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ESTIMATING ENVIRONMENTAL IMPACTS: THE USE-PHASE-ANALYSIS-MATRIX - A USE PHASE-CENTRED APPROACH

Christof Oberender and Herbert Birkhofer

Abstract

Knowledge about the relevant environmental impacts of products and processes are an essential condition in design for environment (DfE). Use processes often have a dominant influence on the environmental impacts during the whole life cycle of products. Designers are frequently overwhelmed in determining environmental impacts, due to the requirements in experience and time to carry out life cycle assessments with an appropriate accuracy. The presented Use-Phase-Analysis-Matrix (UPA-Matrix) was developed, to support the designer in a structured determination of relevant inventory data in the use phase. The structure of the UPA-Matrix is derived from the MET-Matrix and AT&T-Matrix. A rough estimation method like Eco-indicator '99 is intended to process the results. The paper describes the structure and the procedure of the method. Special checklists to support the determination of inventory data in the use phase were developed. A validation of the UPA-Matrix and the accompanying checklists was carried out in project seminar on DfE of the Darmstadt University of Technology. In the paper, the method is applied on a hand drying system with a multiple used textile tape.

Keywords: DfE, life cycle assessment, design for use, behaviour aspects on sustainability.

1 Introduction

Products are essentially developed for their use. Accordingly, the use phase has a high significance within the total life cycle. With respect to environmental impacts during the products' life cycle, the use phase of products plays an important role, too, especially in the case of so-called "active" products [1], [2]. A variety of specific life cycle assessments (LCA) of products, such as refrigerators, television sets or vacuum cleaners show that up to 90% of the total life cycle-related environmental impacts emerge from the use phase [2], [3]. Therefore, it is important to analyse use processes, to identify their inputs and outputs of materials, and their energy consumption, in order to estimate the main environmental impacts. A detailed analysis of use processes is necessary to compare different product concepts or embodiments and to gain first ideas for environmental improvements. Besides this, environmental impacts during the use phase are closely related to the users' behaviour.

Designers are frequently overwhelmed in determining environmental impacts. This task requires a lot of experience due to the complexity in carrying out a LCA with an appropriate accuracy. Therefore, designers need a user-friendly aid in estimating environmental impacts, with the aim of identifying ecological weak points, determined in the use phase. The method is applicable to consumer products and capital goods as well as to product-service-systems.

2 The functional unit - basis of the engineering design process

The main aim of every engineering design process is the fulfilment of the functional unit, demanded by a specific customer or by the anonymous market. The functional unit clearly defines the specifications of the functions, respectively the performance characteristics of the product and creates the basis for the list of requirements. Examples of the functional unit are, e.g., “washing 15 kg of colour and 5 kg of boil laundry per week for 9 years”, or “pressing 0.2 litres of orange juice every day for three years”. The functional unit is served by the definition and realisation of use processes, for which products must be developed. Therefore, the use process, which enables the functional unit, is the essential aim of every engineering design process.

Before starting the design process it must be decided, how the functional unit will be fulfilled. Against the backdrop of developing sustainable solutions, there are two options for fulfilling the functional unit: Besides the conventional selling of products, the question of selling services or selling product-service-systems, instead of selling products must always be answered. In any case, the product must be technically, economically, and ecologically optimised for the use phase. There are many methods for the technical and economical improvement of products and their processes which support designers in the design process, described in PAHL [4] and EHRLENSPIEL [5]. However, design for environment requires additional methods.

3 MET-Matrix and AT&T-Matrix

BREZET et al. [6] developed a MET-Matrix, which looks at the whole products’ life cycle from raw material production to end-of-life. In this matrix, the life cycle phases are arranged in rows. The letters M, E and T stand for Material, Energy and Toxic emissions. The assessment of these inventory data appears in the columns of the matrix. BREZET suggests applying this MET-Matrix just for determining inventory data. Items which require attention in the design process are selected without subsequent life cycle impact assessment or rough estimation just by analysing the quantity of the materials or the energy consumption.

The AT&T-matrix was developed by GRAEDEL et al. [7]. In this matrix, the products’ life cycle phases are also arranged in rows. The columns serve to determine materials’ consumption, energy use, and solid, liquid and gaseous residues. GRAEDEL follows the aim of assessing environmental impacts without carrying out a full LCA. The AT&T-Matrix quantifies environmental impacts with a rating from zero (negative impact) to four (positive impact), based on experience, manufacturing surveys or checklists [7].

