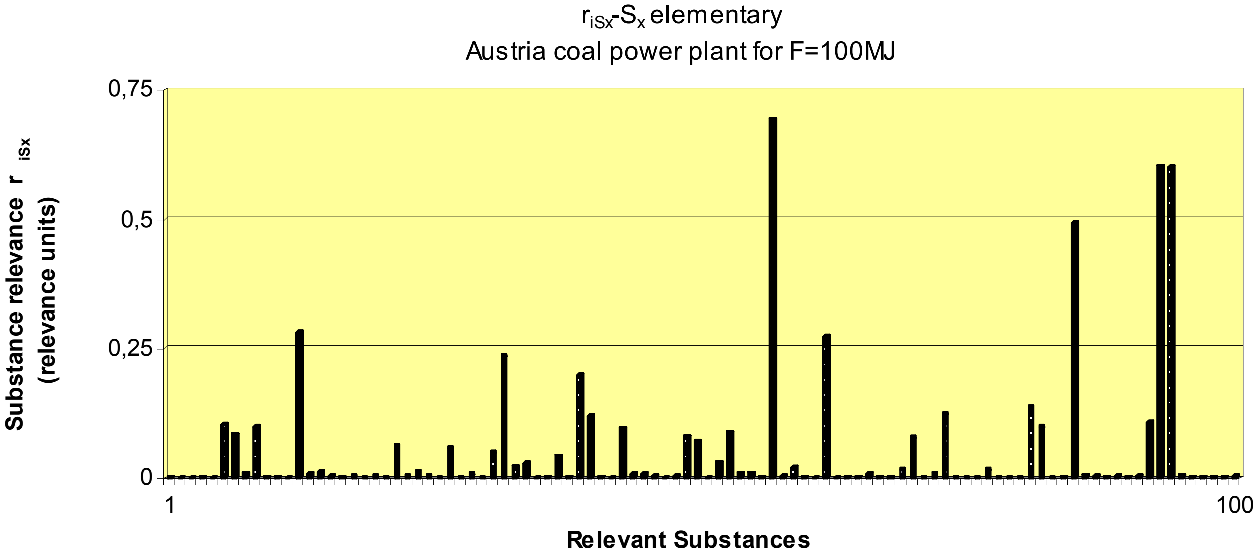
However, the degree of difference among the relevant substance's scores detected in these system elements denotes the importance of the selection of relevant substances. In case of a short substance list several relevant substances scores r_{iSx} would be excluded in the resultant calculation for the respective system element relevance score r_i. This would result in increasing the risk of a low correspondence between the system element relevance score r_i and its respective environmental significance.



Graph 3. Distribution of substance relevance unit scores (r_{iSx}) among the investigated relevant substances (S_x) for the system element of Germany's lignite electricity power plant production. Reference product flow is: F=100MJ.

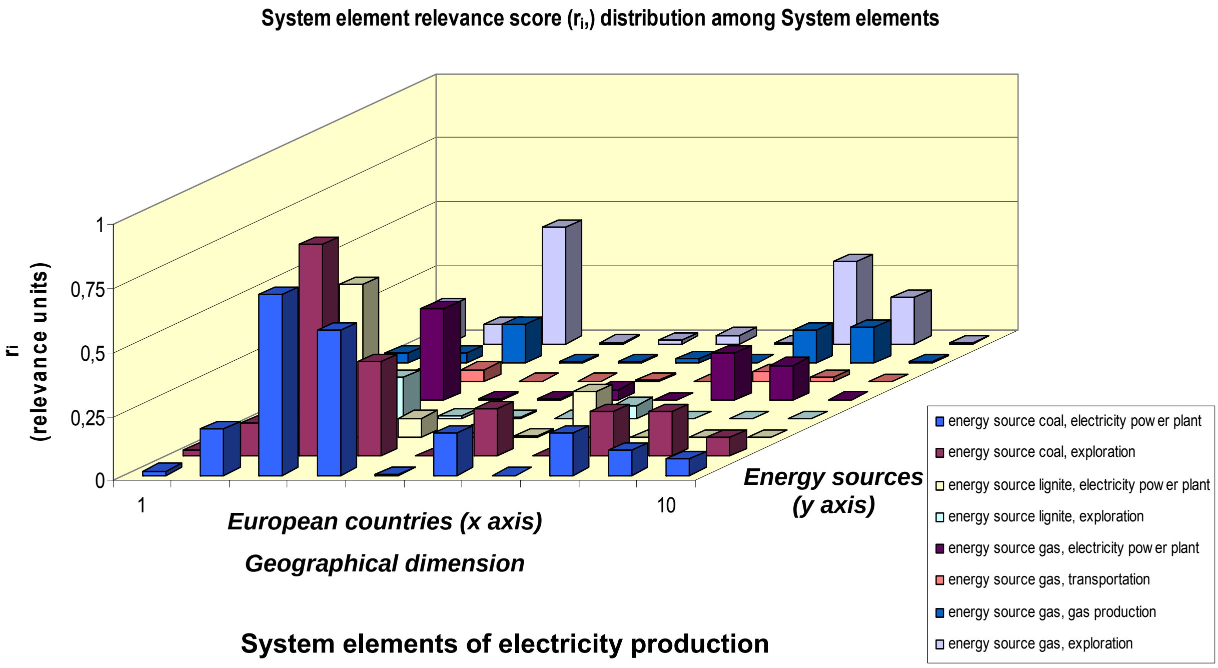


Graph 4. Distribution of substance relevance unit scores (r_{iSx}) among the investigated relevant substances (S_x) for the system element of the German coal electricity power plant production. Reference product flow is: F=100MJ.



Graph 5. Distribution of substance relevance unit scores (r_{iSx}) among the investigated relevant substances (S_x) for the system element of the Austrian coal electricity power plant production. Reference product flow is: F=100MJ.

In the next step, the relevance values of the system elements are calculated using formula 14. In the following graph 6, an example of the distribution of the relevance values r_i among several system elements for the application of the elementary cut-off criterion is shown. Each peak corresponds to the relevance score of a system element (z axis). Additionally, the system elements are sorted according to their geographical dimension (x axis). The y axis shows the life cycle phases for electricity production when using coal, lignite and gas as energy sources (as analyzed in figure 34).



Graph 6. Distribution of the system elements relevance unit scores (r_i) (calculated for the elementary cut-off criterion 4b). These system elements build up the multifunctional module subsystem referring to the electricity production mix for Europe. Reference product flow is: F=100MJ.

Before reaching the final step where the module relevance values are calculated, the system elements modeling hierarchy is determined using formula 13. As analyzed in § III-6.3.5 in the system elements modeling hierarchical order, a pseudo system element has the same position as the system element to which it is directly interconnected and which encloses it in the production chain. In this particular investigation, all the system elements of the module subsystem referring to transportation phases were characterized as pseudo system elements. Table 2 shows the hierarchical order determined for the system elements of the German electricity production mix module when applying the elementary cut-off criterion. The hierarchy of all the employed multifunctional modules is developed in a similar way (s. also III-6.3.5 Hierarchy of system elements).

Table 2. Hierarchical order of system elements for the e-module electricity production mix Germany applying the elementary cut-off criterion 4b

System Element (S.E.)*	Relevance score, r_i	Downward r_i order		**Hierarchical Modeling Order**	
		Position	S.E.	**Position**	**S.E.**
1D	0,0214	1	2D	**1**	1D and 2D
2D	0,0250	2	1D	**2**	3D
3D	0,0187	3	3D	**3**	8D
4D	4,96E-03	4	8D	**4**	4D
5D	9,02E-05	5	4D	**5**	11D and 11.1D
6D	1,37E-03	6	11D	**6**	12D
7D	7,18E-07	7	12D	**7**	8.1D
8D	0,01090	8	10D	**8**	6D
8.1D	0,00155	9	8.1D	**9**	9D and 10D
9D	0,00053	10	6D	**10**	13D
10D	0,00158	11	9D	**11**	5D
11D	0,00447	12	13D	**12**	7D
11.1D	0,00022	13	11.1D		
12D	0,00235	14	5D		
13D	0,00049	15	7D		

* The acronyms of the system elements are given in the appendix 13

The modeling hierarchical order of a module changes when different cut-off criteria are applied. For comparison, table 3 shows, the different hierarchical modeling orders for the investigated case of Germany's electricity production mix when different cut-off criteria are applied.

Furthermore, following the modeling hierarchical order the module relevance score for each cut-off criterion is calculated implementing formula 13 as shown in figure 29. Thus, the (R_M, r_{limit}) pair values which correspond to the step peaks in the R_M-r_{limit} diagram are determined and then used for the R_M-r_{limit} diagrams. In graphs 7, 8 and 9 the R_M-r_{limit} diagrams are given for the developed electricity mix production module for Germany.

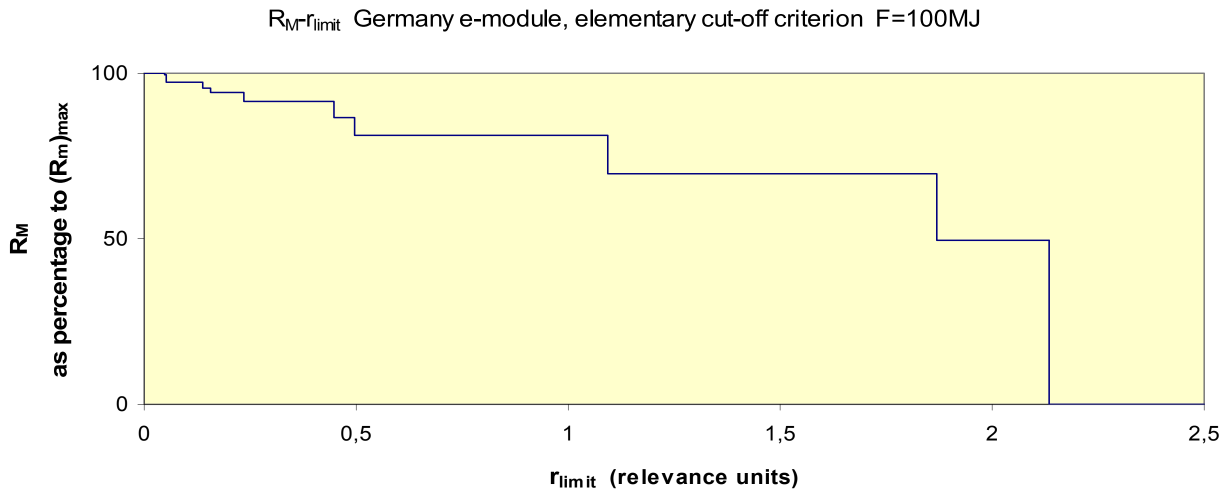
The module relevance R_M score is expressed as a percentage of the maximum module relevance score $(R_M)_{max}$ which is reached when no system element is cut-off. Graph 7 corresponds to the relevance calculation utilizing the elementary cut-off criterion score.

On the other hand, graphs 8 and 9 refer to the environmental impact cut-off criterion normalized to the categories of summer smog and human toxicity respectively (the correlating R_M-r_{limit} diagram for ecotoxicity is given in appendix 14).

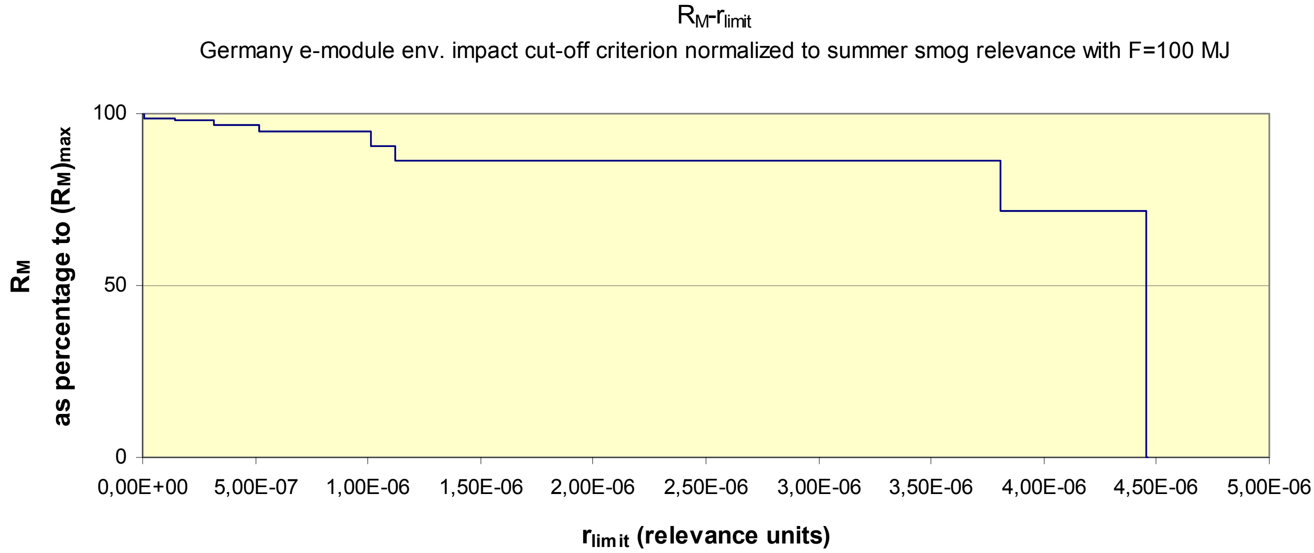
Table 3. Differences in the system elements hierarchical modeling order for German electricity production mix applying the elementary cut-off criterion 4 and the environmental cut-off criterion 7.

Hierarchical Modeling Order	**Elementary cut-off criterion 4b**	**Env. Impact cut-off criterion 6b**		
		Human tox.	**Ecotox.**	**Sum. Smog**
Position	**S.E.**	**S.E.**	**S.E.**	**S.E.**
1	1D and 2D	3D	1D and 2D	1D and 2D
2	3D	1D and 2D	8D	3D
3	8D	11D and 11.1D	3D	8D
4	4D	8D	4D	11D and 11.1D
5	11D and 11.1D	4D	11D, 11.1D, 12D	12D
6	12D	12D	6D	4D
7	8.1D	8.1D	8.1D	8.1D
8	6D	6D	9D and 10D	13D
9	9D and 10D	9D and 10D	13D	6D
10	13D	13D	5D	9D and 10D
11	5D	5D	7D	5D
12	7D	7D		7D

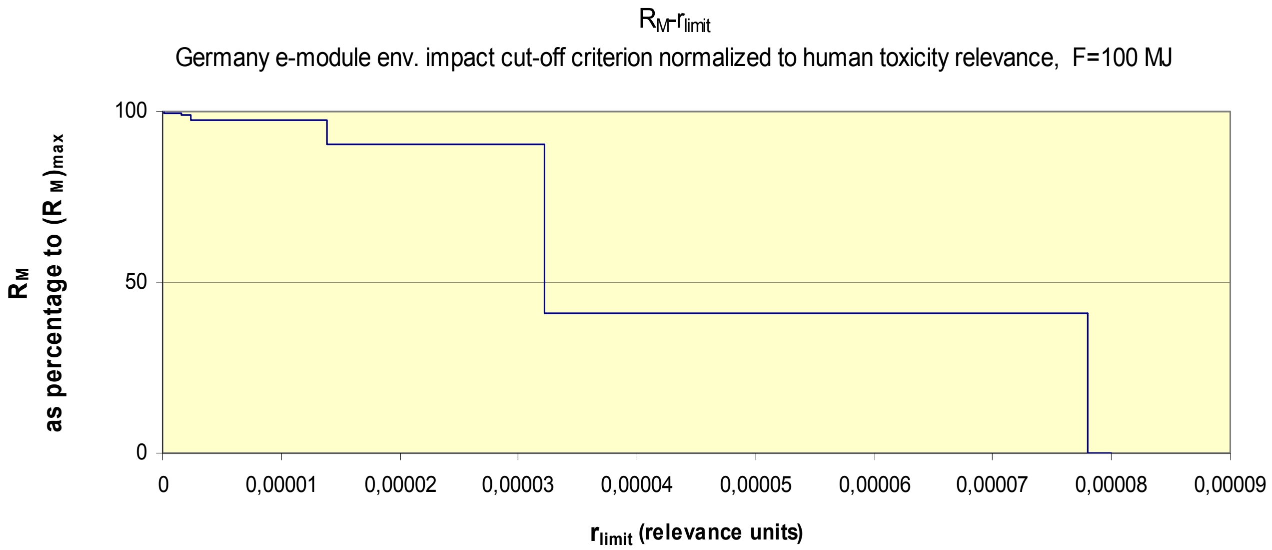
[*] The acronyms of the system elements are given in appendix 13



Graph 7. Module relevance (R_M) to cut-off limit (r_{limit}) diagram for the e-module referring to the electricity mix of Germany. The relevance is calculated referring to the elementary cut-off criterion 4b (for both R_M and r_{limit} relevance units) where reference product flow is F=100MJ.



Graph 8. Module relevance (R_M) to cut-off limit (r_{limit}) diagram for the e-module referring to the electricity mix of Germany. The relevance is calculated referring to the environmental impact cut-off criterion 7a normalized for the category of summer smog (for both R_M and r_{limit} relevance units). The reference product flow is F=100MJ.



Graph 9. Module relevance (R_M) against cut-off limit (r_{limit}) diagram for the e-module referring to the electricity mix of Germany. The relevance is calculated with respect to the environmental impact cut-off criterion 7a normalized for the category of human toxicity (for both R_M and r_{limit} relevance units). The reference product flow is: F=100MJ.

IV-3. Multifunctional modules performance.

Similarly the respective R_M-r_{limit} diagrams are drawn for the highly-detailed e-module referring to the European mix of electricity production (s. appendix 14). All the calculations are based on a reference product output flow F equal to 100MJ.

Firstly the positions of the LCI-system where the fix energy modules will be replaced by the multifunctional ones are identified. In this case, there are 14 positions spread both in the pre-consumption and in post consumption product life cycle phase as given in table 4.

The cut-off criteria limits are defined as followed:

- elementary cut-off criterion: r_{lca} = 0,03 relevance units (referring to the aggregated percentage of the emitted substances' masses).

- environmental impact cut-off criterion limit

per environmental impact category:

for ecotoxicity: ${}_{ec}r_{lca}$ = 0,53 relevance units (refers to ecotoxicity, ECA m^3 mg)

for human toxicity: ${}_{ht}r_{lca} = 5 * 10^{-8}$ relevance units (refers to human toxicity, HCl/HCW)

for summer smog: ${}_{ss}r_{lca}$ = 0,55 relevance units (refers to summer smog, POCP kg)

It is important to outline here that in case of the environmental impact category, a system element is cut-off only if its score is below the respective set limit in all the investigated impact categories.

