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# A PROPOSAL TO ADAPT DESIGN FOR ENVIRONMENT METHODS TO THE LEVEL OF ABSTRACTION NEEDED IN EARLY PHASES OF PRODUCT DEVELOPMENT

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## Summary

In this contribution we describe Design for Environment (DfE) methods for the early phases of product development that are considered state of the art. We also point to the major shortcomings of the state of the art approach. Finally, we show alternative methods and discuss their boundaries of applicability.

## 1 Introduction

In course of the early design phases, the product developer generates solutions by a stepwise concretisation of product models. In these decision makings, he defines product concepts, which are approximate descriptions of systematically generated and assessed principle solutions [1]. By every step, the properties of the product are laid down. One of many properties is the impact that the product causes on the environment. Within design science Design for Environment (sometimes called EcoDesign) stands for methodological support that aims at reducing the overall environmental impact. As the procedural, functional and effectual representations of the product are refined subsequently, ending with the embodiment and detail design, the design degrees of freedom decrease accordingly [2]. The actual dilemma in Design for Environment is that most state of the art methods need detailed information on the product composition. This contradicts the insight that the earlier an environmentally motivated product change is induced in the product development process, the more likely significant reduction of the environmental impact becomes [3]. Typically, in the late phases there is limited room remaining for environmental improvement [4].

## 2 State of the Art Methods

For taking stock of the state of Design for Environment methods in the early phases of product development we established a reference process. Note that the term ‘state of the art’ in this context refers to methods in scientific literature that are ready for application but does not reflect the actual dissemination in industry. The reference process contains two major steps: a rough environmental impact assessment and the identification of appropriate environmental strategies.

### 2.1 Rough environmental impact assessment

The assessment of a product’s environmental profile is typically performed using Life Cycle Assessment (LCA) techniques [5]. However, a ‘full’ LCA requires the identification and quantification of the emissions, energy and material flows throughout the lifecycle of a product. Often several hundreds of processes need to be scrutinised, making LCA a very time-consuming assessment technique. In the product development context, data availability is even more problematic, since many decisions yet need to be taken. Therefore, environmental impact assessment is only suited for *ex-post* assessment of the design process result in view of deriving guidelines for next generation products.

In order to assess products *ex-ante*, rough methods have been developed [6]. These methods are now used by a number of frontrunner companies [7], [8]. They eliminate the extensive data gathering efforts connected to tracing all life cycle processes and their related elementary flows by making use of average data for common sections of a product life cycle. Two standard methods for environmental impact assessment based on these average data are Eco-indicator 99 [9] and EPS [10]. These lead to indicator scores for materials (per kg of material), production processes (per m² of rolled sheet or per kg of extruded plastic), transport processes (per t km), energy generation processes (per kWh or MJ), disposal scenarios (per kg of material), etc.

In order to use these rough environmental impact methods, the bill of materials and a list of product life cycle processes are required. These methods are therefore often used in a material selection context. Multiple commercial software packages are available for this purpose [11], [12], [13].

In general, it is particularly the need for a detailed materials inventory that limits the applicability of rough environmental impact assessment methods in the design process.

- During the early design phases, only functional requirements and product concepts are available. Nevertheless, decisions taken in the conceptual design phases can influence the outcome of a design exercise far more than any optimisation done later in the design process [2]. In Design for Environment, an early recognition of favourable system component solutions is therefore of great importance.
- Even for fully executed products, a detailed materials inventory is difficult to obtain when many components are bought off-the-shelf. This especially holds true for small and medium-sized enterprises, which can provide little incentives to enforce suppliers to provide the requested data.

### 2.2 Strategy-based Design for Environment

Typically, based on the assessment results the further actions are oriented by design strategies [14]. In general, a strategy is defined as ‘a comprehensive plan dependent on the initial situation and influencing factors that is aiming to reach a certain objective applying methods’ [15]. Nevertheless, the strategy notion is widespread and diverse in the field of Design for Environment [16], [17], [18], [19], [20], [21], [22], [23]. The definitions have in common that strategies should help the product developer transforming environment-related requirements into product and process-related actions by grouping design options into consistent sets. According to Brezet and van Hemel [24] DfE strategies stand for ‘the different routes that can be followed in ecodesign’. Thus, the strategy concept imparts developers a first impression of where the relevant environmental impacts reside for a given product and urges them to pay attention to these options during the entire development process. Often, it makes sense to choose one or more subsidiary strategies. But obviously, interdependencies between the strategies must imperatively be taken into account then.