Both matrices focus on the whole products’ life cycle. There is no special focus on the use phase and its processes.

4 The Use-Phase-Analysis-Matrix (UPA-Matrix)

4.1 Initial situation

Knowledge of relevant environmental impacts of products in the use phase is an essential condition in design for environment. Accordingly, the designer must gain clarity about the relevant inputs and outputs of materials, as well as the energy consumption of anticipated use processes. The designer is often overwhelmed in assessing environmental impacts of the conceptual or the embodiment design of his product. In addition, there is usually not enough time in the workday to carry out a full LCA, according to ISO 14001. But an adequately assessment of environmental impacts, practicable in the ordinary weekday, is possible by using rough estimation methods [8] like Eco-indicator ’99 (EI ’99) [9] and because of its low expense in time.

To support this, the Use-Phase-Analysis-Matrix (UPA-Matrix) was developed. This matrix supports the designer in a guided and structured analysis of the use phase to determine all relevant inventory data, with the aim of a subsequent assessment with EI ’99 [9] in combination with the material and process database IdeMat 2002 [10]. The method can be used by experienced designers, as well as by novices in the field of DfE.

4.2 Structure of the UPA-Matrix

The structure of the UPA-Matrix is derived from the structures of MET-Matrix and AT&T-Matrix. The UPA-Matrix focuses on the use phase (see Figure 6). Its sub-phases (see Figure 1) are listed in the first column. Supplementary, there is a column for collecting use processes to ensure their completeness. The following columns serve to note inputs and outputs of materials, related processes, e.g. manufacturing or disposal, and the energy consumption. The UPA-Matrix shows no column to note toxic emissions, because these are already considered in the values of EI ’99 and IdeMat 2002. The last column allows the notation of the influence of the users’ behaviour. In chapter 4.3 further information about the columns are given. The sub-phases are described in the following.

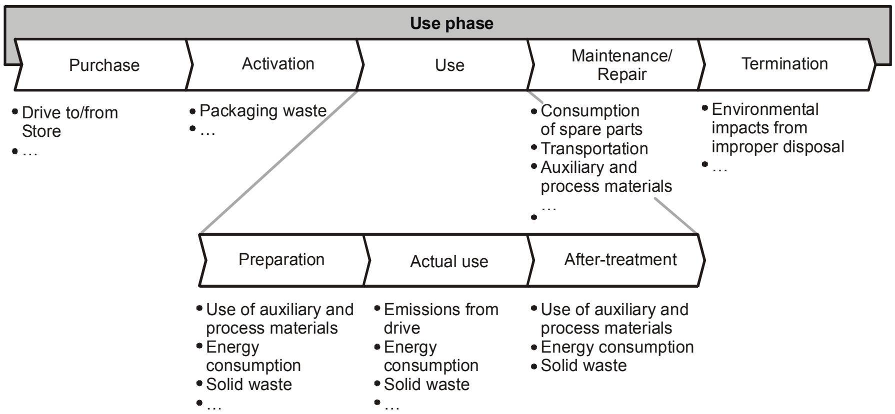

Figure 1. Structuring the use phase in sub-phases and related environmental impacts [2]

Purchase phase: The use phase starts with the purchase phase. Here, the user decides on a certain product. In addition to the obvious environmental impacts from the ride to the store, the user is gathering information about the product in this phase.

Activation: In the sub-phase activation, the product is initially being used. Environmental impacts are mainly packing waste. An impact on subsequent sub-phases may come from the shaping effect of the initial use the intensive use of the instruction set. Environmental impacts from erroneous behaviour in this sub-phase depend on the users’ knowledge about the product, and are dependent on the quality of the instruction manual.

Use: Within this sub-phase the actual use is performed. Usually, in this phase the major part of the environmental impacts are caused. With regard to the use processes, the three further sub-phases preparation, actual use, and after-treatment can be distinguished.

Preparation: This sub-phase serves to preparation of the product for the actual use. In contrast to the sub-phase starting operation, processes of preparation are executed not just once, but before every single actual use.

Actual use: The sub-phase actual use is divided into active and passive use. In the active use, the essential use processes are executed. All environmental impacts that emerge while not using the product in its origin sense are ascribed to passive use, e.g. stand-by mode.

After-treatment: The main target of the after-treatment is, to transfer the product to the condition, appropriate to the moment before starting preparation. Cleaning processes are executed and auxiliary or process materials must be disposed. In some cases it is hard to place certain processes either to the sub-phase preparation or after-treatment, e.g., the loading of accumulators. But it is just important to consider the environmental impacts at all.