Table 4. Positions in the product life cycle where the evolved electricity multifunctional modules replace the fix electricity production modules.

Position Nr.	Module	Demand f in MJ	Connected to System Element
1	Electricity Germany mix	1,66 MJ	Cold transforming/Laugenp.
2	Electricity Germany mix	1,46 MJ	Injection moulding/Einspüls.
3	Electricity Germany mix	1,59 MJ	Cold transforming/ Kompon.
4	Electricity Ucpte mix	12,0 MJ	Steel sheet / Vorderwand
5	Electricity Ucpte mix	9,39 MJ	Train transportation
6	Electricity Ucpte mix	6,20 MJ	Spanplatte/Versteifungsblech
7	Electricity Ucpte mix	5,77 MJ	Kfz Weisse-Ware-Schrott
8	Electricity Ucpte mix	4,83 MJ	Cold transforming/Trommel
9	Electricity Ucpte mix	4,60 MJ	Cold transforming/Gehäuse
10	Electricity Ucpte mix	4,37 MJ	Cold transforming/Motor
11	Electricity Ucpte mix	2,69 MJ	Aluminium/ Riemenscheibe
12	Electricity Ucpte mix	2,48 MJ	Steel sheet / Laugenpumpe
13	Electricity Ucpte mix	2,44 MJ	Cold transforming/Steuerrung
14	Electricity Ucpte mix	2,30 MJ	Cold transforming/Laugenbeh.

IV-4 Symmetric adjustment algorithm

At this phase, the presented in figure 31 algorithm for each investigated position of the LCI-system is strictly followed. In the first step the analogy α value is calculated for each position using:

- formula 48 for elementary cut-off criterion
- formula 50 for environmental impact cut-off criterion

Afterwards, the analogy formula 56 is used to calculate the r_{limit} value which referrs to the product outflow of $_{Out}F_M$=100 MJ on which the R_M-r_{limit} diagrams were based. In the next step, the module relevance value R_M is specified using the respective R_M-r_{limit} diagram.

Finally, with the system elements modeling hierarchy order known and employing formula 13, the system element relevance values are aggregated in hierarchical order. The last included system element j is identified when the previously determined module relevance R_M score is reached.

The system elements which are subordinated to the last included system element are then excluded from the module subsystem and the multifunctional module is integrated in the LCI-system.

IV-5 Results comparison

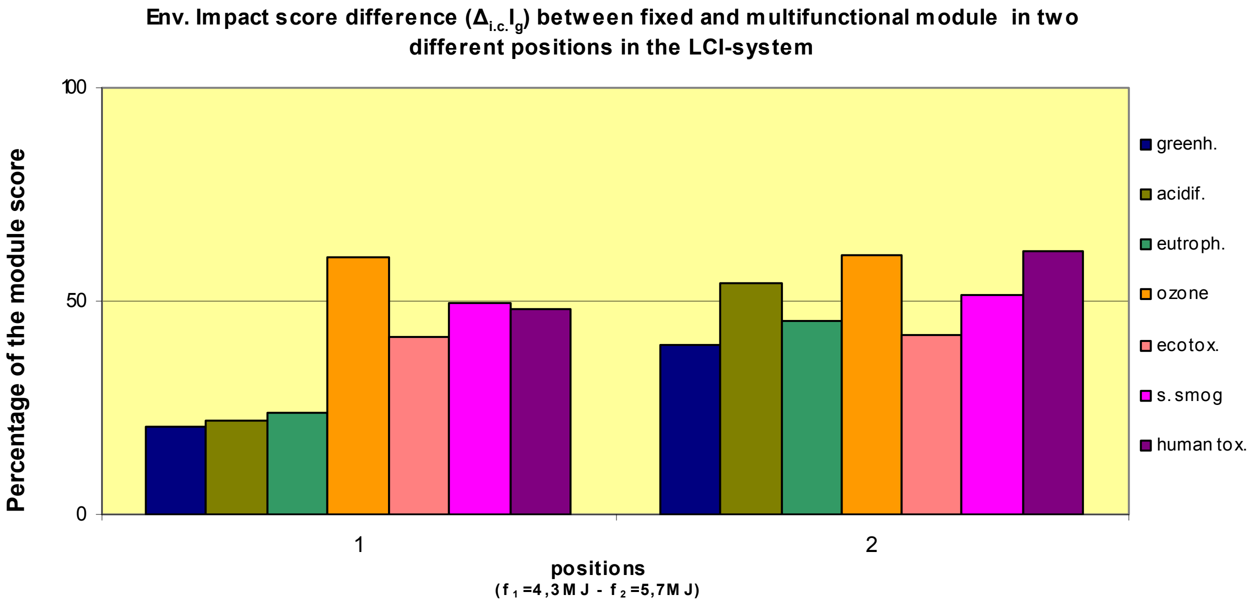
In the beginning, the environmental impact of the fixed and multifunctional electricity modules is calculated for each position of the LCI-system. Thereafter the difference between the fixed and multifunctional module is calculated for each position g, with regard to their environmental impact score, $\Delta_{i.c}I_g$ using the following formula (57).

$$\Delta_{i.c.}I_g = ({}_{i.c.}I_g)_{fix} - ({}_{i.c.}I_g)_{mult} \qquad (57)$$

Where: $\Delta_{i.c.}I_g$: difference in the environmental impact indicator result between fix and multifunctional module in position g for impact category i.c.
$({}_{i.c}I_{g.})_{fix}$: environmental impact indicator result of category i.c. for the fixed module
$({}_{i.c}I_g)_{.multi}$: environmental impact indicator result of category i.c. for the multifunctional module
i.c. : environmental impact category acronym

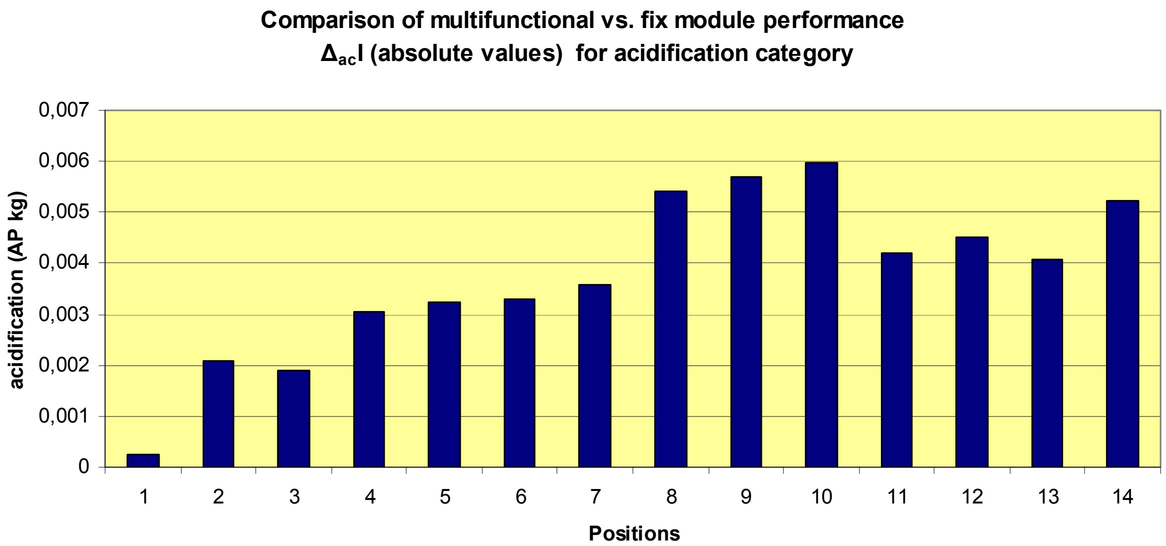
This difference $\Delta_{i.c.}I_g$ is caused by the asymmetrical data, which is found in fixed modules while not present in multifunctional modules.

In graph 10 for the case of elementary cut-off criterion, the $\Delta_{i.c.}I_g$ values of all the investigated environmental impact categories are shown when the multifunctional module replaces the fixed one in two different positions. The environmental impact scores of the several impact categories are expressed as a percentage of the respective score of the fixed module. In graph 10 the product output flow is f_1=4,3 MJ for the first position whereas f_2=5,7 MJ for the second.

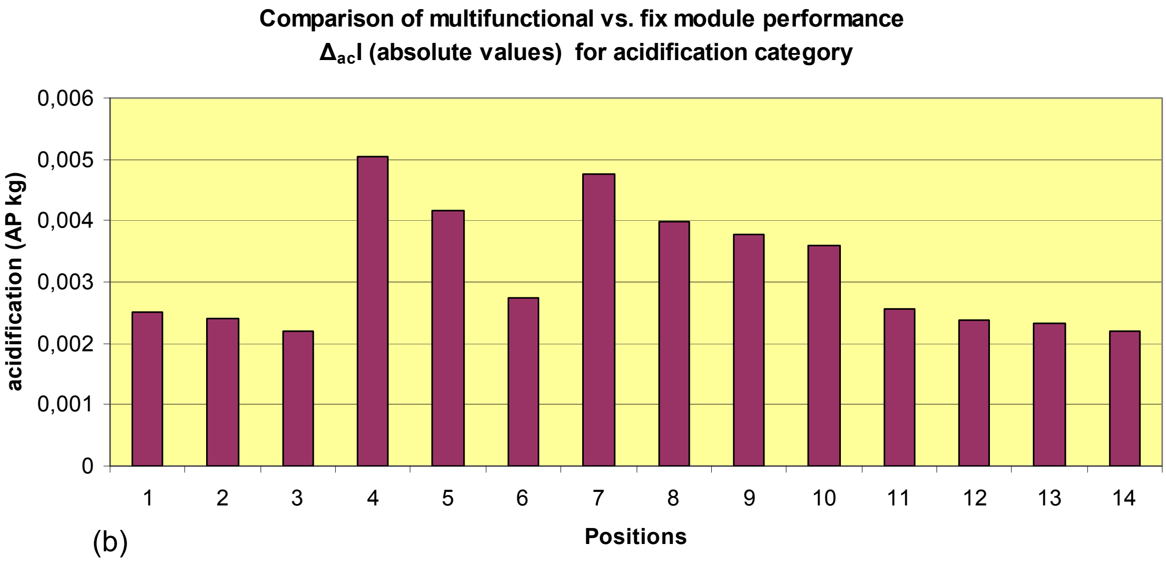


Graph 10. The difference $\Delta_{i.c.}I_g$ refers to the environmental impact score when the fixed module is replaced by the multifunctional one in two different positions. In the first position the product output flow is f_1=4,3 MJ whereas in the latter it is f_2=5,7 MJ.

In each of the environmental category, the performance difference between the fixed and multifunctional module varies for each position and each cut-off criterion. Thus, the ($\Delta_{i.c}I_g$ – module position) graphs can be calculated and drawn, as in graph 11 which is found below. Graph 11a refers to the performance difference $\Delta_{i.c}I_g$ in the environmental impact category of acidification in the case of the elementary cut-off criterion whereas graph 11b for the case of the environmental impact cut-off criterion. Similar results are given for all investigated impact categories for both cut-off criteria in appendix 15.



(a)



(b)

Graph 11. Performance difference between the multifunctional adjusted modules and the fix modules per position per environmental impact category (a) for the case of elementary cut-off criterion and (b) for the case of the environmental impact cut-off criterion.

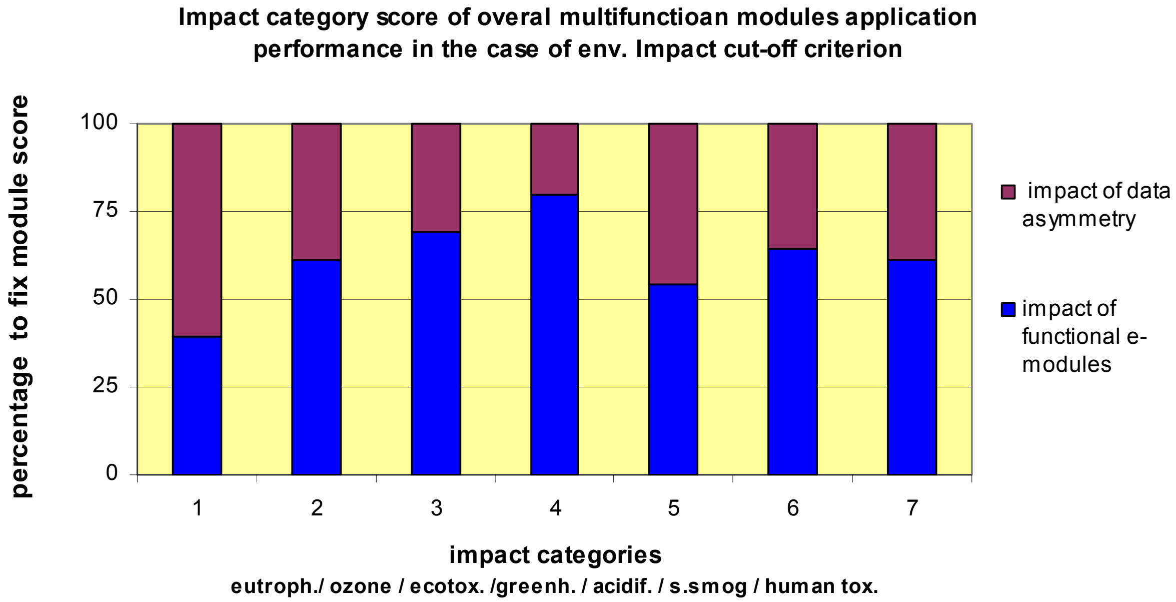
Finally, the overall performance difference (graphs 12 and 13) between the fix module and the multifunctional module is determined with respect to their environmental impact scores for all positions g to h where the e-modules are performed by applying formula (58).

$$\Delta_{i.c.}I = \sum_{g}^{h}((_{i.c.}I_g)_{fix} - (_{i.c.}I_g)_{mult}) \tag{58a}$$

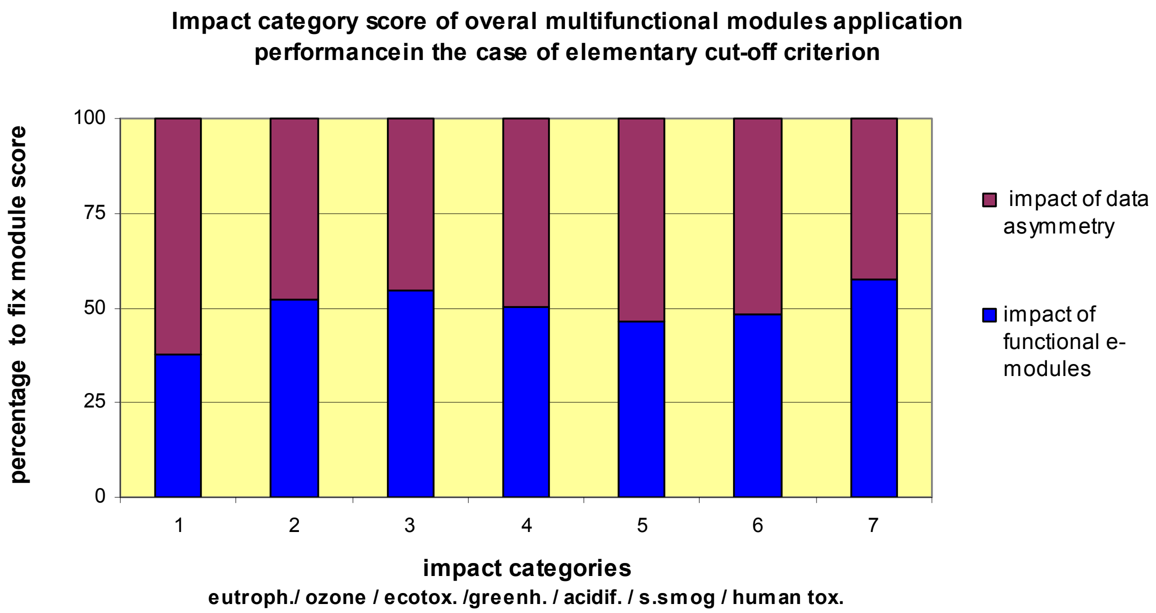
or $$\Delta_{i.c.}I = \sum_{g}^{h} {}_{i.c.}\Delta I_g \tag{58b}$$

Where: $\Delta_{i.c.}I$: overall difference in the environmental impact score between fix and multifunctional module for all the applied positions g to h for impact category i.c.
$\Delta_{i.c.}I_g$: difference in the environmental impact indicator result between fix and multifunctional module in position g for impact category i.c.
$(_{i.c}I_{g.})_{fix}$: environmental impact score of category i.c. for the fixed module
$(_{i.c}I_g)_{.multi}$: environmental impact score of category i.c. for the multifunctional module
i.c. : environmental impact category acronym

The results are again expressed as a percentage of the respective per-category environmental impact score of the fixed module. Graph 12 refers to a case in which the environmental impact cut-off criterion is applied while graph 13 is a case where the elementary cut-off criterion has been applied. It should be noted here that these percentage values refer to the aforementioned 14 positions (s. table 4) of the case study's LCI-system. If the application of the e-modules were to be extended to the complete LCI-system the absolute percentage values of graphs 12 and 13 may vary as there could then be found positions in which the $\Delta_{i.c.}I_g$ reaches certain threshold values i.e either very few system elements or almost all system elements being discarded.



Graph 12. The overall difference of the performance of the multifunctional e-modules in respect to the environmental impact score per category when the environmental impact cut-off criterion (for all the applied positions in the LCI-system) is applied. The environmental impact score is expressed as a percentage of the respective score of the fixed modules.



Graph 13. The overall difference between the performances of the multifunctional e-modules with respect to the environmental impact score per category when applying the elementary cut-off criterion (for all the applied positions in the LCI-system) and the fixed modules. The environmental impact score is expressed as a percentage of the respective score of the fixed modules.

IV-6 Results and discussion

In the current case-study, the application of the evolved multifunctional electricity production modules in several positions of the particular product life cycle proved successfully enabling their comparison with state-of-the-art fixed modules currently used.

In particular, for the 14 positions in which the e-modules were performed, their overall environmental impact score showed an average reduction per environmental impact category of approximately 50% when using the elementary cut-off criterion and 40% for the environmental impact cut-off criterion (see also graphs 12 and 13).