Grüner [15] discriminates strategies into two groups according to their effect on the product life cycle: direct and indirect strategies. While direct strategies aim at the reduction of environmental impacts within one life cycle phase, indirect strategies prevent the product or parts of it from passing through specific processes in the product life cycle or cause a variation of the amount. An example for a direct strategy is the ‘environmentally-friendly material production’. This can be achieved by selecting low-impact materials. As a consequence, this design option modifies the product life cycle in the material production phase only. By contrast, the indirect strategy ‘simplify material recycling’ reduces the environmental impact in more than one phase: in the material production and in the disposal phase. The benefit of closing material loops depends indeed on the recovery rate.

Beside those two types of strategies for incremental optimisation, revolutionary strategies, such as dematerialisation, exist. These scrutinise the product concept and imply a change of the consumer and user behaviour. In view of the limited field of application and the profound organisational changes involved, revolutionary strategies are not considered here.

By examining four different strategy collections [17], [18], [19], [21] Grüner [15] presented a unified set of four direct and three indirect strategies, see Table 1. Being too broad for direct application, the strategies must be broken down to specific design measures. Therefore, the compilation assigns exemplary design guidelines to the strategies.

Table 1: DfE strategies and assigned design guidelines [15]

| Strategy | | Design guideline | process-oriented | product-oriented |
|---|---|---|---|---|
| direct | Environmentally friendly material production | Select renewable materials | ● | |
| | | Minimise amount of material | | ● |
| | Environmentally friendly manufacturing | Provide as few manufacturing steps as possible | ● | |
| | | Avoid manufacturing steps with high plant specific effort | ● | |
| | | Avoid manufacturing steps that require problematic consumables | ● | |
| | | Avoid manufacturing steps with high appearance of waste | ● | |
| | | Avoid manufacturing steps with high energy consumption | ● | |
| | | Avoid rejects | | ● |
| | | Increase material utilisation rate | | ● |
| | Environmentally friendly use | Avoid harmful materials | ● | |
| | | Avoid harmful consumables | ● | |
| | | Minimise replacement part consumption | | ● |
| | | Minimise consumption of consumables | | ● |
| | | Increase efficiency | | ● |
| | | Avoid erroneous behaviour | | ● |
| | Environmentally friendly end-of-life | Use biodegradable materials | ● | |
| | | Avoid environmentally hazardous materials | ● | |
| | | Provide easy removal of parts containing contaminants | | ● |
| | | Minimise amount of material | | ● |
| indirect | Increase lifetime | Design parts containing contaminants for easy removal | | ● |
| | | Provide corrosion protection | | ● |
| | | Simplify cleaning | | ● |
| | | Provide timeless design | | ● |
| | | Simplify repair options | | ● |
| | | Design for upgrading | | ● |
| | | Optimise reliability | | ● |
| | | Simplify maintenance | | ● |
| | Simplify product recycling | Implement product structure for easy disassembly | | ● |
| | | Minimise number of parts | | ● |
| | | Provide returnable packaging | | ● |
| | Simplify material recycling | Select recycled materials | ● | |
| | | Minimise variety of materials | ● | |
| | | Avoid recycling processes with high plant specific effort | ● | |
| | | Select recyclable materials | ● | |
| | | Respect compatibility of materials | ● | |
| | | Label materials | | ● |

Unfortunately, there are some problems in practice:

- The strategy concept inevitably requires an environmental assessment of a reference product. As especially for ‘DfE newcomers’ do not always have a reference assessment at hand, it is hard to tell which strategy suits best for a given product without a considerable amount of preparatory work.
- The authors that introduced the strategy concept in DfE understand the selection of a strategy as one single decision. Of course, the selection of an overriding strategy gives the product developer the ‘big picture’ of what to do. But that leaves him still alone at the rest of the development process. In order to learn really more about the environmental properties of a product and to find appropriate design options, the support requires gradual decision making.

- As the strategies and exemplified design measures in scientific literature should cover a wide range of products their formulation is necessarily of general nature - too general for the application to a specific product, one might say. Thus, one suggestion for improvement is to adjust them to the type of products the product developer is familiar with, e.g. in a company-specific customisation.
- A collection of generalised design options, even if thoroughly formulated, is not likely to fill the product developer with enthusiasm. Case studies with real-world products are far more motivating and reminiscent.

# 3 Proposed Approach

As we have shown, the state of the art methods are not meeting the right level of abstraction in the early phases of product development. Therefore, we propose how to adapt these methods.

