"Welcome to the Jungle" - Survival of the Fittest Environmental Screening Indicators?

Marcel Hagelüken*[1], Karsten Schischke[1], Jutta Müller[2], Hansjörg Griese[2]

[1] BeCAP c/o TU Berlin, Research Center for Microperipherics, Dept. Sustainable Technologies, Berlin,Germany
[2] BeCAP c/o Fraunhofer IZM, Dept. Environmental Engineering, Berlin, Germany

* Corresponding Author, marcel.hagelueken@izm.fraunhofer.de, +49 30 464 03 139

Abstract

The implementation of Design for Environment in companies' R&D departments typically relies on benchmarking of different design options from the environmental (and economical) point of view. Hence, the application of screening methods and indicators is the first choice in supporting decisions in electronics design. This paper brings light into the jungle of available indicators and explores which might be applicable for which focus. Several methods for eco-design support in the electronics industry are analyzed and compared. Within the different classes, many methods show certain similarities. Some could even be merged to form more sophisticated indicators. Further development should concentrate on the industry's demands and the legal requirements, especially those on eco-profiles as described in the upcoming EuP directive. These eco-profiles are likely to be prepared iteratively using the "fittest" environmental screening assessment methods.

1 Introduction

Eco-design of electrical and electronic equipment is a sophisticated effort. For decision making in industrial design of products and processes, technical, economical, environmental, and further aspects have to be regarded and weighted against each other. It is hence important to the persons involved, that all aspects can be represented in comprehensible and traceable form. Life cycle thinking is required, but full Life Cycle Analysis (LCA) is rarely applicable due to numerous constraints like complexity of electronics and its manufacturing, short innovation cycles, gaps concerning specific and generic data, etc.

The implementation of Design for Environment in companies' R&D departments typically relies on benchmarking of different design options from the environmental (and economical) point of view: Minimum data requirements, transparent methodology, and clear design guidance are the key requirements to assessment tools.

Hence, the application of screening methods and indicators is the first choice in supporting decisions in electronics design. Generally, the fields of application of environmental screening indicators for Design for Environment are, e.g.:

- measuring performance of a product, process, or company (e.g., product declaration)
- controlling of environmental policy targets
- benchmarking products, product generations, processes, production sites, or companies
- improving design of an existing product for the next product generation (redesign)
- optimizing design of a newly developed product
- quick and early prioritizing a set of design options
- identification of priorities for future improvement efforts (product or process related)
- ranking of appropriate end-of-life options (decision for a preferred end-of-life option)
- optimization of end-of-life processes and logistics
- preparation of more detailed Life Cycle Analysis studies

The large variety of fields of application for environmental assessments is also reflected by the number of screening indicators developed in the last ten years: "Keep it simple and aim at a specific design aspect" is the main idea behind these indicator developments. Thus, due to the specific approaches, no one-fits-all solution is available.

Decision on which indicator is the best for a certain task depends primarily on the questions: "Which kind of decision do I have to make? What are the basic facts?" This paper brings light into the jungle of indicators and explores which indicator might be applicable for which focus. Additionally, we have observed an “evolution” similar to Darwin’s theory: Convincing concepts gain ground; other concepts have never really left the “eco-design laboratories”.

2 Overview of existing methods

The following overview – see table 1 and the following sections – is based on a selection of assessment tools frequently applied in the electronics industry. Hence, this overview cannot be complete and is only based on some exemplary tools. The inclusion in this study does not mean a preference or recommendation for a tool. There are more tools on the market or currently developed.

The overview is based on available literature. Information on the methods and tools had to be summarized by the authors; therefore we apologize for not being able to explain all features and details. Nevertheless, we have focused on giving a fair, neutral description of each method.

To further shorten this overview, the numerous tools assessing energy inventories and balances have not been included, as these are more or less based on the method of the cumulative energy demand (see below) and mostly differ in which parts of a life cycle are analyzed.

2.1 Basic methods

Two simplified methods for mass and energy balances have been developed that implicitly reflect environmental impacts related to the movement of masses (MIPS) and energy consumption/conversion (KEA). These methods form the basis for many other simplified indicators.