These reduced overall environmental impact scores of the e-modules result from the prevention of the generation of data asymmetry. This was achieved with the application of the cut-off criterion on the system elements of the module subsystem.

In particular, the overall maximum reduction was detected for both investigated cut-off criteria 4 and 7 in the environmental impact category of eutrophication reaching 62% and 60% respectively. On the other hand, the lowest reduction was found for using the elementary cut-off criterion for the human toxicity category with 43% and 20% respectively for the environmental impact cut-off criterion in the environmental impact category of global warming.

This significant overall average performance difference of multifunctional modules versus fixed ones denotes that the usage of data-symmetric adjustable modules is very important for the enhancement of the reliability of the LCA’s final results.

However, how far the data asymmetry influences the final LCI and thereafter the LCA results is not predictable. To which extent the application and replacement of fixed modules by multifunctional ones changes the final LCA outcomes is definitely case-specific. Generalization and prognosis in the context of the performance of other multifunctional modules which do not refer to the production of electricity is also not possible though it is considered to be analogous.

Investigating ($\Delta_{i.c}I_g$ – module position) results like graph 11 (s. also full graph series in appendix 15) it is worth it to point out that among the several environmental impact categories the maximum reduction cannot be located on a single position. This finding applies for both of the studied cut-off criteria and indicates the existence of controversial affecting parameters.

The performance difference $\Delta_{i.c}I_g$ between the e-modules and fixed ones in terms of absolute values of the environmental impact scores varies:

- between the two cut-off criteria
- among the several positions in which the module is applied in the LCI-system
- among the several environmental impact categories

The selection of the cut-off criterion and its respective cut-off criterion limit determines which of the system elements should be cut-off. The lower the cut-off limit value, r_{LCA} is the higher is the number of the module system elements.

In the current case study, it was confirmed that when different cut-off criteria are applied the resultant overall environmental impact calculated for the module subsystem is different. This is also supported by other researches, although concerning the most of the times overall results of the LCI-system [22, 57, 45]. For instance the system element 8D referring to gas electric power plants in Germany is always cut-off from the e-module's subsystem for all the studied 14 positions of the LCI-system when the symmetrical adjustment is based on the implementation of the elementary cut-off criterion.

However, when the respective symmetric adjustment is based on the application of the environmental impact cut-off criterion, the same system element 8D (gas electric power plant production in Germany) is not cut-off due to its relatively considerable contribution to the environmental impact category of ecotoxicity. As stated in the environmental impact cut-off criterion, a system element is excluded only if it does not reach the respective cut-off criterion limit in all of the criterion's investigated impact categories (for this case study it is human toxicity, ecotoxicity and summer smog s. §IV-2.2).

Furthermore, the expected performance difference in terms of the overall environmental impact scores of the multifunctional modules for all the positions per category between the two cut-off criteria the elementary criterion 4 and the environmental impact criterion 7 is also verified. In table 5, the overall environmental impact scores of the multifunctional modules are given and are expressed as a percentage of the respective score of the fixed modules (also show in graphs 12 and 13).

The differences between the cut-off criteria have an overall average of 12% with a maximum difference of 29,7% found in the human toxicity category. The minimum difference is found in the eutrophication category with a value of 1,7%. These differences among the impact category scores are also case study-specific. They depend not only on the selected cut-off criteria but also on the respective cut-off limits defined, thus they should not be generalized. Nevertheless, these differences signify the major importance of the selection of cut-off criterion. Moreover, investigations and comparisons of product systems which are modeled with different cut-off criteria should be avoided due to lack of comparability.

Table 5. Overall performance difference of the e-modules between the elementary cut-off criterion 4 and the environmental impact cut-off criterion 7. The overall environmental impact score of the multifunctional modules (for all the positions in the LCI-system) is expressed as a percentage of the respective overall score of the fixed module.

	Impact category	Overall impact of the multifunctional modules expressed as $(_{i.e.}I)_{mult} / (_{i.e.}I)_{fix}$ % Elementary Cut-off Criterion 4	Env. Impact Cut-off Criterion 7	Difference
1	Eutrophication	37,9	39,6	1,7
2	Acidification	46,5	54,5	8,0
3	Summer smog	48,3	64,6	16,3
4	Global warming	50,0	79,7	29,7
5	Ozone layer depl.	52,2	61,2	9,0
6	Ecotoxicity	54,8	69,0	14,2
7	Human toxicity	57,4	61,4	4,0

Another important factor which is strongly related to the application of the cut-off criteria is the modeling hierarchy. The modeling hierarchy order is also involved in the determination of the number of cut-off system elements (see also tables 2 and 3). The system elements are initially ranked by their cut-off criterion score in a descending order. Afterwards the hierarchy rule (s. § III-6.3.5) is applied to this descending order.

As shown in the example of the multifunctional module of German electricity production mix on table 3 for the elementary cut-off criterion case, the initially descending order of the system elements is modified after the implementation of the hierarchy rule.

In particular, the system element 1D referring to the electricity coal power plant is upgraded from 2nd to 1st position and the pseudo system element 11.1D referring to the transportation of crude oil rises from 13th to 5th position. Conversely, the system element 10D describing raw gas exploration falls from 8th to 9th position. Thus, the modeling hierarchical order has 12 positions which are less three than the actual number of the module system elements. Consequently, these changes can also be detected in the R_M-r_{limit} diagram represented in graph 7 in which the steps are reduced to 12.

The determined modeling hierarchical order is independent from the position of the e-module in the LCI-system and should be established once per module per cut-off criterion (fulfilling prerequisite: black-box modeling is applied see also III-6.3.7.3). In case of comparative LCAs when the cut-off limit is set using one reference LCI-system as described in § III-5.2 the hierarchical order remains the same for all the comparative LCI-systems. The initial descending order is based on the cut-off criterion score values of the system elements therefore is different for the two cut-off criteria 4 and 7 investigated in this study.

This can be proved in table 3 for the case of the modeling hierarchical order of the German electricity production mix module. It should be noted here that the hierarchical modeling order per investigated environmental impact category (i.e. human toxicity, ecotoxicity and summer smog) is determined in the environmental impact cut-off criterion. Among the several impact categories there are different respective modeling orders.

The number of system elements which change their position when the hierarchy rule is applied on the descending order varies among the modules and is case specific. However, it is generally considered that the more highly-detailed a module subsystem is the more possible it is to have a high number of position changes. In this particular case study of the e-module which refers to the European electricity production mix (see also figure 34) up to 44 position changes can be observed (in particular the case of the environmental impact cut-off criterion referring to the ecotoxicity).

These changes in positions prove that there is a considerable number of system elements which, despite their high distance from the main chain, have a higher relevance to the study than some system elements nearer to the main chain. Therefore, in the beginning of the LCI-system modeling, it is very important for the practitioner to collect as much data as possible in order to get an overall picture of the product tree. The final shape of the LCI-system should be formed afterwards by initially setting and later refining the system boundaries through the final application of the cut-off limit. Otherwise, the risk to exclude these aforementioned system elements that are distanced from the main chain but significant for the study is very high.

Hereby, it should be outlined that in the case of using multifunctional modules the practitioner actually shifts the data collection and system boundaries determination to the databank as shown in figure 32. This can become very advantageous as it causes a vast reduction in the time and effort needed for LCI-system modeling. Consequently, the whole LCA study is conducted easily and in a shorter time as LCI phase is the most time consuming and effort demanding phase of LCA. Furthermore, the databank has generally more means to collect reliable data for a multitude of industry sectors than the practitioner has within the frame of a single LCA study. Thus it is meaningful to shift the data collection step to the databanks. Nevertheless, by shifting the data collection step to the databank, the practitioner may find difficulties concerning the data quality evaluation phase as he is more or less obliged to accept the databank data quality evaluation at face value.

Apart from the aforementioned factors (i.e. the selection of cut-off criterion, its cut-off limit r_{lca}, the particular LCI-system investigated and the determined hierarchy order) the position in which the module integrates in the product tree plays a no less important role in the performance difference between the multifunctional modules versus fixed ones $\Delta_{i.c.}I$.

In general the investigated performance difference $\Delta_{i.c.}I_g$ between a multifunctional module and a fixed one when both are applied in one specific position g in the product tree of a certain LCA study depends on:

- The number of system elements which are cut-off from the module's subsystem in order to ensure the data symmetry
- The particular environmental impact value caused by these cut-off system elements.

The module integrates into the product tree through its product outflow ${}_{Out}f_M$ when the module refers to production processes (like the e-modules investigated here) and through its product inflow ${}_{In}f_M$ in case of disposal processes. In general, the higher the module ${}_{Out}f_M$ (or respectively the ${}_{In}f_M$) product flow the fewer system elements are cut-off. A proof of this using the analogy formula 56 follows.

In a specific module the value of the analogy α, is inversely proportional to ${}_{Out}f_M$ (or ${}_{In}f_M$) (s. formulas 48 and 49). In the case of cut-off criterion 7 the analogy α is even inversely proportional to the square of the ${}_{Out}f_M$ (or ${}_{In}f_M$) value (see formulas 50 and 51). Thus, the higher the ${}_{Out}f_M$ (or ${}_{In}f_M$) value the lower the analogy α. Hence, applying analogy formula 56 the lower the analogy α value the lower also will be the resultant r_{limit} value. Eventually, the lower the cut-off limit r_{limit} value the fewer system elements are cut-off.

On the other hand, the environmental impact indicator score of the system elements also depends on the ${}_{Out}f_M$ (or ${}_{In}f_M$) value. The higher the ${}_{Out}f_M$ (or ${}_{In}f_M$) module product flow value, the higher also the respective environmental impact indicator scores of the system elements (see formula 30 and 22).

Thus, if in two different positions of the product tree the same system elements of the module subsystem are cut-off, then the performance difference $\Delta_{i.c.}I_g$ between the multifunctional module versus the fixed one is higher in the position where the module product flow ${}_{Out}f_M$ (or ${}_{In}f_M$) is higher.

Such a case was detected in the second and third position of the investigated LCI-system described in table 4 when the elementary cut-off criterion is applied. In particular, though the e-module subsystem is identical for both positions the performance difference $\Delta_{i.c}I_g$ score in terms of environmental relevance is higher for position 3 because $({}_{Out}f_M)_3 > ({}_{Out}f_M)_2$. This performance difference $\Delta_{i.c}I_g$ is visible in graph 12a which refers to the impact category of acidification. Similarly, a performance difference $\Delta_{i.c}I_g$ concerning the other impact categories is detectable in the graphs given in appendix 15, Ap.15-1 (a) to (g).

However, it is important to point out that if in two different positions after the symmetrical adjustment of the e-module in the product tree its subsystem is not the same, the performance difference $\Delta_{i.c}I_g$ can be higher in the position in which the module product flow ${}_{Out}f_M$ (or ${}_{In}f_M$) is lower. Such cases were detected several times like in the case of the positions 7 and 8 described in table 4 where the elementary cut-off criterion is applied. The difference $\Delta_{i.c}I_g$ is higher in position 8 due to the higher number of cut-off system elements and despite that the module product flow in position 8 is lower than in position 7, $({}_{Out}f_M)_8 < ({}_{Out}f_M)_7$ (s. graph 12a and appendix 15).

Thus, the prognosis of the positions for which the data asymmetry formation is considerably high is risky to make as the influence of the ${}_{Out}f_M$ is controversial. Furthermore, this makes it also difficult to assess whether overall LCI results of comparative assertions which are biased by data asymmetries would remain unchanged and not be overturned with the implementation of multifunctional modules.

In conclusion, the particular outcomes of the e-modules operated in the case study denote the necessity of wider application of multifunctional modules. The empirical application complements the theoretical findings and stresses the importance of symmetric functional modeling of the product system even further.

V. Conclusions

The focus of this analysis was to examine the symmetric modeling of the LCI-system in regard to the application of cut-off criteria. Several kinds of cut-off criteria for example, process related cut-off criteria, product flow based cut-off criteria and elementary flow based cut-off criteria (elementary and environmental impact cut-off criteria) have been thoroughly investigated. Their principles were clarified and were used to classify them according to the level of reliability of their results. The elementary flow based cut-off criteria are the ones which provide highly reliable results. Thus, these cut-off criteria were more intensively researched and newly developed versions of them were coined.

Moreover, the cut-off criteria were investigated with regard to symmetric development of the LCI-system. The most reliable cut-off criteria, namely the elementary and the environmental impact criteria, were the cut-off criteria which ensure the symmetric development of the product system under a life cycle thinking perspective. The symmetric development of the LCI-system was further investigated from the singular perspective of one LCI-system and from the multiple perspective of more than one LCI-system (case of comparative LCAs).

Here, it was identified how the relative nature of the elementary and the environmental impact cut-off criteria score determination can affect the data symmetry of the product tree. Compensation of this effect concerning the symmetric development of the LCI-system from its singular perspective was achieved in the newly developed modified criteria versions as analyzed in § III-5.1

Furthermore, it was detected that the relativity in the cut-off criterion score determination, also affects the comparability among the several investigated LCI-systems in comparative LCA. In this case, a solution which ensures the comparability of the product systems studied was evolved by defining one LCI-system as a reference.

This solution can be realized in two ways. In the first case, the cut-off criterion score limit is the same among the investigated LCI-systems but in the cut-off criterion system element score calculation, only data from the reference LCI-system is used.

Alternatively, the same result can be achieved when the system element cut-off criterion score calculation remains as it is (using the respective data of each LCI-system) but then the cut-off criterion limit value differs among the various LCI-systems investigated. In this case the cut-off criterion limit value for each LCI-system is adjusted with respect to the reference LCI-system (s. also § III-5.2).

Thus by following the solution proposed, the comparability of the LCI-systems in the comparative LCA is ensured. Additionally, the final LCA results are improved as the environmental performance difference among the alternatives increases (as proven in § III-5.2 by formula 12). This outcome is very valuable for the practitioner as the greater the environmental performance differences among the alternative product life cycles, the more reliable support LCA can provide in decision making.

Moreover, symmetric functional modeling of the LCI-system was evolved utilizing aggregated data in the form of modules. The functionality of the modules is achieved with the use of the developed RUN models. In RUN models, the term *relevance* is used to give a theoretical framework to uniformly handle the differently defined cut-off criteria. Additionally, the function of the cut-off criterion and the function of the cut-off criterion limit are also determined.

The measurement in RUN modeling is made in relevance units which substitute the formerly used cut-off criterion scores. Similarly, the cut-off criterion limit determination is formally shifted from cut-off criterion score to relevance score. However, the application of RUN modeling does not cause any change to the original cut-off criterion definition. The integration of the proposed cut-off criteria in RUN models is unhindered by defining the respective cut-off criterion normalization coefficients. Hence, the RUN models are conformed to the fact that different cut-off criteria, or the same one in different LCI-systems, rank the system elements differently. Moreover, the practitioner has still the choice of selecting the cut-off criterion of his LCA study when using RUN modeling.

Based on RUN models, a five step algorithm is established which enables the symmetric adjustment of the module in the product tree. The cut-off criterion is then applied to the module subsystem thus preventing data asymmetry formations and ensuring the symmetry of the LCI-system. The algorithm is constructed in such a way as to enable an effective interrelation between the practitioner and the databank.

In this case the practitioner states the needed module data to the databank and the information concerning the modeling of the particular LCI-system i.e. the module product flow in the product system, the cut-off criterion and the cut-off criterion limit selection. Then the delimitation of the module subsystem is shifted in the databank, which delivers the module in ready-to-use state. Thus, the use of multifunctional modules becomes very advantageous, as then the LCI phase, the LCA phase to which most time and effort is spent, is highly simplified and accelerated, while ensuring the symmetric modeling of the product system. Symmetric modeled product systems deliver results of a high level of reliability.

The successful operability of the developed symmetric functional modeling was verified in the case study involving energy production modules. The geographical and technological coverage of the developed e-modules is very wide, covering the electricity production from five different energy sources in 12 European countries. Hence, in the highly detailed version of the e-module, its subsystem consists of 159 system elements, each one referring to one life cycle stage of the electricity production.

The prevention of data asymmetry, when the developed multifunctional modules are applied in several positions of the LCI-system, was verified. The data asymmetry formation was proven to be dependent on the various modeling parameters applied; namely the specific LCI-system, the module subsystem, the selection of the cut-off criterion, the selection of the cut-off criterion limit and the particular module product flow in the LCI-system. What is remarkable is the controversial effect detected which the module product flow value ${}_{Out}f_M$ (or ${}_{In}f_M$ in the case of disposal processes) has in the formation of data asymmetry. Thus prediction as to the extent of data asymmetries becomes complicated even in the simple case where only one LCI-system under certain modeling parameters is investigated.

Thus there is a lack of knowledge and predictability on how much the data asymmetries bias the final LCI outcomes. The performance of the multifunctional modules showed that the distortion of the LCI results is significant.
The overall performance difference between fixed and multifunctional modules -in all the

environmental categories for both investigated cut-off criteria- was high (over 25%). Even though this difference should not be generalized because it is case-specific, it definitely indicates the need for wider development and application of multifunctional modules. Moreover, all the empirical findings support the theoretical considerations and stress the importance of symmetric functional modeling of the product system even further.

VI. Abstract

Life Cycle Assessment (LCA) investigates the environmental performance of the life cycle of products from cradle-to-grave. In Life Cycle Inventory (LCI) phase of LCA the practitioner models the product system. Modeling of the product system (LCI-system) uses cut-off criteria, which determine the LCI-system's boundaries. The cut-off criteria affect the data symmetry of the modeled LCI-system. Symmetrically modeled LCI-systems result in highly reliable final LCA findings and ensure the LCI-systems' comparability. Current modeling practice often use fixed modules (aggregated data) due to the minimum required time and effort of an LCA. However, this results in the formation of asymmetrical data, which biases the final LCA outcome.

The symmetric modeling of the product system was thoroughly investigated when different cut-off criteria were applied. The advantages and possible drawbacks of the cut-off criteria were detected and new developed versions were coined. Furthermore, the product system modeling in case of comparative LCAs was also further developed in a way that ensures the data symmetry. Based on these findings, module functionality was developed using the so-called RUN modeling. This encompassed successfully the proposed cut-off criteria, which when applied on module subsystem, prevents the formation of asymmetry data. Based on the RUN models, a module symmetric adjustment algorithm has been established which can be used also by databanks. The application of the cut-off criterion has now been shifted from the practitioner (manually) to the databank (automatically), which is quite advantageous.

The easy operation of the developed multifunctional modules when different cut-off criteria are applied was verified in studying energy production modules. The overall performance of these multifunctional modules compared with the current available fixed modules showed an average reduction, due to data asymmetry prevention of the overall environmental score, which exceeds 25%. The empirical findings complement the theoretical considerations and stress the importance of symmetric modeling of the product system even further.