## 3.1 Estimating environmental impacts by functional parameters

As a solution to the data availability problem described in Section 2.1, we have introduced the Eco-PaS (Eco-Efficiency Parametric Screening) methodology [25]. Eco-PaS uses Eco-cost estimating relationships (E-CERs), defined as mathematical expressions relating eco-cost as dependent variable to one or more independent eco-cost driving variables. In this framework, eco-cost can be expressed in monetary units, such as external costs or willingness to pay, or by any other environmental performance indicator. Throughout this paper, we use Eco-indicator 99. The eco-cost driving variables are functional requirements (FR) or design parameters (DP) that product developers have at hand when designing or selecting components from catalogues. Parametric expressions describe the environmental impact $\xi$ as a function $\xi = f(FR, DP)$. For example, the cradle-to-gate Eco-indicator 99 score $\xi$ for small electric motors of a given type can be estimated based on their nominal power $P_{nom}$: $\xi = 0.020 + 0.00065 \cdot P_{nom}$ [W].

Three techniques can be used to derive E-CERs [26]:

- theoretical model development
- regression analysis on empirical data
- growth laws

Theoretical model development can be used for developing E-CERs for relatively simple components for which physical laws are well-known. The technical formulae that describe these physical laws lie at the basis of the E-CER development. For structural components the relationship between functional parameters (such as maximum loads) and deformations on the one hand, and component dimensions on the other hand is known for given load conditions. And the relationship between dimensions and cradle-to-gate environmental impact is straightforward based on geometric formulas [25]. Regression analysis allows deducing E-CERs from empirical data [25]. Finally, in analogy to so-called Cost Growth Laws [27], Voß [28], [29] introduced the Environmental Impact Growth Law (EIGL) approach for predicting the ecological properties of size ranges. The EIGL approach is suitable when an environmental impact assessment has been carried out for a basic design $D_0$. The environmental impact of a subsequent design $D_i$ is then estimated by multiplying the environmental impact of $D_0$ with a growth function, which evolves with size.

Calculating the environmental impact of a product is already subject to a number of uncertainty factors. Logically, estimations on the basis of E-CERs have an even higher degree of uncertainty. The E-CERs should therefore be supplemented with information about the importance of uncertainty factors. Consequently, we have introduced fuzzy sets to deal with these uncertainties [30].

In order to validate the Eco-PaS methodology, we modelled the product concept of an electric fruit juicer. Then, we compared the Eco-PaS results to the results of a standard assessment method that examined the detailed design of a commonly available product. The fruit juicer concept contains five functional blocks: press tip, jug, electric motor, housing and cable (Figure 1). Moreover, the electricity consumption in the use phase was considered.

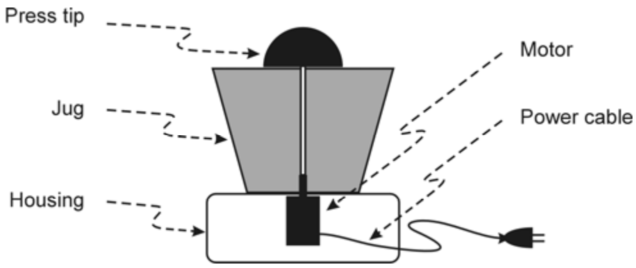



Figure 1: Conceptual representation of an electric fruit juicer

For a complete case study description including the derivation of the E-CERs and the input parameters, please see Dewulf and Duflou [30]. For illustration purposes, only the derivation of the jug E-CER is explained here.

In many design projects, recipients need to be developed that can contain a specified amount V [m³] of gas, liquid or bulk material. Other important design parameters influencing the eventual environmental impact are the material, the shape and the thickness of the recipient. Approximately, the environmental impact can be modelled as $\xi = \gamma \cdot V^{0.66} \cdot t \cdot \kappa$ where:

- $\gamma$ [-] is a dimensionless parameter representing the influence of the recipient shape on the environmental impact score: obviously, a spherical recipient has a lower $\gamma$ than a cubical alternative with similar thickness and volume contents. Table 1 shows the values of $\gamma$ for selected recipient shapes.
- $\kappa$ [Pt/m³] is a material parameter that is obtained by multiplying the specific environmental impact score found in many databases (e.g. in Eco-indcator 99 lists) by the material density.
- t [m] represents the wall thickness of the recipient: obviously, this parameter is typically not available in early design phases. Therefore, a default value range from 0.5 mm to 2 mm is given. Nevertheless, the designer can change these values based on his own experience.