Material Input Per Service Unit (MIPS): The MIPS concept [1] non-qualitatively estimates impacts on the environment by quantifying the amount of resources used for manufacture of a product. The different amounts of resources are then weighted using their material intensities. These values reflect the amount of movement of biotic or abiotic raw material, water, air, and earth in order to extract a certain amount of the desired resource from nature. Thus, all materials and energies used in the life-cycle of a product are lead back to the corresponding resources and necessary amount of material movement in order to extract them.

Cumulative Energy Demand (KEA): The KEA ("Kumulierter Energie Aufwand") concept [2][3] bases on the assumption that data on energy consumption are easily measurable and accessible. As many environmental impacts during a product’s life-cycle are related to the emissions of energy conversion processes, the aggregated sum of all primary energy inputs to the product’s life cycle (including those for raw material extraction and supply) is used as an indicator for these impacts.

Comparison: Both MIPS and KEA do not directly calculate environmental effects but use related operations (material movement and energy consumption) to implicitly reflect impacts. Greater simplifications are achieved regarding the impact assessment.

2.2 Methods based on material intensities

These methods base on mass balances and evaluate the environmental impacts of mass flows, generally directly or indirectly regarding the aspect of resource consumption.

Eco-Efficiency Analysis - Material Consumption (EIA-MC): Within the BASF eco-efficiency analysis [4], the raw material consumptions of products and processes are weighted according to the calculated raw material years of reserves, i.e., how long the particular raw material will be producible with today’s economical methods and assumed that the consumption stays the same.

Eco-Efficiency Potential Assessment (E2-PA) – Material Intensity, Recovery Intensity, Duration Intensity: Based on the mass balance of the system under study (either product or process), the E2-PA method [5] evaluates material flows regarding the calculated reserves of resources. This is called the Material Intensity. The Recovery intensity expresses the saved Material Intensity due to recovery of a resource after subtraction of the Material Intensity of the recovery process. The Duration Intensity is the relation between lifetime of the product and the total material intensity of the product. See also 2.3 for the Hazardous Material Intensity.

Factor X – Reduction of Resources, Reduction of harmful substances: The Factor X [6] describes the relation between the eco-efficiency before and after a change in products or processes. Environmental improvement is assessed as reduction of material and toxic material amounts. Energy is also assessed but has been left out in this compilation as it is done with all methods presented.

Comparison: The EIA-MC and E2-PA methods work similar, as they relate mass flows of resources to calculated reserves and both methods can be regarded as compatible. There are similarities to the MIPS concept, though it does not include the reserves of raw materials - only the scarcity of a resource via the material movement for its extraction.