Maintenance and Repair: According to DIN 31051, maintenance subsumes all processes which lead to keep the desired condition. Repair serves to restore the desired condition. Environmental impacts during maintenance and repair stem from the consumption of auxiliary materials and spare parts, transportation or from disassembly and reassembly. Increased impacts on the environment may result in lower ones in other life cycle phases, e.g., when a preventive maintenance results in a longer lifetime [11].

Decommissioning: The decommissioning sub-phase usually starts with a longer period of not using the product, e.g. an intermediate storage before the disposal. Usually, there are no environmental impacts related to that. However, with regard to closed loop economies the delayed entrance into disposal and recycling processes has significant impacts. Other manifestations of the decommissioning may be selling, donating or disposal.

Transportation processes: Transportation processes are not a sub-phase, but nevertheless it is important to consider them. Transportation processes can appear in a sub-phase and at the transition of two sub-phases. Some transportation processes are quite relevant in comparison to other environmental impacts in the life cycle of the product. E.g. the transportation of non-skid chains of 5 kg weight in an automobile over a whole year, approximated 20000 kilometres, leads to the same environmental impact than the production of about 40 kg of polypropylene, including the injection moulding process, according to IdeMat 2002 [10]. In case of a comparative analysis of different systems it is quite relevant to consider transportation processes. One example is the comparative analysis of different systems of hand driers or different systems of citrus presses, where transport plays an important role. Transportation processes will be assigned to the sub-phases of their incidence.

4.3 Procedure

The UPA-Matrix can be applied by single users, as well as in a team. To avoid forgetting relevant environmental impacts, the appliance of the method is supported by checklists, which are especially developed for analyzing processes in the use phase (see chapter 5). In the following, the procedure for carrying out the UPA-Matrix is described (Figure 2).

Step 1: Determining the system boundary: Initially, it is necessary to determine the system boundary of the analyzed object. The object can be a single product or a product-service-system. It is sensible, not to focus just on the product, but to look at the processes in the whole use phase. In addition, the user should be regarded. Often, his/her behaviour has a relevant influence on the execution of use processes and their environmental impacts.

Step 2: Defining of use processes in sub-phases: To carry out a process analysis, it is important to define all use processes. Use processes will be determined separately for each sub-phase to ensure their completeness. Processes, which arise in more than one sub-phase, must be registered each time, if they have different instances. For example, transportation processes in the purchase phase mostly are not identical with transportation processes in the sub-phase actual use or between two other sub-phases. Step two will be carried out for all sub-phases, before starting with step three (see Figure 2).

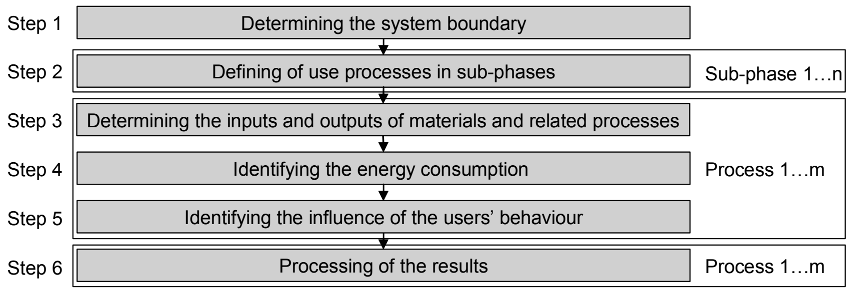

Figure 2. Steps for processing the UPA-Matrix

Step 3: Determining the inputs and outputs of materials and related processes: After determining all environmental relevant processes within the use phase in step two, inputs and outputs of materials will be identified and quantified. In addition, manufacturing and recycling/disposal processes must be determined, if they result from the use phase.

Step 4: Identifying the energy consumption: The energy consumption must be determined for all sub-phases and for transportation processes within and between sub-phases. The declaration of inventory data must be adapted to the subsequent processing with EI '99 and IdeMat 2002. For example, the energy caused by transportation is not declared in litres of fuel, but in ton-kilometres. Materials and emissions that result from energy consumption are quoted in the column of energy consumption, too. This is important to enable traceability.