In our example case, the product developer considers only plastics, which is modelled as a $\kappa$ value ranging from 300 to 600 Pt/m³ (cf. Table 2). The default wall thickness is retained. The only geometrical restriction on the recipient is that the top side should be open. A more exact shape has not been determined yet. Therefore, the $\gamma$ parameter ranges from 3.8 to 6.4 (cf. Table 3).

Note that when the product developer would have selected a cylindrical shape with a diameter equalling the height (which is a good approximation for many fruit juicers commonly found on the market), the $\gamma$ value would be restricted to the crisp value 4.6. Consequently, postponing the exact shape determination of the jug introduces an uncertainty of only +/- 30% on the result for the jug.

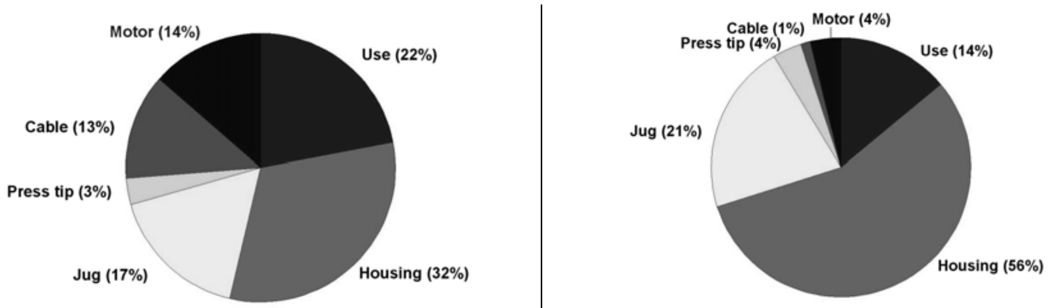
Table 2: Value of the material parameter $\kappa$ for different plastics

| *material* | *material parameter $\kappa$* |
|---|---|
| ABS | 428 Pt/m³ |
| PC | 600 Pt/m³ |
| PP | 300 Pt/m³ |
| PS | 420 Pt/m³ |

Table 3: Value of the shape parameter $\gamma$ for different geometrical forms (one side open)

| *shape* | *shape parameter $\gamma$* | *constraints* |
|---|---|---|
| cube | 5.0 | |
| half sphere | 3.8 | |
| cylinder | 4.4<br>4.6<br>5.2 | Diameter = height*2<br>Diameter = height<br>Diameter = height /2 |
| cone | 6.4<br>4.6<br>4.0 | Diameter = height *2<br>Diameter = height<br>Diameter = height /2 |

Based on the E-CERs and a set of input parameters, a fuzzy estimation of the environmental impact of the fruit juicer is obtained. The interpretation of this fuzzy set leads to a defuzzified 'average' estimated impact of 0.35 Pts (based on a point of gravity defuzzification approach) with an uncertainty interval of [0.13; 0.48] at membership level $\alpha$=0.5 of the fuzzy set. Besides the total estimated impact of the fruit juicer, Eco-PaS also provides information about the repartition of impacts on a component level and about the related uncertainties (Figure 2).




(a) (b)

Figure 2: Eco-PaS analysis result: contribution of the building blocks to (a) the estimated impact and (b) the overall uncertainty.

From these figures, the product developer learns that the housing is a crucial element of the fruit juicer, since it combines a high contribution to the overall impact (Figure 2a) with a significant contribution to the overall uncertainty of the result (Figure 2b). The latter indicates that this component has a high improvement potential. In the second place, the designer needs to focus on the jug design as well as on elements influencing the total energy consumption. However, in contrast to most active products, the electricity consumption of the juicer is not the first concern in this environmental optimisation. Finally, the motor and the cable have important contributions to the total environmental impact (Figure 2a), but represent very little improvement potential (Figure 2b). Of course, this conclusion is only valid as long as no other radically different solutions are selected that were not yet represented in the utilised E-CERs.

The rough environmental impact assessment that was made to validate the Eco-PaS results amounts to 0.315 Pts. This score fits well in the interval indicated by the Eco-PaS results. Furthermore, the results show that for most components the share in the overall environmental impact indicated by the ex-post assessment and Eco-PaS is similar. Two exceptions appear: the housing and the electric motor. The deviation on the housing can easily be explained by the large uncertainty on this component. This uncertainty range tells the product developer that he has a significant opportunity to influence the environmental profile of the product by making appropriate DfE choices. Hence, Eco-PaS can effectively influence the DfE process during early design phases. Scrutinising the electric motor data reveals that the type of electric motor used by Voß [28] when developing the E-CER was fundamentally different from the type used in the validation product. This points at a basic weakness of the Eco-PaS approach: E-CERs are only valid for the component range they were developed for, and cannot be extrapolated. Thus, a larger range of motors needs to be assessed in order to deduct a more reliable E-CER.