Class	Name	Organisation/Company	Type	Data Input by User	Background Data Requirements	Type of Result/Indicators
Basic methods	Material Input Per Service unit (MIPS)	Wuppertal Institute for Climate, Environment, and Energy	Material intensity	• Mass balances of processes and materials ("material intensities")	• Database on mass balances of (up- and downstream) processes and materials	Single number
	Cumulative energy demand (KEA)	VDI/Umweltbundesamt	Energy balance	• Energy balances of processes and materials	• Database on energy balances of (up- and downstream) processes and materials	Single number
Material Intensity	Eco-Efficiency Analysis - Material Consumption	BASF AG, Ludwigshafen, Germany	Material intensity	• List of raw material consumption of processes and their masses	• Calculated reserves for raw materials	Single number
	E2-PA Material Intensity	Environmental Management for Sustainability, Inc., Japan	Material intensity	• Mass balances of processes and materials	• Reserve of a resource • Annual production rate of a resource	Single number
	E2-PA Recovery Intensity	Environmental Management for Sustainability, Inc., Japan	Material intensity	• Mass balances of processes and materials	• Reserve of a resource • Annual production rate of a resource • Resource consumption of recovery processes • Efficiency rates of recovery processes	Single number
	E2-PA Duration Intensity	Environmental Management for Sustainability, Inc., Japan	Material intensity	• Mass balances of processes and materials • Lifetime of the product • Total consumption resource intensity	• Reserve of a resource • Annual production rate of a resource	Single number
	Factor X - Reduction of Resources	Mitsubishi Electric, Japan	Material intensity	• List of components of a product ("Bill of Materials") and their masses • List of material contents of components and their masses • Reduction of material consumption • Increase of recycled material	• Detailed knowledge on product design • Detailed knowledge on product properties • Selection of reduction items derived from this knowledge	Single number
	Factor X - Reduction of Harmful Substances	Mitsubishi Electric, Japan	Material intensity	• List of components of a product ("Bill of Materials") and their masses • List of material contents of components and their masses • Reduction of the mass of harmful substances	• Detailed knowledge on product design • Detailed knowledge on product properties • Selection of reduction items derived from this knowledge	Single number
Hazards by product contents(cont. on next page)	Product Toxicity Index	Motorola Inc., Schaumburg (IL), USA	Relative toxicity of product contents	• List of components of a product ("Bill of Materials") and their masses • List of material contents of components (no quantities required)	• Published legislative limits of hazardous substances (e.g. ChemVerbotsV Germany, US EPS RCRA 33/50)	Single number
	IZM EE Toolbox - Toxic Potential Indicator (TPI)	Fraunhofer IZM, Dept. Environmental Engineering, Berlin, Germany	Relative toxicity of product contents	• List of components of a product ("Bill of Materials") and their masses • List of material contents of components and their masses	• R-Phrases • Maximum tolerable workplace concentrations (MAK) • Water pollution classes (WGK)	Single number
	IZM EE Toolbox - Toxic Emissions Potential (TEP)	Fraunhofer IZM, Dept. Environmental Engineering, Berlin, Germany	Relative toxicity of product contents and related emissions	• List of components of a product ("Bill of Materials") and their masses • List of material contents of components and their masses • Type of potential chemical emissions related to material contents	• R-Phrases • Maximum tolerable workplace concentrations (MAK) • Water pollution classes (WGK) • Chemical structure of related emissions	Single number
	IZM EE Toolbox - Simple Emissions Screening (SES)	Fraunhofer IZM, Dept. Environmental Engineering, Berlin, Germany	Relative impact potential of complete product incineration	• List of components of a product ("Bill of Materials") and their masses • List of material contents of components and their masses	• Impact assessment methodology for emissions of complete combustion (CO_2, SO_x, NO_x, metal oxides, etc.), e.g. Eco-Indicator 99	Depending on impact assessment methodoloy
	Eco-Efficiency Analysis - Toxicity Potential	BASF AG, Ludwigshafen, Germany	Relative toxicity of product contents and/or process inputs/outputs	• List of inputs and outputs of processes along the life-cycle and their masses • Use patterns • Exposure Route	• R-Phrases • Total production volume of substances	Single number

Table 1: Overview of environmental screening assessment methods (cont. on next page)