Zusammenfassung

In der Ökobilanz (engl. Life Cycle Assessment, LCA) werden die mit einem Produkt verbundenen Umweltaspekte und produktspezifischen potentiellen Umweltwirkungen im Verlauf des Produktlebenswegs von der Wiege bis zur Bahre abgeschätzt. Die Sachbilanz (engl. Life Cycle Inventory, LCI) ist der Teil der Ökobilanz, in dem der Produktlebensweg (LCI-system) modelliert wird. In der Modellierung des Produktlebenswegs bestimmen die Abschneidekriterien die Systemgrenzen. Die Abschneidekriterien beeinflussen die Datensymmetrie des Produktsystems. Symmetrisch modellierte LCI-system gewährleisten eine hohe Aussagesicherheit der Ökobilanzergebnisse sowie auch die Vergleichbarkeit der untersuchten LCI-Systeme. In der gegenwärtigen Modellierung werden oft aggregierte Daten in der Form von fixierten Modulen benutzt. Die Anwendung von Modulen minimiert erheblich den Zeit- und Arbeitsaufwand der Ökobilanz-Studie und ermöglicht ihre Durchführbarkeit. Die Anwendung von fixierten Modulen führt allerdings auch zur Bildung von Datenasymmetrien, die zur Folge haben, dass die Endergebnisse verzerrt werden.

Die symmetrische Modellierung des Produktsystems wurde gründlich untersucht, wenn verschiedene Abschneidekriterien verwendet wurden. Vorteile und mögliche Nachteile von Abschneidekriterien wurden festgestellt und neu entwickelte Versionen von den zuverlässigsten Abschneidekriterien entwickelt. Darüber hinaus ist die Modellierung des Produktsystems im Fall von komparativen Ökobilanzen (eng. comparative LCAs) auf eine solche Art und Weise weiterentwickelt, die die Datensymmetrie gewährleistet. Anhand von diesen theoretischen Untersuchungen wurde die Module-Funktionalität entwickelt, die durch die entwickelte RUN Modellierung umgesetzt wird. In dieser Modellierung können verschiedene Abschneidekriterien erfolgreich integriert werden, die anschließend auf das Modul Subsystem angewendet werden können. Dadurch werden Daten-Asymmetrien vermieden. So ist ein symmetrischer Anpassungsalgorithmus entstanden, der auch bei Datenbanken durchgeführt werden kann. Die manuelle Anwendung von Abschneidekriterien wird durch den Ökobilanzierer nun innerhalb der Datenbanken automatisiert betrieben. Die Durchführbarkeit der entwickelten multifunktionellen Module im Fall von verschiedenen Abschneidekriterien ist an der Fallstudie von Energieerzeugungsmodulen überprüft worden. An den multifunktionellen Modulen wird Datenasymmetriebildung verhindert. Daher übersteigt die durchschnittliche gesamte Performance, eingegeben in Umweltrelevanzreduzierung von den multifunktionellen Modulen im Vergleich zu den derzeitigen konventionellen Modulen 25%. Die empirische Untersuchung bestätigt alle theoretischen Überlegungen und betont die zwingende Notwendigkeit von symmetrischer Modellierung des Produktsystem.

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Appendix

Appendix 1

The detail level in both screening and streamlined LCAs is much lower than in full scale LCAs. Lower detail level results in lower time and effort, which counts as an advantage for both screening and streamlined LCAs. On the other hand, comparative LCAs need outcomes which reach a higher reliability level, which can be ensured solely from full scale LCAs [5, 22, 43, 13]. A study by US Environmental Protection Agency (EPA) [37] showed that the results of some screening or streamlined methods do not necessarily correspond with respective outcomes from more reliable full scale LCAs, a finding that confirms the concerns of the LCA community [5, 22, 43] concerning the application limitations of these simplified LCAs.

Appendix 2

The visualization of the LCI-system in the clepsydra form is not realistic as there are several kinds of flows which have been omitted i.e. the elementary flows in the production, use, recycling and disposal phases, the recycling material flows.

In addition, the processes prior to or after the use phase are classified respectively as production and disposal processes. This is not always realistic as i.e. disposal processes exist also in the prior consumption phase and vise versa.

Appendix 3

A rather commonly used subdivision of the product system is in the foreground and the background system. A common used definition for the foreground system defines it from the life cycle management perspective (LCM) as the part of the system which consists of those process steps of the LCI-system on which the commissioner and final decision maker of the LCA study can take actions according to the LCA's outcomes. On the contrary, the background system is the rest part of LCI-system which is not under the direct influence of the decision maker [57]. Other definitions are similar [5, 11, 43] or made from different perspectives such as data availability. In this case original data is used in the foreground system while generic data is used in the background system [43].
A rather similar division of the LCI-system is in the product system's part which includes the main-chain of the product's life cycle (in germ. Hauptkette) and in the remaining system part which includes the product's life cycle by-chains (in germ. Nebenkette) [21, 22, 45].

In many LCA's the foreground system includes the product's life cycle main-chain and the background system the product's life cycle by-chain process steps so the definitions can be often considered as complementary for the same LCI-system subdivision [45]. Both the main-chain and the foreground system form the heart of the LCI-system.

Unfortunately, both definitions of the LCI-system subdivisions are insufficient in practice. Most of the time it is not clear beforehand which of the LCI-system parts the decision maker can directly influence. Similarly, the main-chain, defined [21, 45] as "the chain with the minimum number of process steps starting from the end-product (middle of clepsydra) and going up (for pre-consumption phase) and down (for past-consumption phase) ending up at the borders with nature", is also not straightforwardly ascertainable. Nevertheless, these subdivisions of the product system have proven very useful in practice, in terms of communication.

Appendix 4

The term unit process as defined in the ISO norm 14040 [14] refers more here to the term of system element which could also be defined as:

> the LCA practitioner's *smallest element considered in the life cycle inventory analysis for which input and output data are quantified* [14]

It should be remarked here that (according to ISO definition), what a unit process is for one practitioner, could be for another a module which is equal to an aggregation of unit processes as *the boundary of a unit process is determined by the level of modeling detail that is required to satisfy the goal of the study* [14].!

Therefore it is useful to use the umbrella term of "system element". System elements are the units of the LCI-system and always refer to the LCI-system. The units of different LCI-systems could be different, in this way, possible misunderstanding could be avoided.

Appendix 5

The “inside-outside” modeling approach as described in § II-7 is the only one widely applicable today [21]. Alternatively, if the whole product system is already known to the analyst (maybe in the future this will become possible) it is considered that the analyst could then start delimiting the LCI-system by applying the “outside to inside” approach [21, 45].

In this case the analyst will check the system element’s cut-off criteria score one by one starting from the system element which lays closest to the LCI-system’s border (figure Ap.5-1). In the following step the system elements which do not reach the cut-off criteria limit will be sequentially discarded one by one. This process goes on until the first system element which reaches the cut-off criteria limit is found. Then the limit is set on this system element. For comparison reasons, figure Ap.-5 2 shows the respective decision flow chart for the case of the “inside to outside” approach. This “inside-outside” decision flow chart is described in §II-7.

The “outside to inside” modeling approach presents many drawbacks at present. The major one is that for the LCA analyst there are no ready-to-use fully (meaning with determined zero cut-off criteria limits) modeled product systems available. Consequently, the analyst has to firstly model the product system with the “inside to outside” approach making the “outside to inside” approach more or less superfluous.

Even so, it is possible that in the future this requirement will be fulfilled but this raises no less important methodological issues. First and foremost, why should be delimited a whole full scale modeled LCI-system?

A first answer on this is in the case of the LCI-system being only partly full scale modeled. Then the application of cut-off criteria (especially concerning module’s subsystems) is obligatory in order to ensure data symmetry (see also § III-1.3 Data symmetry with respect to system boundaries determination).

Another important methodological question is the following: Are the LCI-system boundaries identical when applying the same cut-off criterion limit using the two approaches, “inside-outside” vs. “outside-inside”?

Outcomes of the current work showed that these limits are not always identical when using these two approaches. This is attributed to the fact that the cut-off criteria score is not always decreasing according to the system element’s “distance” from the main-chain. Hence, if the results of the two approaches are not identical, which of them is the right one? These issues are not yet resolved and could become the focus of future research works.

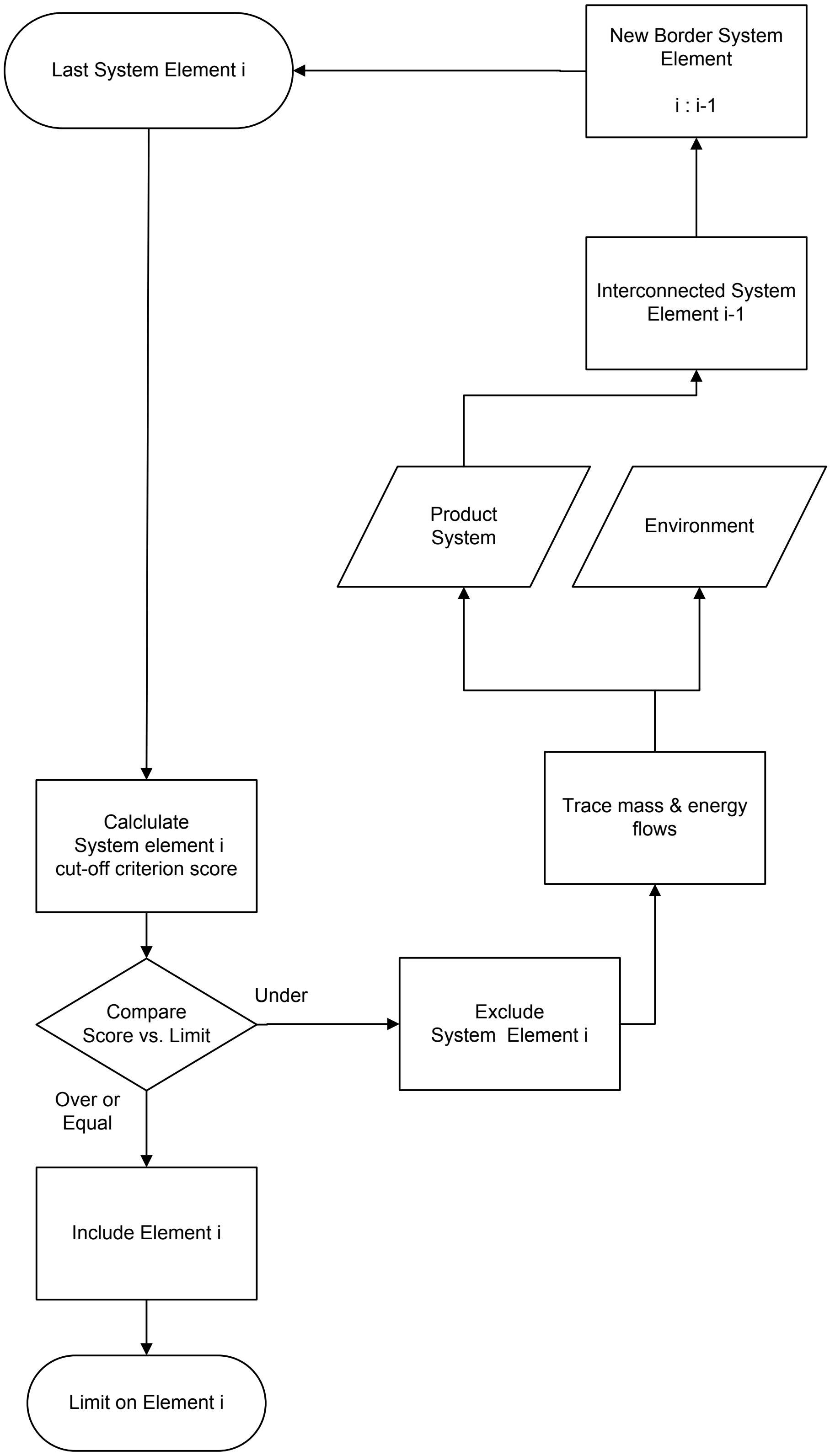


Figure Ap.-5 1. Decision flow chart in LCI-system “outside-inside” modeling

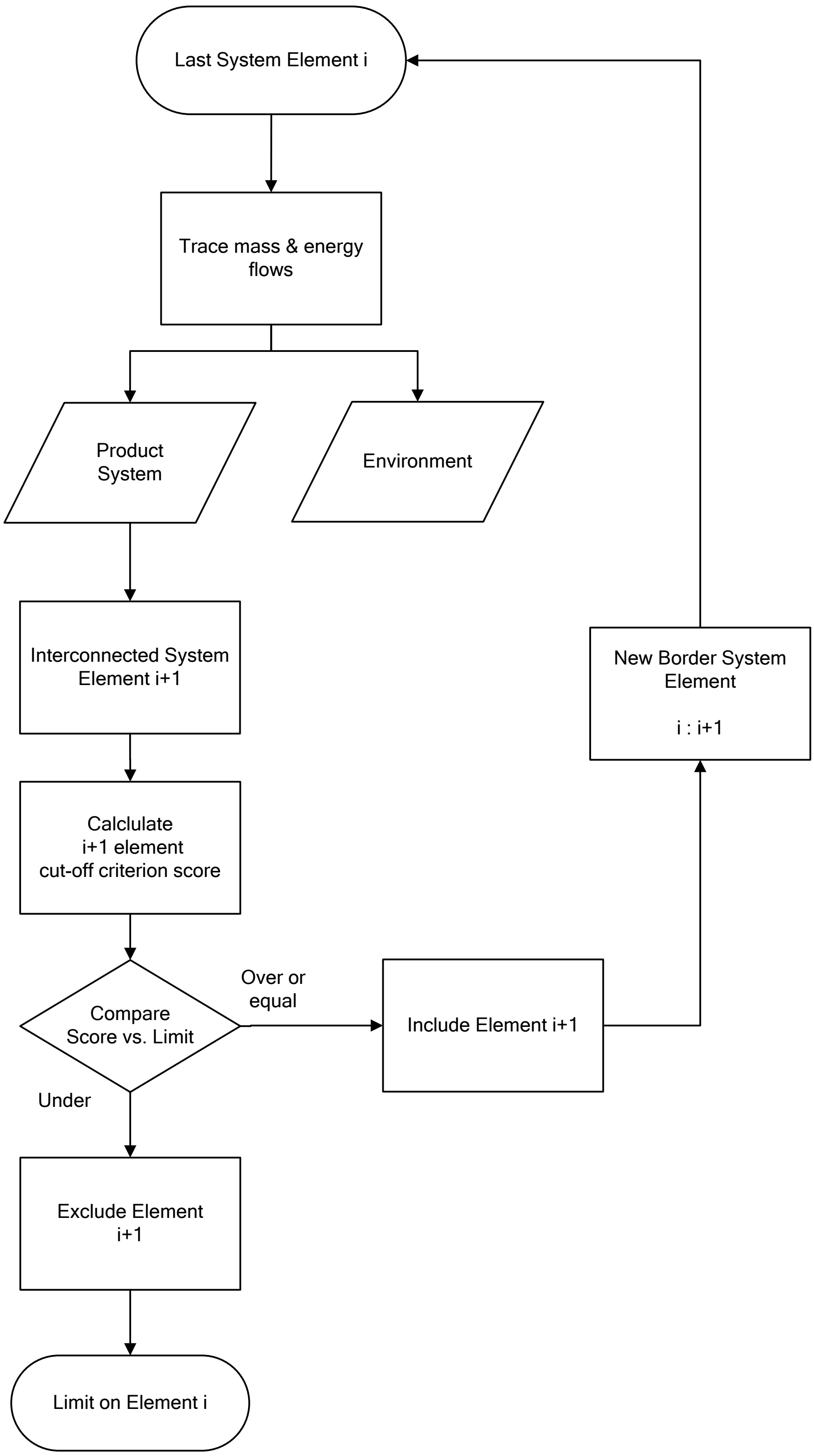


Figure Ap. 5 -1. Decision flow chart in LCI-system “inside-outside” modeling

Appendix 6

In the next figure, Ap.6-1, the possible adjustment of the system elements flows in the classical also called sequential calculation is shown. In the beginning the system element i+1 has its initial product flow ${}_{out}F_{i+1}$. When system element i+1 gets interconnected to system element i its product flow is normalized to $f'_{i+1} = {}_{In}F_i$. The elementary flows (omitted in the flow chart) are always adjusted respectively according to the applied linear model.

When the system element i is interconnected to the LCI-system (adjust the flow ${}_{Out}F_i$ to f_i) then the f'_{i+1} is adjusted to f_{i+1}, which is its final flow in the LCI system. The system elements i and i+1 are assumed to describe production processes. If the system elements describe disposal processes then the respective adjustment is the same but normalized to the input product flows.

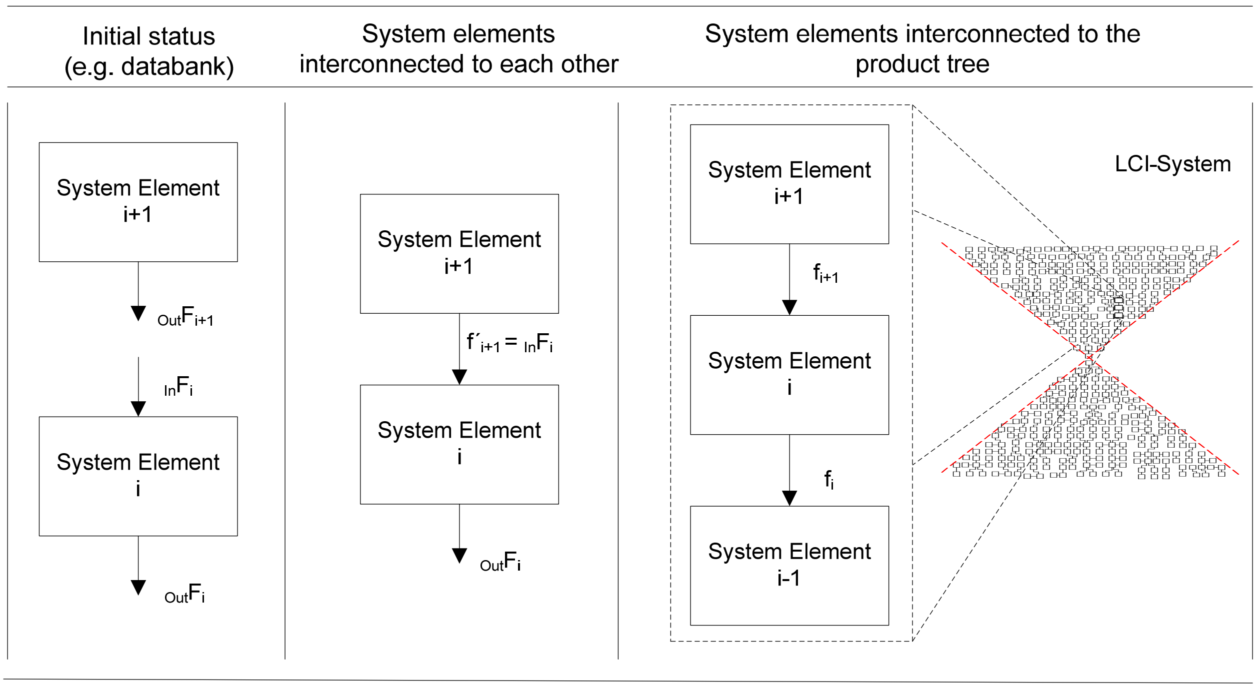


Figure Ap.6-1. System element product flow stepwise adjustments out of initial F to interconnected f´ and final in the LCI-system f

The adjustment described above is the simplest. A more comprehensive adjustment is when applying the mass multiplier calculation [21] in which the second step where the two system elements are adjusted to one another is not necessary. Thus, the system elements are linked directly from their initial state to the LCI-system.