In fact, assessing functions with respect to the environmental impact always contains a contradiction. By definition, environmental impact assessment is based on an inventory of inputs and outputs in the product life cycle. Therefore, an assessment of functions requires anticipating how these functions will be accomplished. If the innovativeness of the design lies in the innovativeness of the combination in which standard solutions are brought together, the estimation of environmental impacts using the Eco-PaS philosophy is feasible. However, if radically new working principles are to be explored, other support tools need to be applied.

### 3.2 Inferring from case studies

Another approach goes one step further. It abandons a formal assessment of the environmental impact caused by a considered product. Instead, the approach is based on cluster analysis. Therefore, environmental experts have to prepare a collection of case studies before product developers can work with it.

In the preparation phase, products are clustered by quantitative functional parameters. For doing so, we have tested nine parameters so far, namely

- product mass
- intensity of use
- useful lifetime
- degree of mobility
- prevailing location of operation
- price segment
- product complexity expressed by the approximate number of parts
- water consumption
- electricity consumption

For each case study, the design options that have been taken to reduce the impact on the environment must be described. We have chosen a standardised format based on the strategy approach. Therefore, we detailed Grüner's four direct and three indirect strategies [15] with 52 design measures and further broke them down into 294 specific design guidelines. For keeping the effort low, the preparatory work consists of selecting the applied design guideline out of the predefined list.

With help of such a collection of case studies, the product developer can find similar products. Again, the clustering is not a proper environmental impact assessment. Its only objective is to stimulate the product developer to find creative solutions himself.

For testing the approach we have programmed a software tool called *Case Study Collection* using a standard database management program (Microsoft Access), see Figure 3. The tool runs the time consuming cluster analysis. The product developer just has to key in the functional parameters of his product. The tool determines to which cluster the examined product fits best. Each cluster is characterised with respect to the main impacts the contained products usually cause. Additionally, the most similar product is determined. The tool permits to browse through the design options which have been recommended for this product. The query starts to give specific design guidelines which can be gradually traced back to the generalised design strategy on demand.

The approach is limited in several ways:

- As indicated above the clustering can easily be mistaken for an environmental impact assessment.
- How suitable the suggested case studies are for the product developer depends on the skilful choice of the quantitative functional parameters.
- The administration effort is a critical factor that lets many similar databases fail. For testing we have incorporated thirty case studies.
- The description of the case studies must have a trustworthy source. Otherwise, the validity of the given design guidelines is put in jeopardy.

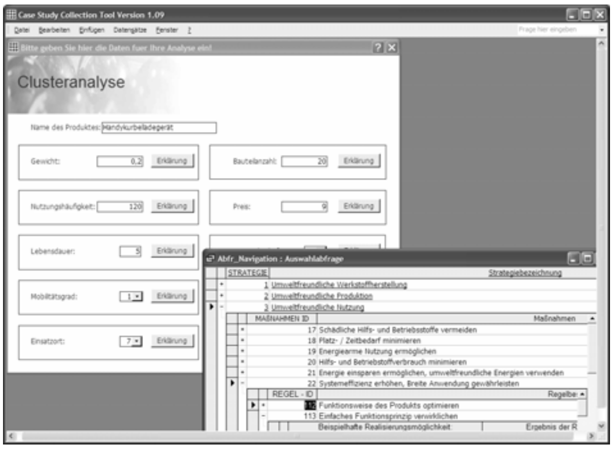



Figure 3: *Case Study Collection.* The upper left window in the background shows the input mask for entering functional parameters, the window to the lower right in the foreground permits to navigate through the design strategies, design measures and design guidelines.

## 4 Conclusions

In this contribution we point out the shortcomings of state of the art methods on Design for Environment. Environmental impact assessment methods, even when streamlined, only suit for ex-post analyses in view of deriving guidelines for next generation products. Selecting an overriding strategy gives the product developer the ‘big picture’ of what to do, but for the actual implementation there is a lack of support.

Furthermore, we recommend how to adapt these methods with respect to their applicability in early phases of product development. Both proposals given allow the product developer a functional view on the product. We show that it is possible to express the environmental impact of components as a function of functional requirements and design parameters. With respect to stimulate the product developer to find creative solutions we describe a case-based clustering approach.

We are aware that the described approaches still have major limitations. Therefore, we conclude at the end of each section in which direction future research must be directed.

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