Step 5: Identifying the influence of the users' behaviour: In this step, impacts of the users' behaviour on environmental impacts will be identified. The users' behaviour, especially erroneous behaviour has a significant influence on the environmental impacts of consumer products in the use phase [12], [13]. It is sensible to reduce these influences by design measures [13]. To reach this, an analysis of the influence of the users' behaviour is needful [2], [12], [14]. The last column of the UPA-Matrix is intended to support the designer in the systematic question of possible influences of the users' behaviour. This must be done for each process in the second column. To assess the relevance, the "error-types and error-causes matrix" [2], [14], [15] and the "Eco-FMEA" [2], [14], [15] support this in a suitable way.

Step 6: Processing of the results: The inventory data, determined with the UPA-Matrix are the input for the impact assessment, based on EI '99 [9] in combination with IdeMat 2002 [10]. If there are no values available in EI '99 or in IdeMat 2002, the needed values can be determined with the LCA tool SimaPro [16]. To get compatible values in SimaPro, the EI '99-methodology in H(ierarchist)-version must be chosen.

5 Checklists for the UPA-Matrix

Derived from checklists for DfE, developed by BREZET et al. [6], TISCHNER et al. [17], WIMMER [18] and WIMMER et al. [19], special checklists were developed. These checklists enable to analyse environmental impacts, which emerge from the use phase (Figure 3 and Figure 4). They are adapted on the appliance with the UPA-Matrix and structured corresponding to the sub-phases of the use phase (see chapter 4.2). The checklists support the designer in a guided and almost complete analysis of use processes.

General data to determine the system boundary

To quantify the in-/outputs of materials and the energy consumption the system boundary must be determined:

- What is the average technical lifespan of the product?
- For how many use cycles is the product designed for?
- How often is the product at work on average?
- How long is the aesthetic life duration of the product?
- Is the product expected to be used until the end of its technical life duration?
- Is the product to be used after the end of its technical life duration in other usage cycles by other users?

Purchase

Which environmental impacts result from transportation to the user?

- How long is the average distance to the user?
- By which means of transport is the major part of the departure distance travelled predominantly?
- Is a special means of transport required?
- Is the delivery of the product carried out by a separate forwarding agent/company? How large are the proportionate environmental impacts?
- Is the transport efficiently conducted?
- What types and amounts of energy are required for the transport?
- What types and amounts of aux. / proc. mat. are required?
- Is an additional transportation packaging required?
- What type of additional transportation packaging is used (size, weight, material, application, availability)?
- What is the mass of the transported product, including its packaging and the additional transportation packaging?

What environmental impacts result from the supply of the product at the sales site?

- Does the service at the sales site have an important influence, e.g. storage period, space consumption (proportionately)?
- What types and amounts of presentation materials for selling the product are used and which materials or energy consumption result from them (proportionately)?

Activation

What environmental impacts result from the activation?

- What types and amounts of auxiliary and process materials and consumption parts are required for the activation?
- Are there any special tools required for the activation?
- What additional environmental damages result from the provision of and the operation with those tools (proportionate)?

What environmental impacts result from the product's packaging?

- What types and amounts of product's packaging come up?
- Is a reusable transportation packaging used? How, respectively, by what means of transport will the return of the transportation packaging occur?
- What possibilities of disposal of the product's packaging or additional transportation packaging exist?
- How will the user dispose of the product's packaging or the additional transportation packaging?

What environmental impacts result from potential erroneous behaviour in the activation?

- Does the instruction manual influences environmental damages, caused by erroneous behaviour? If yes, what?
- What influences do neglected operating instructions or activation by trial and error have on energy consumption or types and amounts of auxiliary and process materials?
- What influences do missing knowledge, low information or lack of skills have on energy consumption or types and amounts of auxiliary and process materials?

What environmental impacts result from the expected surroundings of the product?

- Do additional environmental impacts result from an unfavourable choice of the surroundings?
- If yes, what types and amounts of materials or energy consumption do result?

Preparation

Which environmental impacts result from the preparation?

- What types and amounts of energy are required for the preparation?
- What types and amounts of auxiliary and process materials are required?

Do any environmental impacts result from improper filling capacities?

- What influences do ignored operating instructions or use by trial and error have on energy consumption or types and amounts of auxiliary and process materials?

What environmental impacts result from transportation processes between two uses?

- How long is the average distance between two uses?
- By which means of transport is the transportation carried out? Is a special means of transport required?
- What types and amounts of energy are used for transport?
- What types and amounts of auxiliary and process materials are required?
- What is the mass of the transported product, including its transportation packaging?

What environmental impacts result from the energy supply of mobile products?