The mass multiplier (μ) is actually the factor with which the initial system element's flows are multiplied in order to be directly adjusted to the LCI-system. As already mentioned, the adjustment is based on the system element's product outflow for the production process steps while for the disposal process steps it is based on the respective system element's inflow. For the example of system element i+1 in figure 9 the calculation is:

$$f_{i+1} = \mu_{i+1} * {}_{out}F_{i+1} \qquad \text{(Ap.6-1)}$$

The calculation formulas [21] of the mass multiplier are as follows:

Production processes:

$$\mu_i = \frac{Input_{i-1}}{Output_i}\mu_{i-1} \Rightarrow \mu_i = \frac{{}_{In}F_{i-1}}{{}_{Out}F_i}\mu_{i-1} \qquad \text{(Ap.6-2i)}$$

or

$$\mu_i = \prod_{i=1}^{n}\frac{Input_{i-1}}{Output_i} \Rightarrow \mu_i = \prod_{i=1}^{n}\frac{{}_{In}F_{i-1}}{{}_{Out}F_i} \qquad \text{(Ap.6-2ii)}$$

Disposal processes:

$$\mu_i = \frac{Output_{i-1}}{Input_i}\mu_{i-1} \Rightarrow \mu_i = \frac{{}_{Out}F_{i-1}}{{}_{In}F_i}\mu_{i-1} \qquad \text{(Ap.6-3i)}$$

or

$$\mu_i = \prod_{i=1}^{n}\frac{Output_{i-1}}{Input_i} \Rightarrow \mu_i = \prod_{i=1}^{n}\frac{{}_{Out}F_{i-1}}{{}_{In}F_i} \qquad \text{(Ap.6-3ii)}$$

where: μ_i: Mass-multiplier of system element i

μ_{i-1}: Mass-multiplier of system element i-1 through which is system element i interconnected to the LCI-system

${}_{In}F_{i-1} = Input_{i-1}$: Product inflow of system element i-1 in its initial state (see also figure Ap.6-1)

${}_{Out}F_i = Output_i$: Product outflow of system element i in its initial state (see figure Ap.6-1)

${}_{Out}F_{i-1} = Output_{i-1}$: Product outflow of system element i-1 in its initial state

${}_{In}F_i = Input_i$: Product inflow of system element i in its initial state

The mass multiplier is dimensionless and expresses the direct correspondence of the initial system element's flows to the adjusted ones and, therefore, is a characteristic parameter of the system element. Hence, the use of the mass multiplier as a cut-off criterion [21, 45] (see also §III-3.2.1 System related cut-off criteria based on product flow data) is proposed.

Appendix 7

Limit of documentation

A further step for the data collection step transparency and consistency is to also define the substance *limit of documentation* (l_d). Like in chemical analysis the analyst in LCA should not only know which substances are searched for but also their detection limit which for LCA is introduced here with the term documentation limit.

> *Limit of documentation* (l_d) *of a substance (or material)* is defined the *lowest concentration for which this substance (or material) is documented* in the LCI.

A way to define it objectively ensuring fair handling among the substances using their environmental impact equivalents values follows.

The analyst sets a limit of the minimum environmental impact equivalent value. Every substance with potential environmental relevance value as high as this limit should be documented. With the environmental impact characterization factor of the substance known, the substance documentation limit value can be calculated, converting formula (3) to formula (Ap.7-1). When the substance is investigated in more than one impact category its *limit of documentation* (l_d) is equal to the lowest calculated concentration.

$$ {}_{Sx}l_d = \frac{{}_{i.c.}I_{\lim it}}{{}_{i.c.}c_{fSx}} \qquad \text{(Ap.7-1)} $$

${}_{Sx}l_d$: *Limit of documentation for substance x*

${}_{i.c.}I_{limit}$: *minimum limit value of environmental category indicator*

${}_{i.c.}c_{fSx}$: *characterization factor of substance x for impact category im.c.*

In conclusion, the introduction of the pre-defined elementary substance list set with the additional substance's documentation limit ensures high transparency and traceability in the data collection step.

Ideally, the elementary substance list set with the respective substances' documentation limits should be identical among the utilized system elements of one LCA study. In a case where the data is not under collection but has already been collected (case of modules usage) it becomes inevitable not to compromise on the substances' documentation limits due to reasons of operability.

However, specification of the substances' documentation limits is valuable for monitoring the data asymmetries formation and therefore it is recommended to be integrated into the system element's meta data. In figure Ap7-1 the classification of the information referring to the detail level depth domain is given.

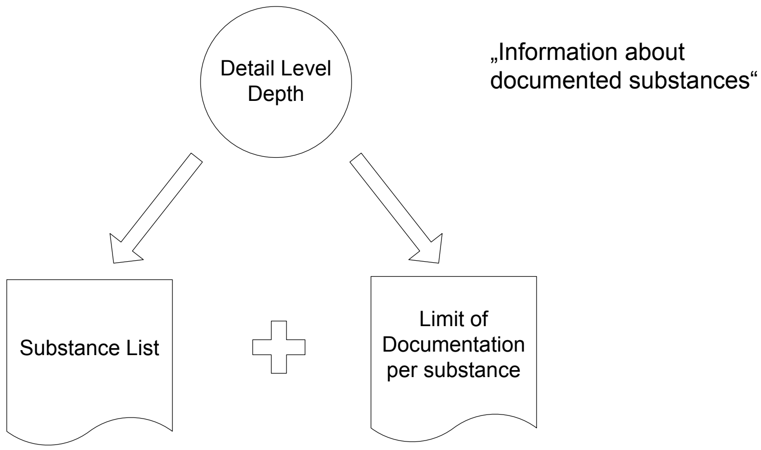


Figure Ap.7-1. Module detail level depth domain (extensive presentation)

Appendix 8

Symmetric adjustment on the detail level depth

According to the symmetry principle the system elements should be coequal to each other. In the case where the data is not yet collected the system elements are *ab initio* coequal to each other when their pre-defined elementary substance sets are identical. If this is not the case then it should be judged how the module's list of documented substances can be adjusted to the pre-defined substance list of the LCA study.

Data asymmetry referring to the detail level depth can be formed in two cases. The first one is when there are no substances present in the module substance list because they have not been searched for. Adjustment of the module here is not operable and only re-collection of data can be recommended. The second case is when the module has superfluous data. The symmetrical adjustment then is possible and can take place in the following steps:

I. The analyst defines the detail level depth of the LCA study.
II. The elementary substance list of the module detail level depth is cut down in order to be identical with the one of the LCA study

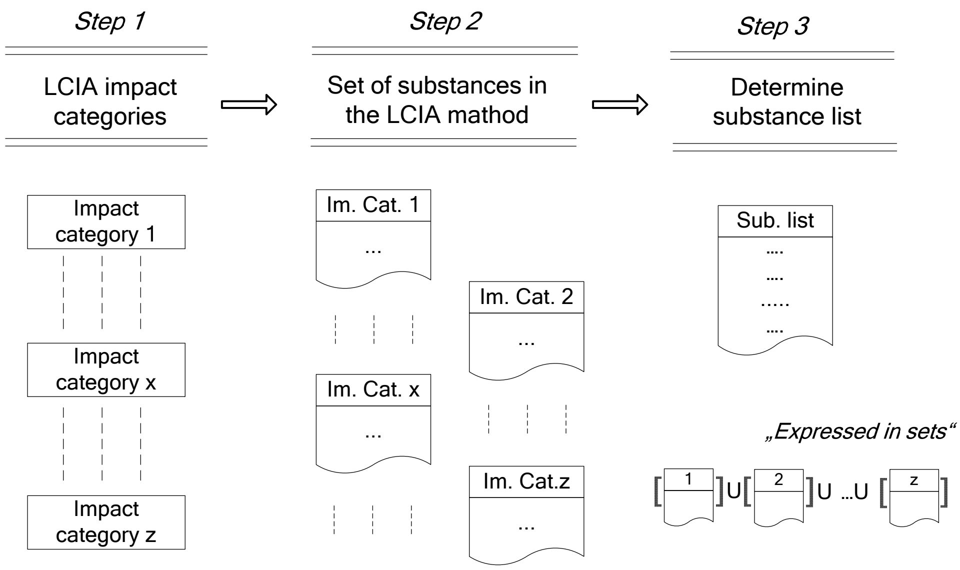


Figure Ap.8-1. Determination of LCA elementary substance list (detail level depth)

At this point it is recommended to determine the detail level depth of the study through the selected environmental impact categories and the respective LCIA method. In particular for each environmental impact category the set of substances which are investigated in the LCIA methods are collected. The final elementary substance list is then created from more than one impact category substance list set (figure Ap.8-1.).

Thus, the elementary substance list is determined in such a way as to ensure that no substance involved in the potential environmental relevance calculation can be excluded. Furthermore, the detail level depth of the study is objectively ascertained from the LCIA method and, therefore, is the longest reasonable determinable elementary substance list.

On the other hand, as data collection requires effort and is time consuming the analyst may under special circumstances judge as necessary to re-define the LCA substance list according to the particular needs and goals of the specific study. Nevertheless, this is not recommended here as exclusion of environmentally relevant substances causes, consequently, a significant decrease in the reliability of the study.

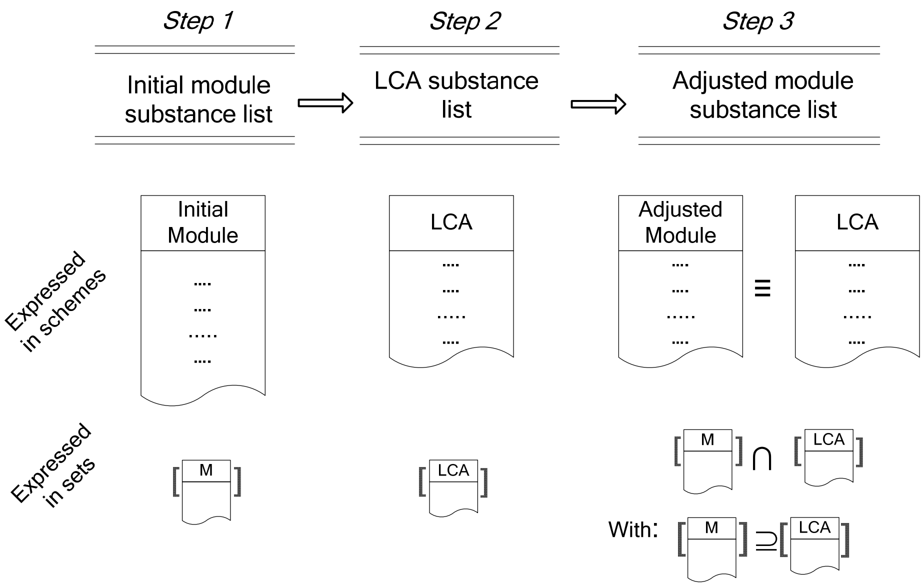


Figure Ap.8-2. Adjustment of module detail level depth

Phase II of the module detail level adjustment is illustrated in the above figure Ap.8-2. In step 3 potential superfluous data of the module is discarded. This adjustment approach includes the precondition that the LCA elementary substance list set is a subset of the initial module's elementary substance list (s. also Figure Ap.8-2) and indirectly assumes that no additional data needs to be collected.

It should be remarked here that the longer the module substance list set is the wider becomes the module multi-functionality application range.

Appendix 9

Comparison of cut-off criteria 4 and 5 on their versions a and b

Hereby, a comparison between:

- Cut-off criterion 4a versus Cut-off criterion 4b
- Cut-off criterion 5a versus Cut-off criterion 5b

The difference between versions a and b of the aforementioned cut-off criteria is implied in the determination of the final system element cut-off criterion score.

In the first case, the system element score is determined by the highest system element's substance score (version a) whereas in the latter it is determined by the aggregation of the entire system element's relevant substances scores (version b). Therefore, in versions a, the distribution of the initial system element substances scores and the dominance of a substance score affect the final cut-off criterion score, whereas this is not the case for b versions.

In b versions every investigated substance has its share in the final cut-off criterion system element score. Thus, *correspondence between the system element's cut-off criterion score and its environmental relevance score is ensured*. Based on this statement it can be argued that b versions of these cut-off criteria are superior to a versions. A proof on this follows.

<u>Case-study</u>

Two fictitious system elements A and B are investigated. These have the same environmental relevance, even though their substances' cut-off criterion scores distribution is different.

In the case of system element A the highest cut-off criterion substance score does differ slightly from the remaining relevant substances cut-off criterion scores, while in system element B there is a significant difference between the highest cut-off criterion substance score and the one of the remaining substances.

For the cut-off criterion score calculation the following data information is needed:

- Definition of the relevant substances
- Definition of the LCIA method
- Determination of the relevant substances mass values in the system elements and in the LCI-system
- Definition of the environmental impact category which is investigated in the

environmental impact cut-off criteria

- Determination of the LCI-system environmental relevance (cut-off criterion 5)

In this particular example the relevant substances to be investigated in the cut-off criteria are CCl_4, CFC-11 and dibromodifluoromethane (HALON-1202). The investigated environmental impact category is the ozone layer depletion (ODP) defined in the CML standard [12, 81] LCIA method. For reasons of simplification only one impact category is being defined. The definition

Table Ap- 9.1 Data of integrated system elements A and B

	System Element A		**System Element B**	
Emitted substances	Mass S_x (kg)	Impact $_{ODP}I_{Sx}$ (kg CFC-11 eq)	Mass S_x (kg)	Impact $_{ODP}I_{Sx}$ (kg CFC-11 eq)
CCl_4	**3**	3,24	**7**	7,56
CFC-11	**3**	3	**1,18**	1,18
Halon-1202	**3**	3,75	**1**	1,25
Other	0	0	0	0
	Total $_{ODP}I_a$:	**9,99**	**Total $_{ODP}I_b$:**	**9,99**

of one impact category does not affect the comparison as the results of each category are independent to one another. The data of the system elements A and B, integrated into the LCI-system, is given in Table Ap.9-1, while the data of the LCI-system is given in Table Ap.9-2.

Table Ap.-9.2 Data LCI-system

	LCI-System		
Emitted substances	Mass S_x	Characterization factor $_{ODP}c_{fx}$	Impact $_{ODP}I_{LCAx}$ (kg CFC-11 eq)
CCl_4	100 kgr	1,08	108
CFC-11	100 kgr	1	100
Halon-1202	100 kgr	1,25	125
Other substances			300
		Total $_{ODP}I_{LCA}$:	633

Thereafter, the substances cut-off criteria scores for the two system elements are calculated (Table Ap. 9.-3.). The final cut-off criteria scores for each system element are given in the following Table Ap. 9.-4.

Table Ap.-9.3 Substance cut-off criteria scores

Substances	System Element A		System Element B	
	Cut-off criterion 4	Cut-off criterion 5	Cut-off criterion 4	Cut-off criterion 5
CCl_4	0,0300	0,00512	0,0700	0,0119
CFC-11	0,0300	0,00474	0,0118	0,00186
Halon-1202	0,0300	0,00592	0,0100	0,00197

Table Ap. -9.4 System elements cut-off criteria scores

	System Element A	System Element B
Cut-off criterion 4a	0,0300	0,0700
Cut-off criterion 5a	0,00592	0,0119
Cut-off criterion 4b	0,0900	0,0918
Cut-off criterion 5b	0,0158	0,0158

As mentioned previously, the environmental relevance value of system element A in the investigated ozone layer depletion category $_{ODP}I_a$ is 9,99 ODP kg and equal to the respective environmental relevance of system element B $_{ODP}I_b$ (given in Table ap.9.-1).

If the cut-off criterion score value of a system element corresponds with its environmental relevance value then the cut-off criteria scores of system element A and B ought to be the same as their environmental relevance values are the same.

Comparing the final system elements cut-off criteria scores as calculated in Table Ap. 9.-4 it is found that in the case of cut-off criterion 4a and 5a there is a major difference between the scores of system element A and B (of 60% and 48% respectively).

On the other hand, in the case of cut-off criterion 4b there is a minimal (less than 2%) difference between the system elements' scores while in the case of cut-off criterion 5b the cut-off criterion score values are the same.

The aforementioned difference of the system elements' cut-off criterion scores in the case of criterion 4a and 5a implies an unfair handling among the system elements. This difference is generated from the respective difference among the substances' cut-off criterion scores. Hence, the selection of the highest substance cut-off criterion score causes a systematically unfair handling among the system elements. The system elements in which the highest cut-off criterion score is not close to the remaining relevant substances' cut-off criterion scores are ranked much higher compared with ranking with respect to their actual environmental relevance values.

Consequently, the cut-off criterion versions 4b and 5b are superior to 4a and 5a respectively as in the b version the ranking of the system elements using the cut-off criterion scores has ensured a higher correspondence to the ranking obtained using the system elements' environmental relevance values.

Appendix 10

Cut-off criterion mass-multiplier

In this section it will be proven why the mass multiplier in the current calculation form cannot serve as a cut-off criterion.