Class	Name	Organisation/Company	Type	Data Input by User	Background Data Requirements	Type of Result/Indicators
Hazards by product contents(cont.)	Monoethylene Glycol Equivalents (MEG)	Öko-Institut e.V., Freiburg, Germany	Relative toxicity of product contents	• List of components of a product ("Bill of Materials") and their masses • List of material contents of components and their masses	• R-Phrases • TRGS 440 potency factor model	Single number
	E2-PA Hazardous Material Intensity	Environmental Management for Sustainability, Inc., Japan	Material intensity	• Mass balances of processes and materials	• Reserve of a resource • Annual production rate of a resource • Resource consumption of detoxification process or recycling process	Single number
Hazards by process operation	IZM EE Toolbox - Process Toxicity (ProTox)	Fraunhofer IZM, Dept. Environmental Engineering, Berlin, Germany	Relative toxicity of process inputs/outputs	• List of inputs and outputs of a process and their masses	• R-Phrases • Maximum tolerable workplace concentrations (MAK) • Water pollution classes (WGK)	Single number
	Eco-Efficiency Analysis - Emissions	BASF AG, Ludwigshafen, Germany	Relative impact potentials of emissions during life-cycle	• List of emissions of a process and their masses	• Characterisiation values of different air emission categories (GWP, AP, etc.) • Limits of wastewater regulation for calculation of critical volumes • Waste disposal costs for "emission" of solid waste • Weighting factors (for aggregation to single number)	Single number
End-of-Life	Recyclability Evaluation Method (REM)	Hitachi Ltd., Japan	Disassembly and recyclability of product contents	• List of components of a product ("Bill of Materials") and their masses • Compilation of disassembly operations • List of material contents of components (no quantities required)	• Process data on disassembly operations (Costs) • Process data on recycling/disposal operations (Costs, Revenues)	Ranking based on recycling rate (and costs) for each recycling/disposal process
	IZM EE Toolbox - Recycling Potential Indicator (RPI)	Fraunhofer IZM, Dept. Environmental Engineering, Berlin, Germany	Recyclability of product contents	• List of components of a product ("Bill of Materials") and their masses • List of material contents of components and their masses	Process profiles of recycling and disposal processes: • Range of desired substance concentrations • Range of undesired substance concentrations	Ranking based on single number for each recycling/disposal process
	Quotes for Environmentally Weighted Recyclability (QWERTY)	TU Delft, The Netherlands	End-of-life scenario analysis	• List of components of a product ("Bill of Materials") and their masses • List of material contents of components and their masses • Definition of scenarios	• Transfer coefficients of materials within end-of-life processes • Data on environmental impacts of extraction and production of materials • Data on on environmental impacts of end-of-life processes	Ranking based on single number for each recycling/disposal process
Eco-Design Implementation	Eco-PaS	Katholieke Universiteit Leuven, Mechanical Engineering Departmen, Heverlee, Belgium	Analysis of environmental impacts/issues related to product functions ("functional parameters") and their fulfillment by standard solutions	• Definition of required functions • Functional parameters (constraints)	• Database with known solution principles • Expert system for technical feasibility • Environmental assessment method • Modelling of technical parameters depending on functional parameters	Ranking based on the environmental assessment as a function of the functional parameters
	Eco-Value Analysis	Darmstadt University of Technology, Institute for Product Development and Machine Elements, Germany	Analysis of environmental impacts/issues related to product functions (same for costs)	• Detailed analysis of the product, functional structure of the product • Environmental impacts per component • (Costs per component) • Allocation of functions to components	• Customers requirements and their weights • Knowledge on functional interrelations between product components, engineering metrics, and customer demands	Portfolio: Importance to customer in relation to environmental value (same for economic value)
	Quality Function Deployment for Environment (QFDE)	National Institute of Advanced Industrial Science and Technology, Ibaraki, Japan; *et. al.*	Analysis of environmental impacts/issues related to product functions	• Detailed analysis of the product, engineering metrics of the product • Numerical rating of the interrelation between voice of customer and engineering metrics ("relational strength") • Numerical rating of the interrelation between engineering metrics and component characteristics ("relational strength")	• Voices of customers and their weights (market survey) • Knowledge on functional interrelations between product components, engineering metrics, and customer demands	Numbers: Matrix of improvement rates of engineering metrics regarding customer requirements

Table 1: Overview of environmental screening assessment methods (cont.)

The Factor X-Assessment does not relate the reduction of material consumption and hazardous material content to the reserves of resources. However, the reductions of materials could be assessed with the MIPS, EIA-MC or E2-PA methods. The reduction of hazardous material content is not sorted into the methods regarding the hazardous material content of products (section 2.3) as no evaluation of the toxicity is carried out.

2.3 Methods regarding hazards due to product contents

These methods evaluate the potential hazards of materials incorporated in products and thus are only implicitly connected to physical material flows.

Product Toxicity Index: The Product Toxicity Index [7] assesses the qualitatively known materials contained in product components using legislative threshold concentrations. Each threshold value is related to defined reference value (e.g., 50.000 ppm). The resulting score is multiplied with the component's weight and all components' scores are summarized to the product's toxicity index.

IZM EE Toolbox - Toxic Potential Indicator (TPI), Toxic Emissions Potential (TEP), Simple Emissions Screening (SES): The TPI [8][9] assesses the potential hazards of the product material content by evaluating information available in the material safety data sheets. Each R-Phrase (see [10]), MAK, and WGK corresponds to a numerical value on a logarithmical scale.. The mass fraction of a material within the product multiplied with its specific TPI (ranging from 0 (no hazard) to 100 (extreme hazard)) results in the product's TPI.

The TEP [9] assesses the hazards that may be caused by emissions formed from the product's material contents under different conditions during the lifetime. Using rules of thumb, literature data, and expert knowledge, potential emissions of the product material content are identified. These emissions are weighted, grouped in substance classes, and aggregated according to their specific TPI values. The highest values from each substance class are then aggregated to the TEP value.

The SES [9] bases on the thought experiment of a complete combustion of the product. The amounts of the resulting emissions can be assessed using different impact methods, e.g., the Eco-Indicator method [11].