- What types and amounts of energy does the charging process require?
- What types and amounts of energy result from the loss in idle of the equipment?
- What amounts of energy result from overcharge?
- What amounts of energy are generated by self-discharge?
- What types and amounts of waste are generated by mobile energy supply?
- What types and amounts of transportable energy storage devices (e.g. batteries) are required?

Figure 3. Checklist 1 for analyzing environmental impacts in the use phase associated with the UPA-Matrix

Actual use (active)

What environmental impacts result from processes during the actual use (active)?

- What active processes are carried out in the actual use?
- What types and amounts of in-/output of materials result from the active processes during the active use?
- What types and amounts of energy are required for the processes during the active use?
- What types and amounts of waste are generated?
- What types and amounts of additional tools or devices are required (proportionately)?
- What types and amounts of energy result from control processes?

What environmental impacts result from misuse?

- What possibilities of misuse exist?
- What misuse processes are expected to be carried out?

What environmental impacts result from the surrounding, in which the product is expected to be used mostly?

- Is a mobile energy supply required?
- What type and amounts of materials are required for building up additional safety guards (e.g. shelter)?

The establishment of data about misuse follows correspondingly from the queries about environmental impacts by the main and auxiliary processes.

Actual use (passive)

What environmental impacts result from processes during the actual use (passive)?

- What passive processes are carried out in the actual use?
- Which stand-by-modes exist (e.g. sleep-mode, rest-mode for PC)?
- What types and amounts of energy result from the controls in stand-by-modes?
- What types and amounts of energy result from the stand-by-processes (e.g. electrode preheating by cathode ray tubes, flame ignition by gas heating, perpetuate of memory contents by answering machines)?
- What environmental impacts result from storage/ageing?

After-treatment

What environmental impacts result from after-treatment?

- What and how frequent are the cleaning processes after the actual use?
- What types and amounts of energy result from the cleaning processes?
- What types and amounts of cleaning materials are required?
- What types and amounts of supportive cleaning process materials are required (e.g. water to dilute the cleaning material or to wash out)?
- What types and amounts of supportive cleaning accessories are required (e.g. rags, protection gloves)?
- What types and amounts of waste are generated?

Maintenance/Repair

What environmental impacts result from the maintenance/repair?

- What environmental impacts are generated by the manufacturing and the distribution of spare parts?
- What types and amounts of regularly planned maintenance processes are carried out?
- Are maintenance actions time- or event-controlled?
- What types and amounts of expected repair processes will be carried out?
- What environmental impacts result from neglected maintenance?
- Which components are wearing elements and must be replaced regularly?
- What types and amounts of in-/outputs result from the maintenance/repair processes?
- What types and amounts of energy are required for the maintenance/repair processes?
- What types and amounts of waste are generated by the maintenance/repair processes (e.g. used oil, wearing elements)?

What environmental impacts result from the transport to the maintenance/repair site?

- How long is the average distance to the maintenance/ repair site?
- By what means of transport will the transport to the maintenance/repair site be carried out?
- Are the maintenance/repair processes carried out at the customer's place by customers' service?
- Are the maintenance/repair processes carried out by the user, so transportation processes are actually avoided?

Decommissioning

What environmental impacts result from the decommissioning?

- Is a user-performed pre-disassembly carried out?
- What disassembly processes are expected to be carried out by the user?
- What in-/outputs of materials or energy consumption result from the user-implemented disassembly processes?

What environmental impacts result from the transport to the decommissioning?

- How long is the average departure distance to the recycling/disposal site?
- Is a special means of transport of the product from the latest owner to the recycling/disposal site required?
- By which means of transport is the greater part of the departure distance carried out?
- Is an additional transportation packaging required?
- What type of additional transportation packaging is used (size, weight, material, application, availability)?

Figure 4. Checklist 2 for analyzing environmental impacts in the use phase associated with the UPA-Matrix

6 Example of use

The example of use is a hand drying system with a multiple used textile tape (Figure 5). The clean textile tape is rolled in the upper half; the used tape is rolled in the lower half of the housing. The tape will be washed by the manufacturer. The system boundary includes the hand dryer itself, the transportation system for the textile tape and its cleaning process. The lifetime of the dryer amounts to 5 years, the technical lifetime is equivalent to the aesthetic lifetime. The lifetime of the tape is about 120 cycles, in the regarded scenario, the dryer is used 50 times per day. An extract of the filled-in UPA-Matrix is presented in Figure 6.