The mass multiplier score is calculated by the following formulas (Ap.10-1) and (Ap.10-2) [21]

Production processes: $$\mu_i = \frac{Input_{i-1}}{Output_i}\mu_{i-1} \Rightarrow \mu_i = \frac{{}_{In}F_{i-1}}{{}_{Out}F_i}\mu_{i-1} \qquad \text{(i)} \qquad \text{(Ap.10-1)}$$

or $$\mu_i = \prod_{i=1}^{n}\frac{Input_{i-1}}{Output_i} \Rightarrow \mu_i = \prod_{i=1}^{n}\frac{{}_{In}F_{i-1}}{{}_{Out}F_i} \qquad \text{(ii)}$$

Disposal processes: $$\mu_i = \frac{Output_{i-1}}{Input_i}\mu_{i-1} \Rightarrow \mu_i = \frac{{}_{Out}F_{i-1}}{{}_{In}F_i}\mu_{i-1} \qquad \text{(i)} \qquad \text{(Ap.10-2)}$$

or $$\mu_i = \prod_{i=1}^{n}\frac{Output_{i-1}}{Input_i} \Rightarrow \mu_i = \prod_{i=1}^{n}\frac{{}_{Out}F_{i-1}}{{}_{In}F_i} \qquad \text{(ii)}$$

with: μ_i: Mass-multiplier of system element i

μ_{i-1}: Mass-multiplier of system element i-1 through which is system element i interconnected to the LCI-system

${}_{In}F_{i-1} = Input_{i-1}$: Product inflow of system element i-1 in its initial state (see also figure Ap.6-1)

${}_{Out}F_i = Output_i$: Product outflow of system element i in its initial state (see also figure Ap.6-1)

${}_{Out}F_{i-1} = Output_{i-1}$: Product outflow of system element i-1 in its initial state

${}_{In}F_i = Input_i$: Product inflow of system element i in its initial state

The value of the initial system element product output (or respective input) flow is not strictly defined in these formulas. In particular, in accordance to formulas (1) and (2) the flows not having been strictly defined are:

- ${}_{Out}F_i$: in formula (Ap.10-1i)
- ${}_{In}F_i$ in formula (Ap.10-2i)

These values are arbitrarily defined by either the practitioner or the databank (in the case of generic data). In the case-study of electricity production modules the following values are found:

1. ${}_{Out}F_i$ = 1 TJ — Source: ETH-ESU 96 System Processes
   Module Identification: Electricity mix w-D S
   Project ETH-ESU 96 System Processes [81, 76]

2. ${}_{Out}F_i$ = 1 MJ — Source: Industry data (Boustead)
   Module Identification: Electricity on site A
   Project: Industry data (Boustead consulting, ecoprofiles of chemicals and polymers) [81, 80]

3. ${}_{Out}F_i$ = 1 kWh — Source: Ecoinvent System Processes
   Module Identification: Electricity production mix DE
   Project Ecoinvent System Processes [81, 71]

4. ${}_{Out}F_i$ = 99 kWh — Source: BUWAL 250
   Module Identification: Electricity Germany B250
   Project: BUWAL 250 national statistics (1996) [81, 83]

If we try to compare the calculated mass multiplier values ${}_1\mu_i$, ${}_2\mu_i$, ${}_3\mu_i$ *and* ${}_4\mu_i$ (respectively for each above numbered module) referring to the same position of an LCI-system it will be determined that:

$${}_1\mu_i = 10^{-6} * {}_2\mu_i = 3{,}6 * 10^{-6} * {}_3\mu_i = 3{,}56\ 10^{-4} * {}_4\mu_i$$

These results can differ by up to 6 orders of magnitude to one another. These outcomes are not limited to the electricity modules but can similarly be found in other modules or unit processes.

Hence, given that there is no generally applicable way to determine the initial system element product flow ${}_{Out}F_i$ (for production processes) or ${}_{In}F_i$ (for disposal processes) the mass multiplier cannot be used as a cut-off criterion.

Appendix 11

Modified version of elementary cut-off criterion

The following modification takes place in order to compensate for the propagation of transaction errors as described in § III-5.1.

In this modified version the substance cut-off criterion score is equal to the squared substance mass value found in the system element over the overall mass value of the substance in the LCI-system. The remaining steps of the calculation are identical to the ones given in the original version. The following figure Ap.11-1 shows the stepwise calculation.

In this case the substance cut-off criterion score is not solely dependent on the distribution of the investigated substance among the system elements of the product system. The substance cut-off criterion is no longer a relative value. Assuming the conditions given in §III-5.1 where the S_{LCIx} value is in absolute terms relatively low and the S_{ix} is in comparison to the remaining system elements relatively high (but in absolute terms also low) then the substance cut-off criterion score would be as follows:

Version I (initial)	Version II (proposal)
$Sc= S_{ix}/S_{LCIx}$ (high)	$Sc= (S_{ix}/S_{LCIx})*S_{ix}$ (quite low)

Thus, in the aforementioned case the transaction error propagation, which is formed due to incorrectly determined high value of the substance cut-off criterion in version I, is now compensated for in the proposed version II. Nevertheless, it should be noted that the proposed version is more complicated. Furthermore, the cut-off criterion limits should be set differently as the two criteria versions are not directly comparable to another. The cut-off criterion limit in the new proposed version is also more difficult to define.

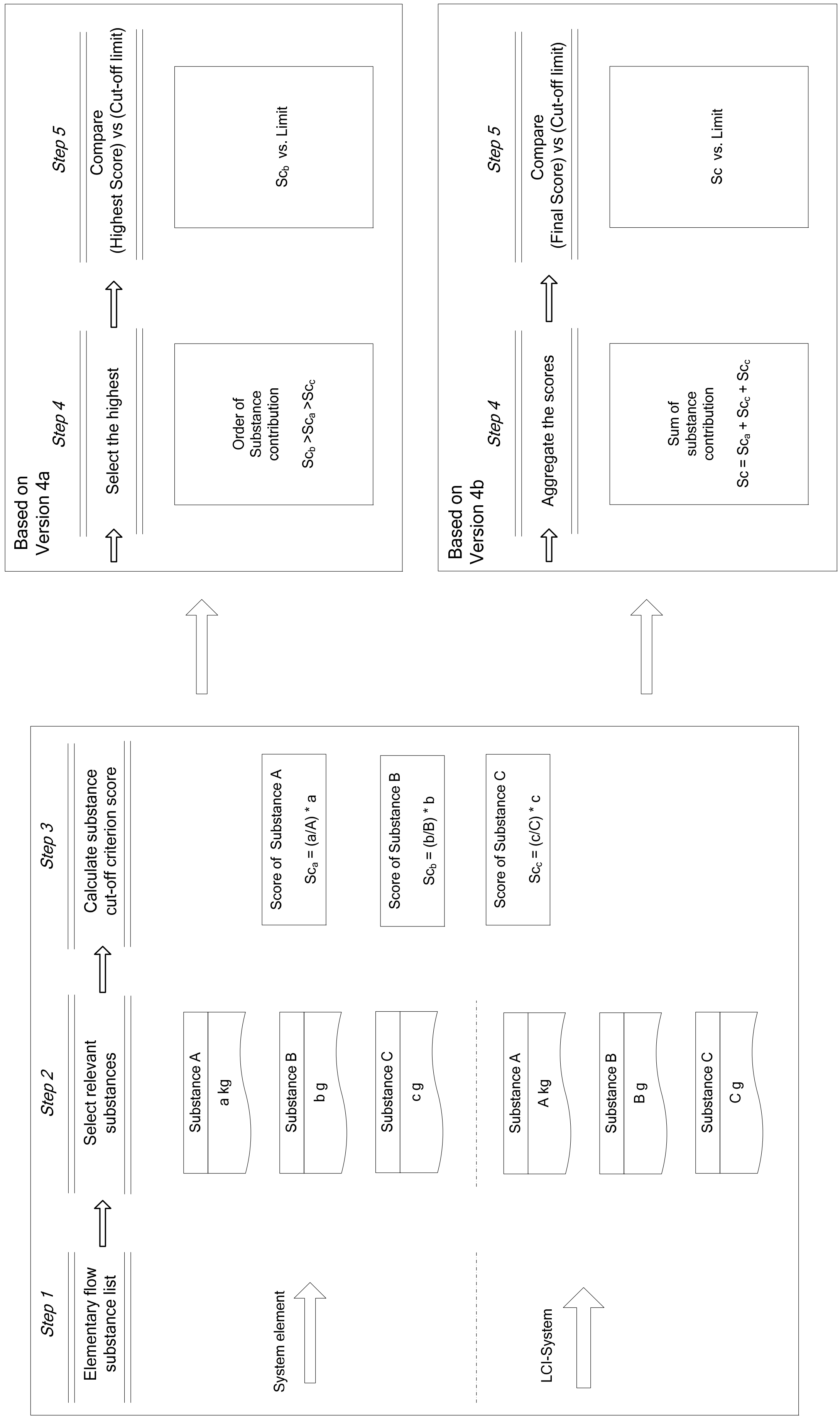
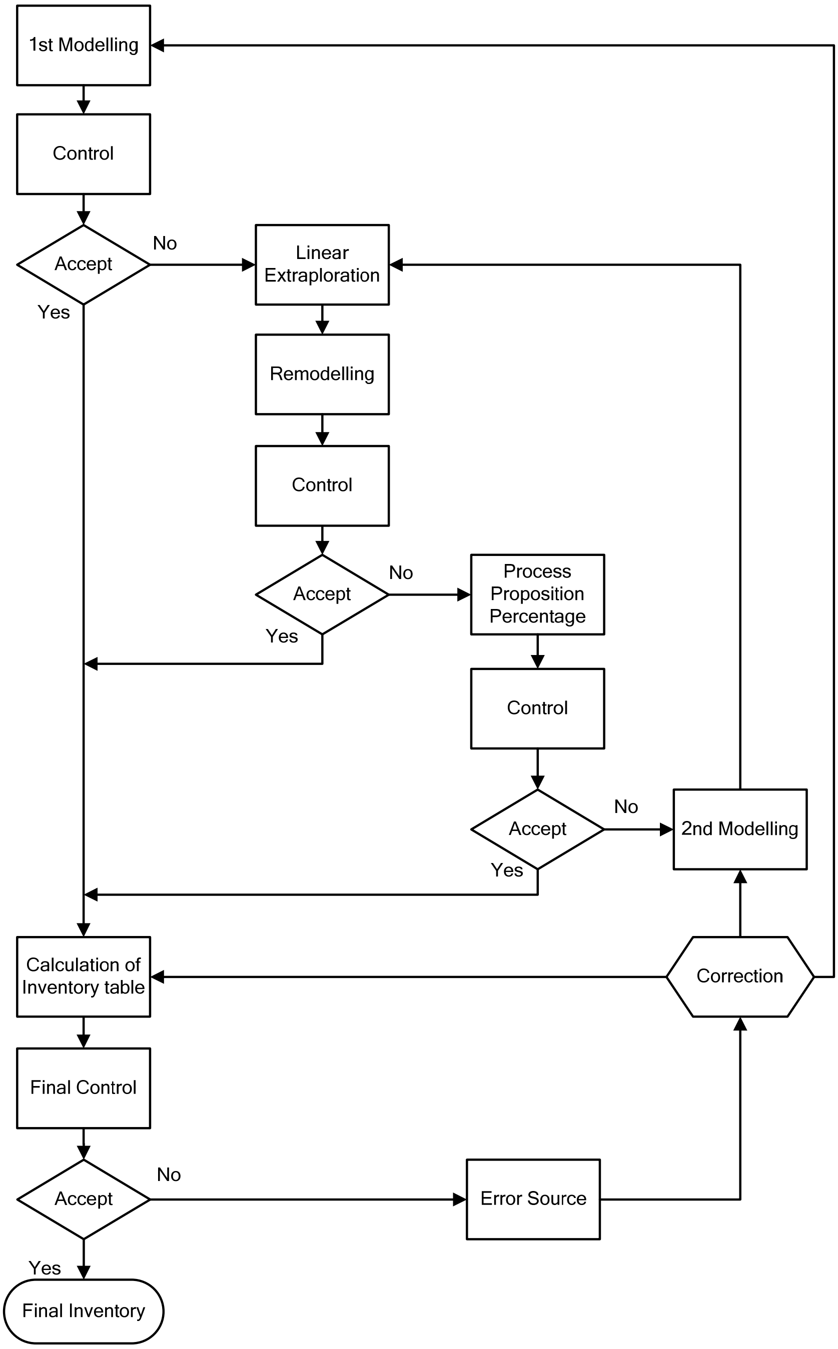


Figure Ap.11-1. Stepwise application of a new proposed elementary cut-off criterion.

Appendix 12

Consistency control and validation

The final modeled data of the developed module's system elements was controlled and validated in terms of consistency with the respective supplied database data according to the following figure Ap.12-1.



Schema Ap.12-1 Controlling and validating the system elements data

In the case where remodeling of the data was needed, the process contribution was first corrected and then the proposition percentage rechecked. System element’s data (manually aggregated) which was inconsistent with the respective database data (in their fixed aggregated form) has been detected in the case of system elements referring to energy production from nuclear power. In order to ensure the investigation’s reliability these system elements were left out of the final study, restricting the module technological coverage.

In most cases the inconsistency is caused from the numerous multiplication factors used, which were partly rounded up. Moreover, inconsistency is also caused from unpreventable software double counting calculations in case of close-loops (for energy production, energy is needed). Therefore, mass balance checks were also undertaken. In a few cases deviant values were detected and were afterwards corrected. Additionally, there were also a small number of random errors detected which were also corrected for.

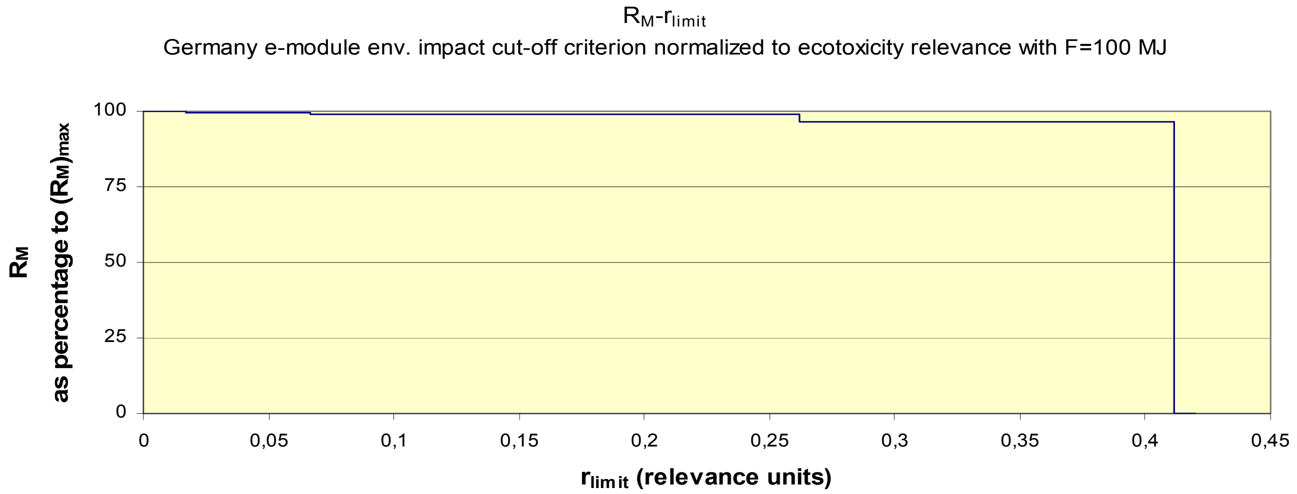
Appendix 13

Acronyms of module for electricity production mix Germany (s. also Table 3)

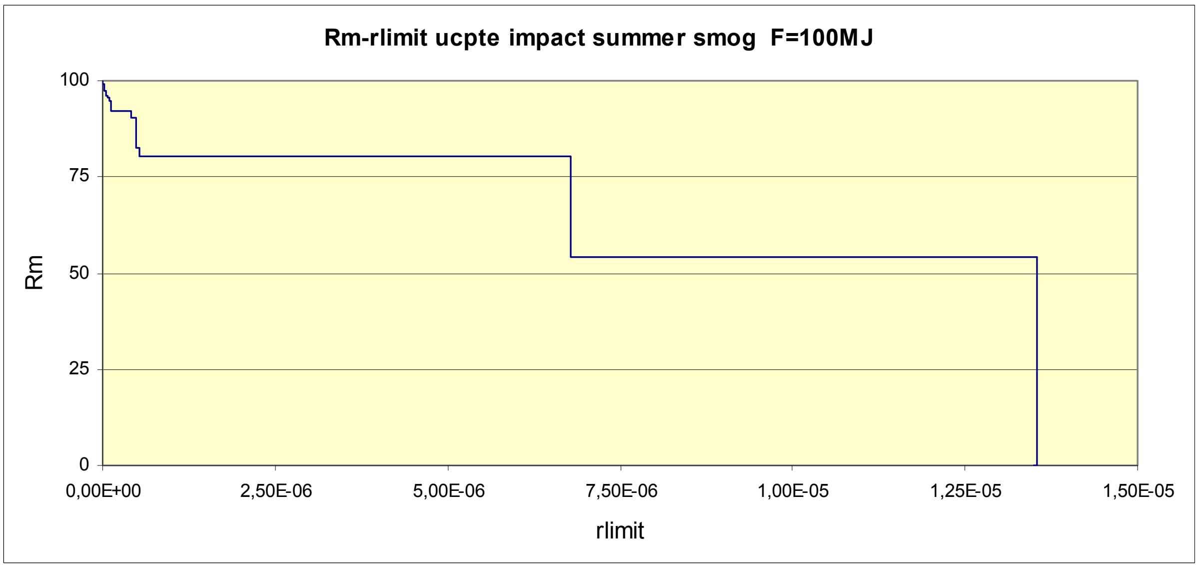
1D: Electricity coal power plant for Germany
2D. Coal mining and production for Germany
3D: Electricity lignite power plant for Germany
4D: Lignite mining and production for Germany
5D: Flow through electricity hydropower plant for Germany
6D: Pumping storage hydropower plant for Germany
7D: Reservoir electricity hydropower plant for Germany
8D: Electricity gas power plant for Germany
8.1D: Transportation gas for Germany (pseudo-system element)
9D: Production gas for Germany
10D: Exploration gas for Germany
11D: Electricity oil power plant for Germany
11.1D: Transportation oil for Germany (pseudo-system element)
12D: Production oil for Germany
13D: Exploration oil for Germany

Appendix 14

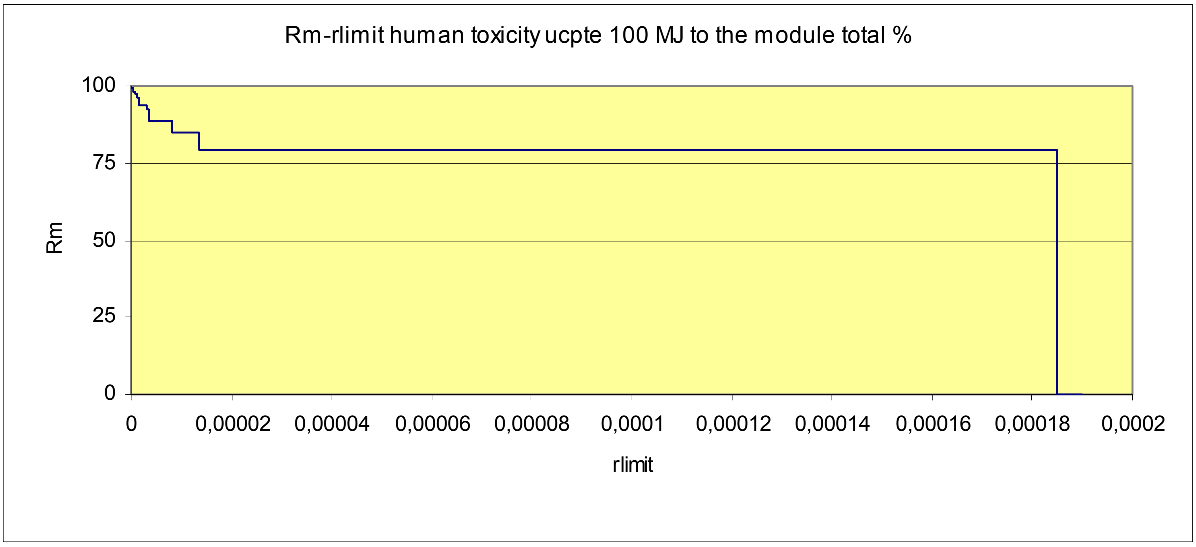
Hereby, the module relevance to cut-off criterion limit, R_M-r_{limit} diagrams are given, worked out for the evolved multifunctional modules referring to a product output flow F equal to 100MJ.