Eco-Efficiency Analysis – Toxicity Potential (EIA-TP): The Toxicity Potential [12] evaluates substances using the R-Phrases of the EU classification [10] by assigning a numerical score reflecting the toxic effect. Additionally, the number of persons that may be exposed to a substance (the use pattern), the total production volume, and the exposure route are also numerically evaluated, thus describing the exposure. The product of toxic effect and exposure results in the toxicity potential score of a substance (see also 2.4).

Monoethylene Glycol Equivalents (MEG): The MEG method [13] uses R-Phrases for the assessment of a substance. According to the TRGS 440 [14], each R-Phrase is translated into a potency factor that corresponds to the severity of the hazard described by the R-Phrase. This potency factor is related to a reference value (the value of Monoethylene Glycol).

Eco-Efficiency Potential Assessment (E2-PA) – Hazardous Material Intensity: Working like the methods described in 2.2, the Hazardous Material Intensity [5] reflects the potential hazards due to the toxic material contents of a product by calculating the Material Intensities of processes necessary to detoxicate and treat the product or to safely recover the hazardous material. It can be thus used to express the severity of the hazard potential of the product's material contents.

Comparison: In contrast to the other methods, the Product Toxicity Index does not require the real concentration of a substance within the product but works with threshold values.

The PTI, TPI, TEP, EIA-TP, and MEG methods use legislative data like R-Phrases or threshold values to assess the toxicity of a substance. Especially TPI/TEP, EIA-TP, and MEG show methodic similarities.

The TEP and SES methods exceed the usual toxic assessment of a product's material contents by also taking account of related emissions that might emerge under different conditions during a product's lifetime.

The E2-PA hazardous material intensity method covers a different aspect of hazardous materials: While other methods focus on possible risks due to a product's material content, this method regards the efforts of detoxification or recovery of hazardous materials during end-of-life processes.

2.4 Methods regarding hazards due to process operations

These methods evaluate the potential hazards and damages due to process operations.

IZM EE Toolbox - Process Toxicity (ProTox): The ProTox [9] uses the specific TPI values to assess the potential hazards of in- and outputs of processes, including emissions.

Eco-Efficiency Analysis - Emissions (EIA-Emissions): The emissions assessment within the Eco-Efficiency Analysis [4] differentiates process related emissions to air, water, and soil. Emissions to air are assessed using the impact assessment categories. Emissions to water are characterized by calculating the necessary dilution of the emission to meet the threshold values.. Emissions to soil are separated into three waste types. These three types are characterized using the costs for land filling.

Comparison: The ProTox method focuses on the potential toxicity of materials that are used in or emitted from a process. It does not include the exposure route. The EIA-Emissions method does not account the inputs of a process but differentiates emission pathways.

Mentioned above (see 2.3), the EIA-Toxicity Potential method can also be used to assess the toxicity of process in and outputs. This method has many similarities to the ProTox method and additionally includes factors for the potential exposure.

2.5 Methods regarding End-Of-Life

These methods are used to analyze the performance of the product in end-of-life processes, i.e., recycling and disposal processes.

Recyclability Evaluation Method (REM): The recyclability evaluation method [15] enables the designer to enter the disassembly procedure of product components. Subsequently, costs and revenues of recycling processes for these components can be calculated.

IZM EE Toolbox - Recycling Potential Indicator (RPI): The Recycling Potential Indicator [9] correlates the product material contents with the process profiles of recycling and disposal processes. These process profiles include ranges for the mass fractions of wanted and unwanted (or forbidden) materials contained in a product or its components. The better the correlation with a process profiles (e.g., copper smelter) the less problems and the higher revenues are to be expected when applying the specific process.

Quotes for Environmentally Weighted Recyclability (QWERTY): The QWERTY method [16] starts at the point of the disposal of a product. Two standard end-of-life scenarios are calculated and assessed using an environmental impact method (e.g., Eco-Indicator [11]): One scenario represents the recovery of all materials and the other represents the worst possible end-of-life scenario. The product and its parts are then analyzed regarding different end-of-life scenarios. These scenarios can be compared using their scores, which lie between the scores of the two reference scenarios.

Comparison: The REM and RPI methods do not explicitly evaluate environmental impacts during the end-of-life phase. The focus of these methods lies on the technical performance of the product or product parts in treatment processes The REM method also includes an analysis of disassembly operations. Hence, both methods focus on the design for recyclability of a product.

In contrast to this, the QWERTY method aims primarily at the whole end-of-life management of products, using more comprehensive modeling of take-back and recycling processes to support decision finding.