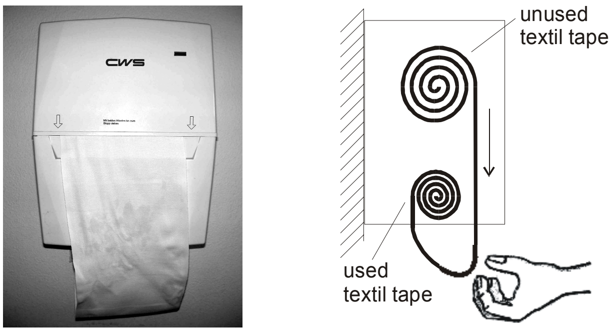

Figure 5. The hand drying system

Sub-phase	Use process	Material/ process	Quantity/ Unit	Energy	Quantity/ Unit	Users' behaviour
Purchase	purchasing decision (direct order from manufacturer)	catalogues: I/O: paper manufacturing disposal	 3.120 kg ignored 3.120 kg	ignored	---	intensity of acquisition of information
	transportation or the hand dryer from manufacturer to user	one-way transport packaging*: I: wood I: steel I: PE	 0.625 kg 0.055 kg 0.015 kg	transport (lorry): →fuel, wear, emissions, ...	3.37 ton kilometres	route, way of driving, capacity utilisation, …
Activation	unpacking of the hand dryer and disposal of packaging	one-way transport packaging*: O: wood O: steel O: PE products' packaging: O: cardboard	 0.625 kg 0.055 kg 0.015 kg [illegible]	---	---	behaviour of disposal
	installation of the hand dryer	screws: I: steel I: pressing dowel: I: nylon (PA6) I: injection moulding	 0.076 kg 0.076 kg 0.012 kg 0.012 kg	electrical energy	0.020 kWh	behaviour of installation
Preparation	transportation of the drying tape from manufacturer to user	transport packaging	returnable system, wear ignored	transport (lorry): →fuel, wear, emissions, ...	1366 ton kilometres	route, way of driving, capacity utilisation, lot size, …
Actual use	feed of the drying tape	---	---	muscle power	---	repeated feed per one drying process

Figure 6. The UPA-Matrix: Example of use

7 Validation

The UPA-Matrix was successfully applied in the project seminar on DfE at the Darmstadt University of Technology in the last winter term. Further information about the project seminar will be found in [20] and [21]. The method was carried out by four teams with five participants, each. Four different products were analysed. The students were video taped while carrying out the method. Afterwards, a questioning was done.

The effort to carry out the method was medium. The participants were almost satisfied with the results. One team stated that the analysed product and its processes were too simple. The support to determine inventory data was described from good up to very good. The comprehensiveness and the structure of the checklists are appropriate. The checklists are describes completely. They ensure, not to forget relevant inventory data. In general, the users were largely contented. Especially, the structured procedure is well supported by the method. The assign of processes to sub-phases was unmistakable.

The conclusion of the validation was an improvement of the description of the method. The suitability of the checklists was confirmed. Just some little supplementations were done.

8 Conclusions and Outlook

The main aim of the UPA-Matrix is to support designers in estimating environmental impacts of different product concepts, based on the identification of environmental weak points with an acceptable effort. This is realized by a guided and structured determination of inventory data in combination with a rough estimation method and a material and process database.

The presented method is applicable to the conceptual design phase in early stages of the design process, as well as in the late stages of embodiment design and detailed design. The time needed for carrying out the method depends on the complexity of the processes and on the degree of accuracy.

Combined with additional methods, e.g., Eco-FMEA, the UPA-Matrix supports the designer in quantifying the influence of the users' behaviour on environmental impacts. The method is also suitable to compare products with product-service-systems or different product-service-systems among themselves.

The first validation of the UPA-Matrix was applied in the project seminar on DfE. The participants of this seminar were novices in environmental issues. Therefore, further researches to improve the developed checklists will be carried out with environmental experts.

In further steps the UPA-Matrix will be used to analyse the use processes of a wide spectrum of products with the aim of identifying ready made models that describe inventory data of use processes. These models support the designer in an efficient estimation of environmental impacts of products in the use phase. To reach this, a modular structure is aimed, using "basic modules" and "supplement modules".

9 Acknowledgments

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Dipl.-Ing. Christof Oberender

Darmstadt University of Technology; Institute for Product Development and Machine Elements, Magdalenenstrasse 4, 64289 Darmstadt, Germany; Tel: +49-(0)6151-16-3055; Fax: +49-(0)6151-16-3355, E-mail: oberender@pmd.tu-darmstadt.de; URL: www.pmd.tu-darmstadt.de