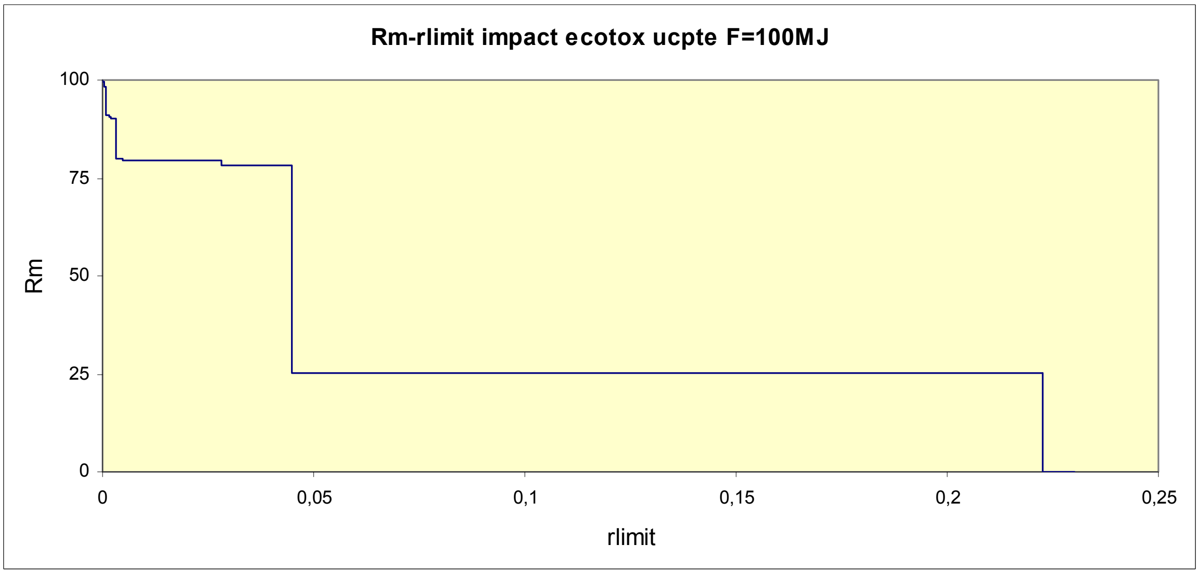
Graph Ap.14-1. Module relevance (R_M) to cut-off limit (r_{limit}) diagram for the e-module referring to the electricity mix of Germany. The relevance is calculated referring to the env. impact cut-off criterion 7a normalized for the category of ecotoxicity (for both R_M and r_{limit} relevance units). The reference product flow is: F=100MJ.



Graph Ap.14-2. Module relevance (R_M) to cut-off limit (r_{limit}) diagram for the e-module referring to the electricity mix of Europe (ucpte). The relevance is calculated referring to the env. impact cut-off criterion 7a normalized for the category of summer smog (for both R_M and r_{limit} relevance units). The reference product flow is: F=100MJ.



Graph Ap.14-3. Module relevance (R_M) to cut-off limit (r_{limit}) diagram for the e-module referring to the electricity mix of Europe (ucpte). The relevance is calculated referring to the env. impact cut-off criterion 7a normalized for the category of human toxicity (for both R_M and r_{limit} relevance units). The reference product flow is: F=100MJ.

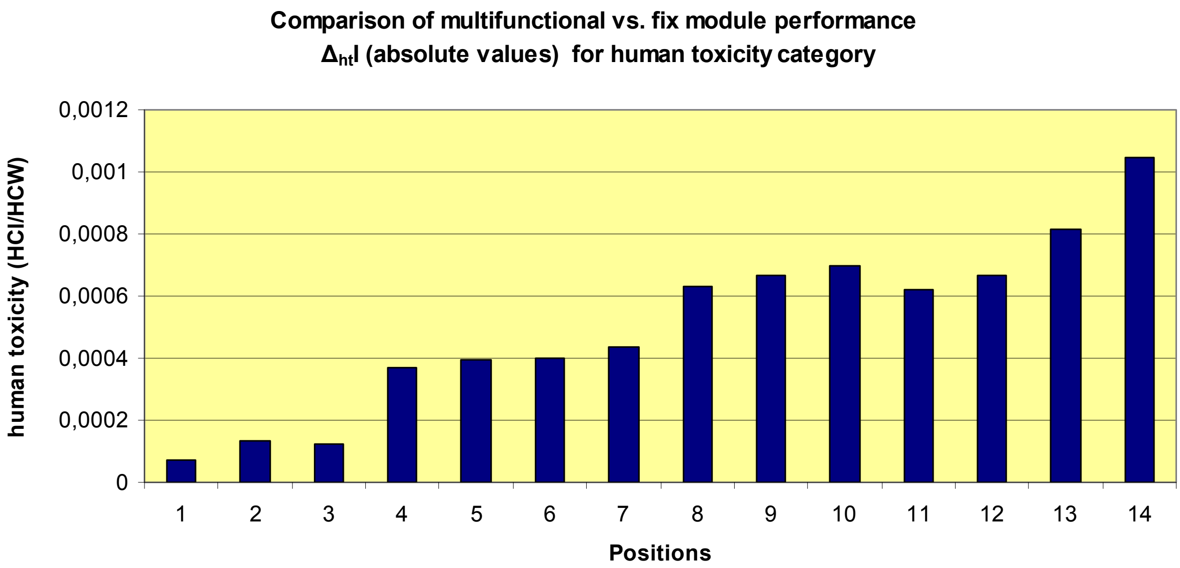


Graph Ap.14-4. Module relevance (R_M) to cut-off limit (r_{limit}) diagram for the e-module referring to the electricity mix of Europe (UCPTE). The relevance is calculated referring to the env. impact cut-off criterion 7a normalized for the category of ecotoxicity (for both R_M and r_{limit} relevance units). The reference product flow is: F=100MJ.

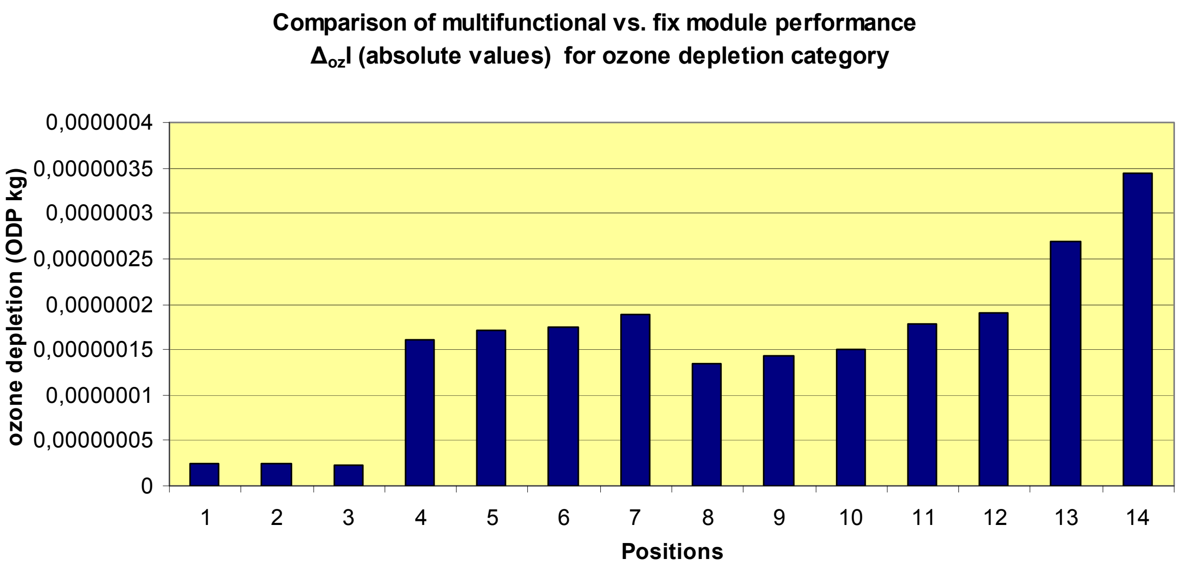
Appendix 15

Comparison multifunctional vs. fix module in absolute values per position

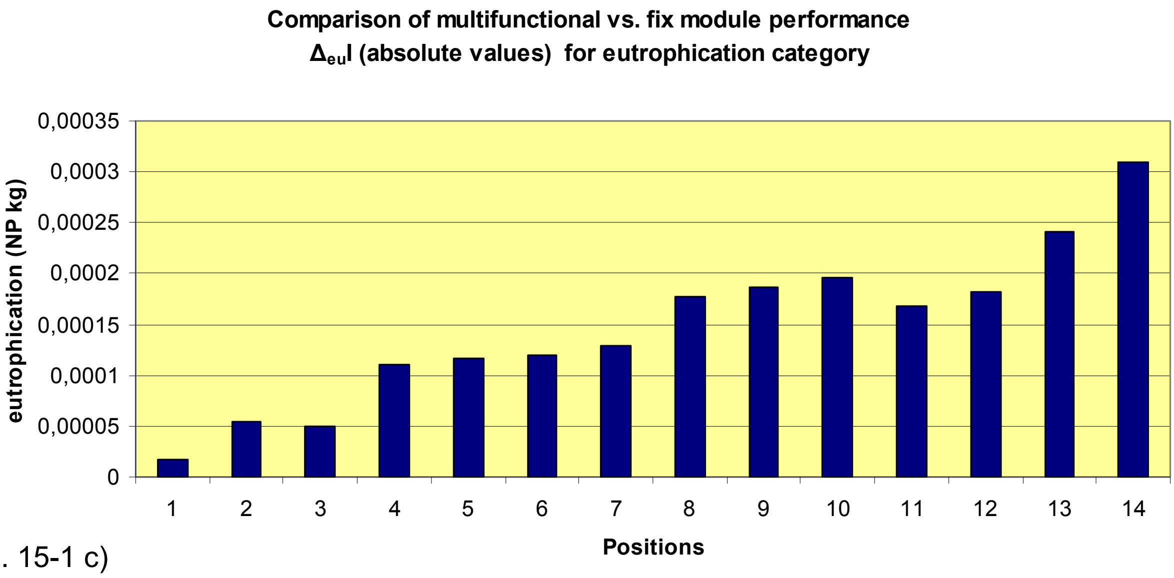
After the symmetrical adjustment of the multifunctional modules for each position is calculated the performance difference $\Delta_{i.c.}I$ (formula 30) of the symmetric adjusted modules and the fixed one in reference to their environmental impact score. Thus, the following graph series can be made Ap.15-1 (a) to (g) and Ap.15-2 (a) to (g). Graph Ap.15-1 wherein the blue columns refer to the case of the elementary cut-off criterion 4b whereas in graph Ap.15-2 the red columns refer to the environmental impact cut-off criterion 7a.



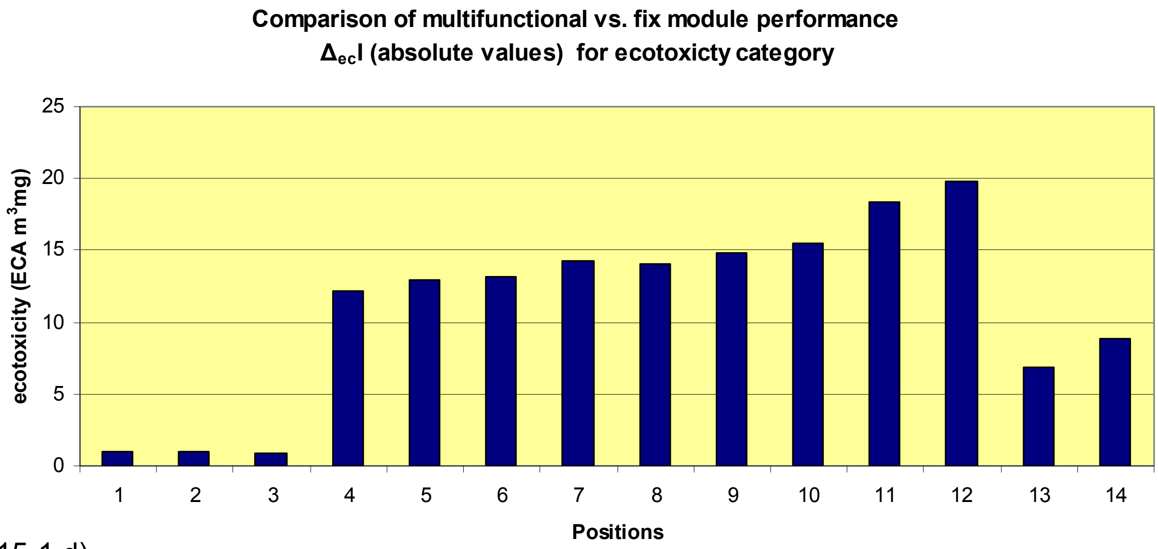
(Ap.15-1 a)



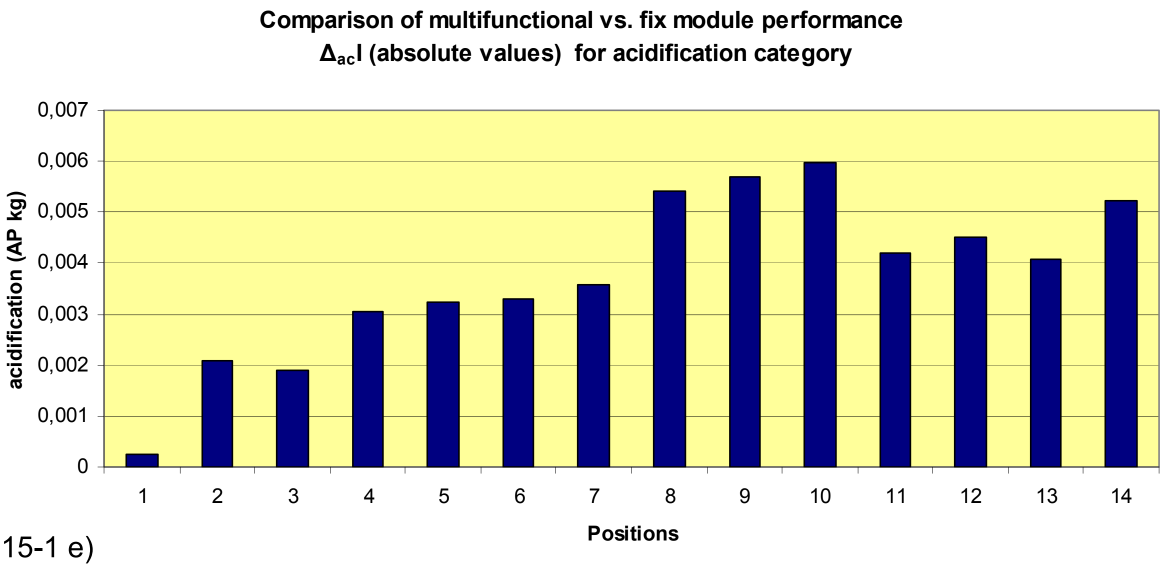
(Ap.15-1 b)



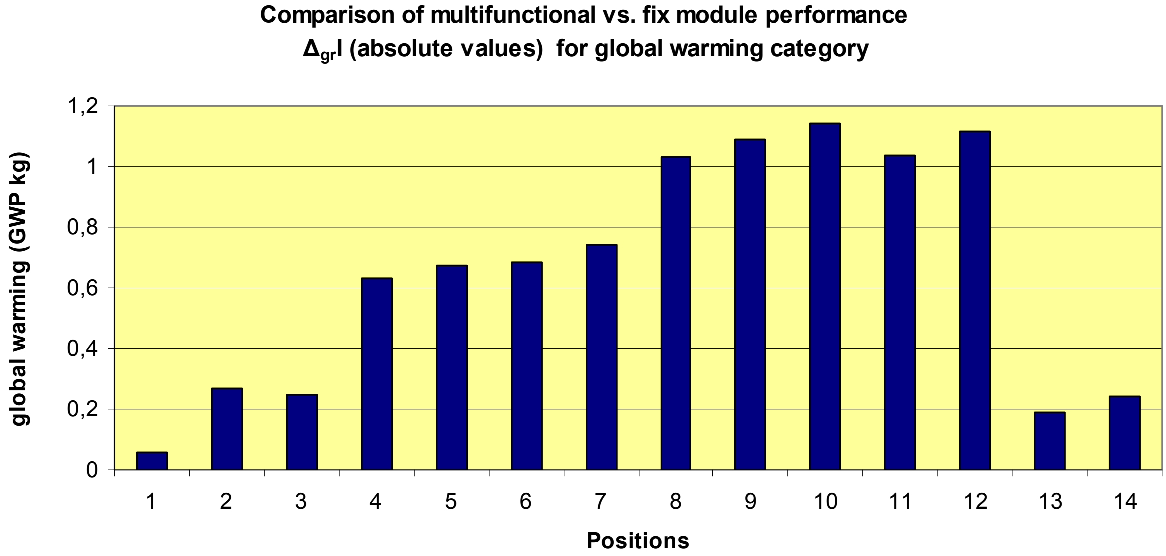
(Ap. 15-1 c)