2.6 Methods for Eco-Design implementation

These methods focus on the identification of environmental (and economical) “hot-spot” components of a product to support eco-design. This is done by analyzing the functional relationships (quantitatively or qualitatively) between the product’s functions and environmental impacts.

Eco-Efficiency Parametric Screening (Eco-PaS): The Eco-PaS method [17] aims at establishing a quantitative functional relationship between the functional parameters of a product (e.g., the isolation of rotational motion using a ball bearing and the desired maximum rotational speed) and its environmental impacts and costs. These relationships may be derived either empirically or theoretically. Various methods can be used for the assessment of environmental impacts and costs. As a result, the estimated environmental impacts and costs of different technical solutions in dependence of different functional parameters and constraints can be compared.

Eco-Value Analysis: The Eco-Value Analysis [18] investigates a product's components regarding their practical (i.e., necessary for technical and economical usability of the product) and added functions (prestige gains, esthetics). The different components are allocated to the fulfillment of practical and added functions of the product. Subsequently, the environmental score and costs of a component (measured using an environmental impact method) are allocated accordingly. Thus, the contribution of each function to costs and environmental impacts can be determined.

Quality Function Deployment for Environment (QFDE): The QFDE method [19] is a matrix oriented method. First, a matrix is created reflecting the correlation between required and desired functions (e.g., easy to transport, low energy consumption) and the engineering metrics (e.g., amount of energy consumption). The results are weighted according to the customer requirements and reflect the importance of the engineering metrics to the most desired functions. Environmental aspects are included as required and desired functions; hence the correlation of these with engineering aspects has to be already identified and known. In the second matrix the weighted engineering metrics are correlated with the different product components. The third matrix lists possible improvements in the components' design regarding the engineering metrics. The fourth and last matrix combines the possible improvements with the correlation between engineering metrics and desired functions and the customer weights of these functions. The result is numerical ranking of functions that are characterized by high customer weight and high improvement rates of correlated engineering metrics.

Comparison: The Eco-Value and QFDE methods use qualitative relationships between environmental impacts and product functions while the aim of the Eco-PaS method is the identification of quantitative functional relationships, either from empirical or theoretical considerations. Hence, all three methods require expert knowledge regarding which product functions and components are connected to environmental impacts. To evaluate these impacts, any environmental indicator can be implemented.

3 Conclusion

Several methods for eco-design support in the electronics industry have been analyzed and compared. Two main trends can be identified:

1. Most indicators do not only require a bill of materials (i.e., list of components of a product) but also the material composition of these components.
2. Many methods and indicators rely on legislative regulations and data to assess the hazards or toxicities of substances.

The first trend will be supported by legal and industry activities, e.g., RoHS directive [20], Umbrella Specs [21], IMDS [22] regarding material declaration practice of products and components. Hence, screening methods which base on the material composition of a product will become easier to use.

The second trend is generally fulfilled according to the legal process of registration and assessment of hazardous substances. The upcoming REACH regulation [23] will further strengthen this approach.

Interpretation of indicators and screening results always demands expert knowledge, as the validity is limited depending on the grade of simplicity of the methods. Hence, all methods should always stress transparency (including calculation methods and data quality).

Carrying out an assessment is only one step in eco-design. The implementation of the assessment results within the (re-)design process has also to be realized. The methods presented in section 2.6 are examples of such an implementation. To be applicable for these and other design methods, transparency and quality reporting of screening assessments is also required.

As within the different classes many methods show certain similarities, there is potential to learn from each other. Some could even be merged to form more sophisticated indicators. Further development should concentrate on the industry's demands and the legal requirements, especially those on eco-profiles as described in the EuP directive [24]. These eco-profiles are likely to be prepared iteratively using more and more significant assessment methods.

As in nature, the survival of the fittest (methods) will thus be determined by the crossover of the fittest members of the present generation to form a new generation that meets the requirements of the changed (business and legal) environment. However, this will not mean the survival of only one method – as nature demonstrates by its diversity. Another key to success is the specialization of methods to the requirements of a specific field of application, e.g., screening indicators limited to certain product groups.

Therefore, we call all interested parties to join a discussion on harmonization and standardization of simplified assessment methods, regarding, e.g., significance and limitations of results, data quality reporting, generic component/process data, and presentation of results.

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