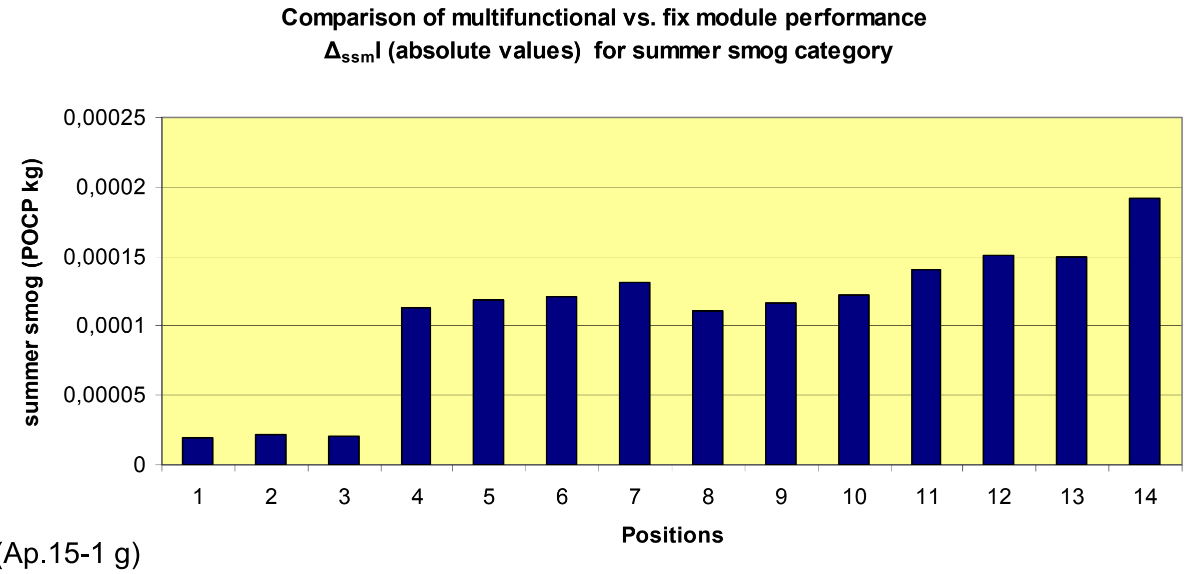
(Ap.15-1 d)



(Ap.15-1 e)

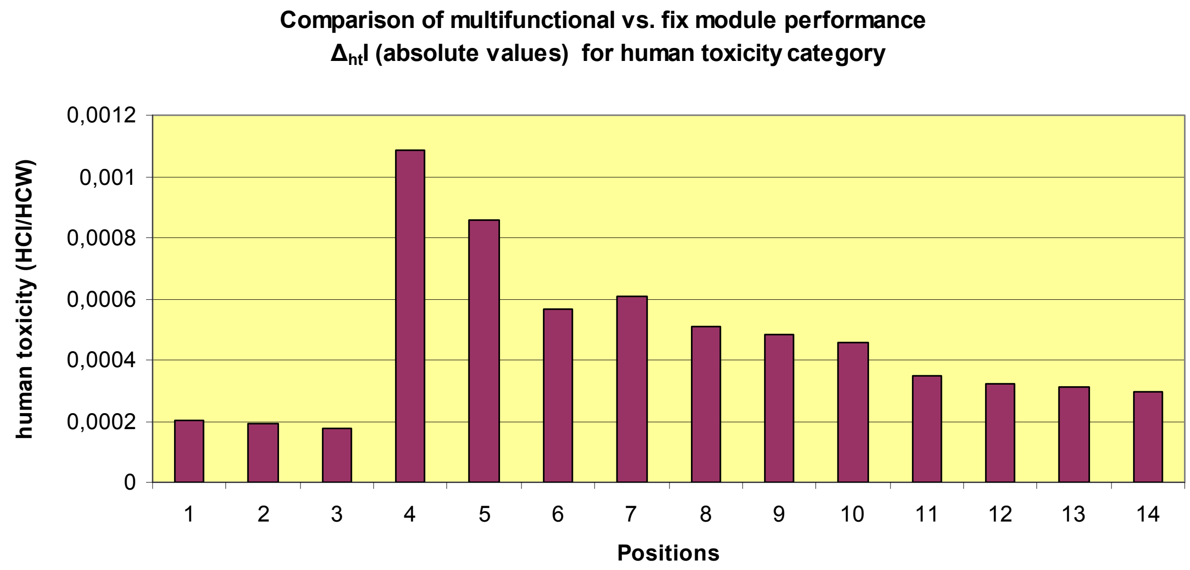


(Ap.15-1 f)

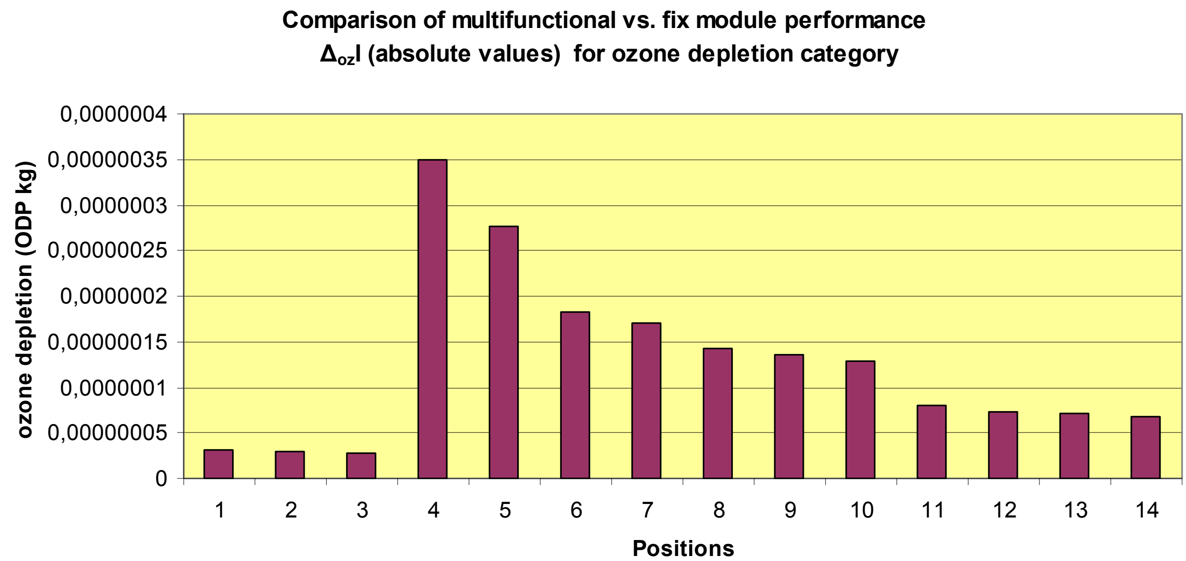


(Ap.15-1 g)

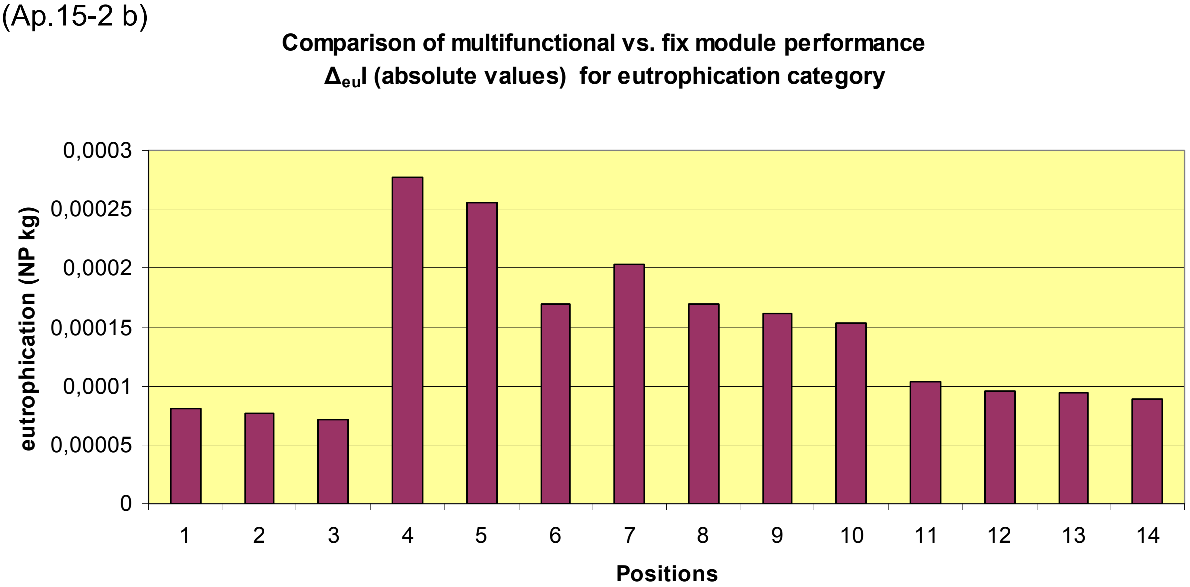
Graph Ap.15-1 (a) to (g) Performance difference between the multifunctional adjusted modules and the fix modules per position per environmental impact category for the case of elementary cut-off criterion 4b



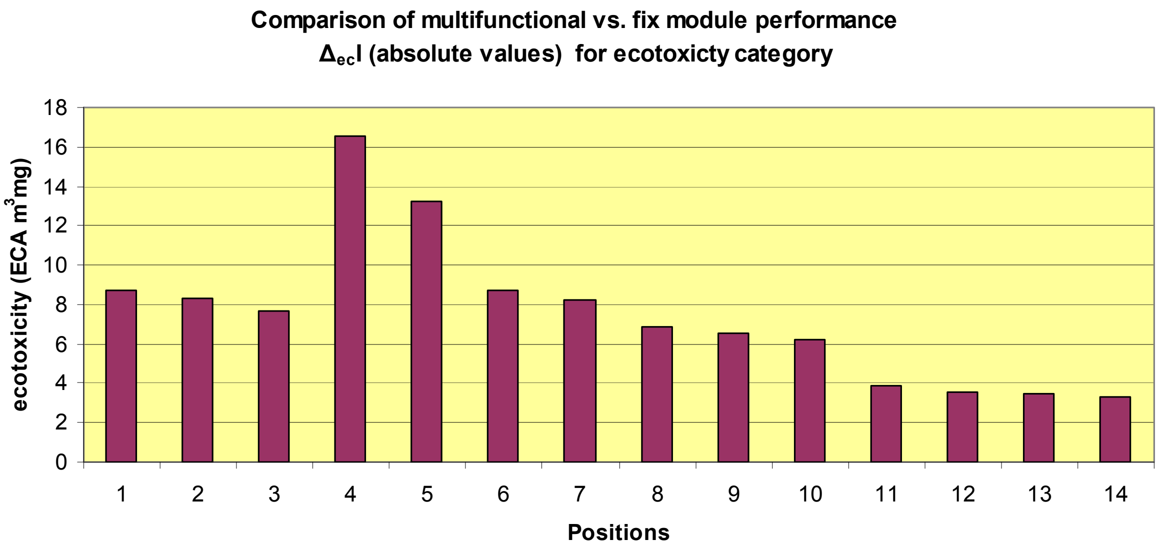
(Ap.15-2 a)



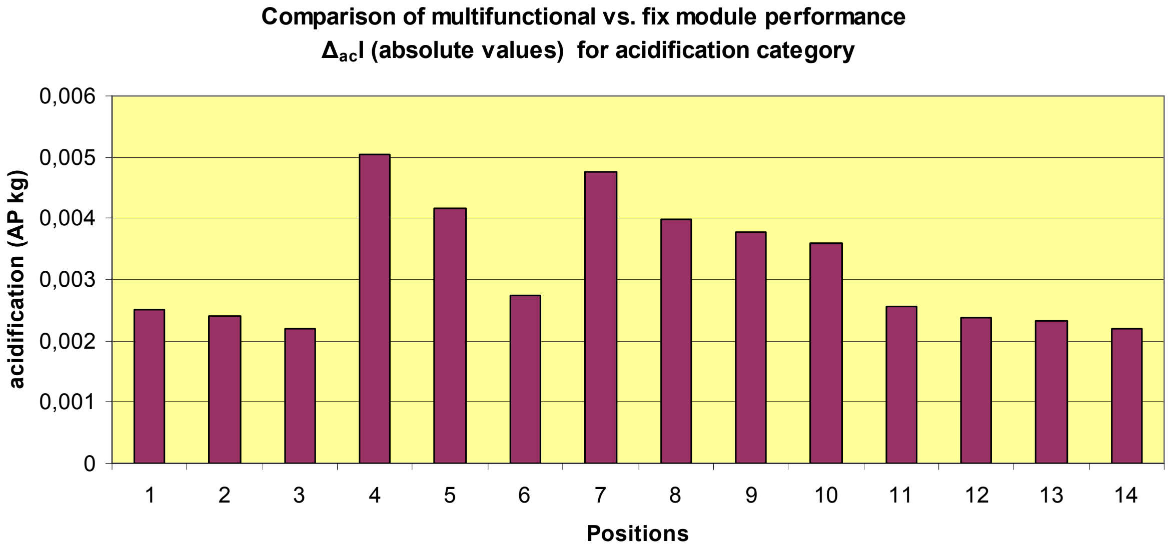
(Ap.15-2 b)



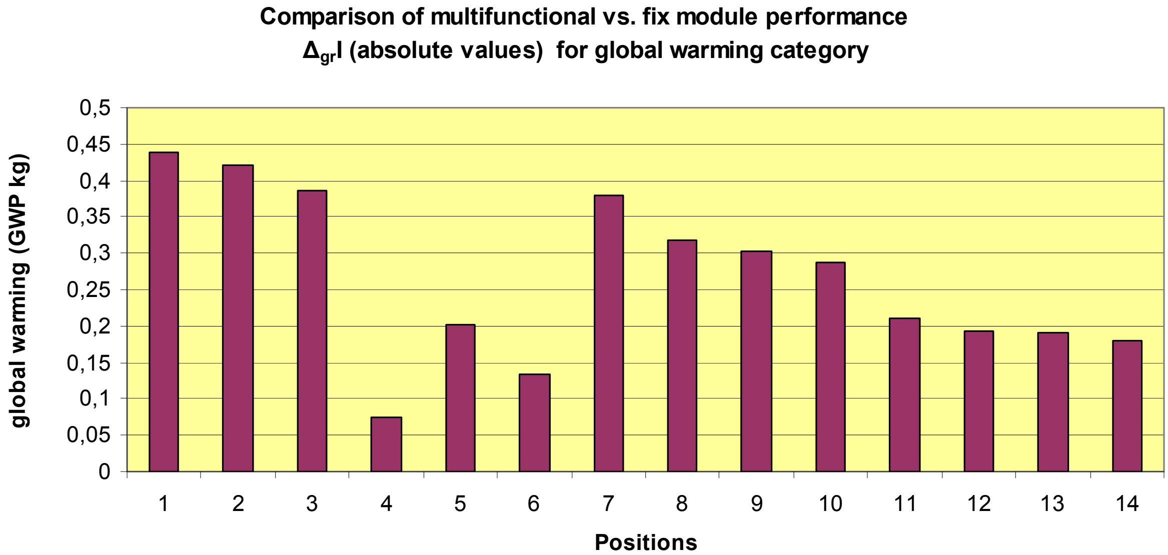
(Ap.15-2 c)



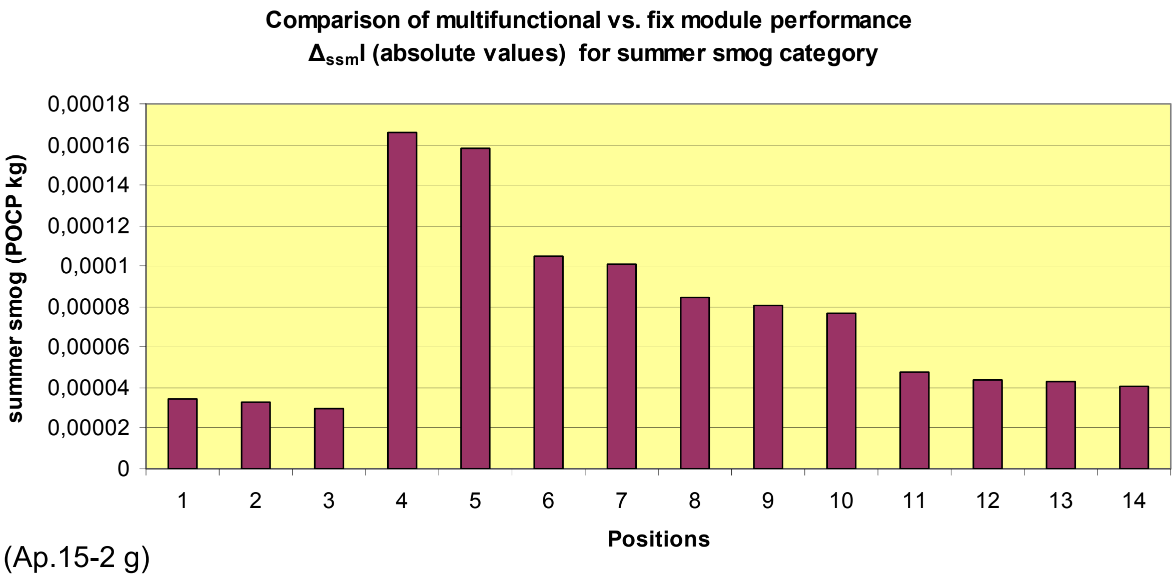
(Ap.15-2 d)



(Ap.15-2 e)



(Ap.15-2 f)



(Ap.15-2 g)

Graph Ap. 15-2 (a) to (g) Performance difference between the multifunctional adjusted modules and the fix modules per position per environmental impact category for the case of environmental impact cut-off criterion 6b