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ECO-PAS - ESTIMATING THE ENVIRONMENTAL PERFORMANCE OF CONCEPTUAL DESIGNS USING PARAMETRIC MODELLING

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Abstract

A wide range of LCE support tools has been developed over the years. Major limits of conventional analytical LCE support tools are however: too much input and too late output. This paper presents the Eco-PaS system providing pro-active DfE support based on functional requirements available in early design stages. Parametric models, called Eco-Cost Estimating Relationships (E-CERs), form the core of the system. They are an extension of the Cost Estimating Relationships, commonly used in design and development projects, to environmental performance. Next to the estimated environmental performance, the uncertainty of the estimation, caused by the parametric model as well as by the input parameters available in conceptual design, needs to be known. First concepts for uncertainty calculations are presented.

Keywords: design for the environment, eco-efficiency, early phases of design

1. Introduction

Increased environmental awareness throughout all levels of present-day society has led to an extended responsibility of manufacturers with respect to their products' environmental performance. As a result, industry has, over the last decade, started to increasingly apply the principles of Life Cycle Engineering and Design for Environment (DfE): the total environmental impact of a product can only be optimally controlled when considered already during product development. A wide range of LCE support tools has been developed over the years (See e.g. [1], [2]). On the one hand, rather generic life cycle thinking and guideline approaches have been proposed. On the other hand, a range of environmental performance analysis tools have been developed. Both approaches are complementary: the earlier analysis tools provide feedback on the actual environmental hot spots of the design, the better the life cycle thinking approaches can be tailored and focussed. This paper presents an approach that aims at providing the first feedback much earlier in the design process than in current ecodesign practice.

Figure 1 gives an overview of the major types of holistic LCE tools - which cover the whole life cycle of the product - categorised on the basis of two criteria: type of feedback versus time of application. The figure reveals one of the major limits of conventional analytical DfE support tools: too much input and too late output. Currently available quantitative tools can only be used in late design phases. The main reason is the need for input data in terms of - at least - a detailed materials inventory, which is not available in early design phases. Moreover, even in late design phases, input in terms of a materials inventory is, especially in case of electromechanical design, not in line with a designer's thinking pattern, especially when considering that the eventual product largely consists of components that are purchased off-the-shelf. Instead, electromechanical designers think in terms of components and component selection parameters. A clear void exists for tools making use of the functional parameters available in the early concept development phase of the design process: designers still feel that tools for the early design phases are lacking ([3], [4]).

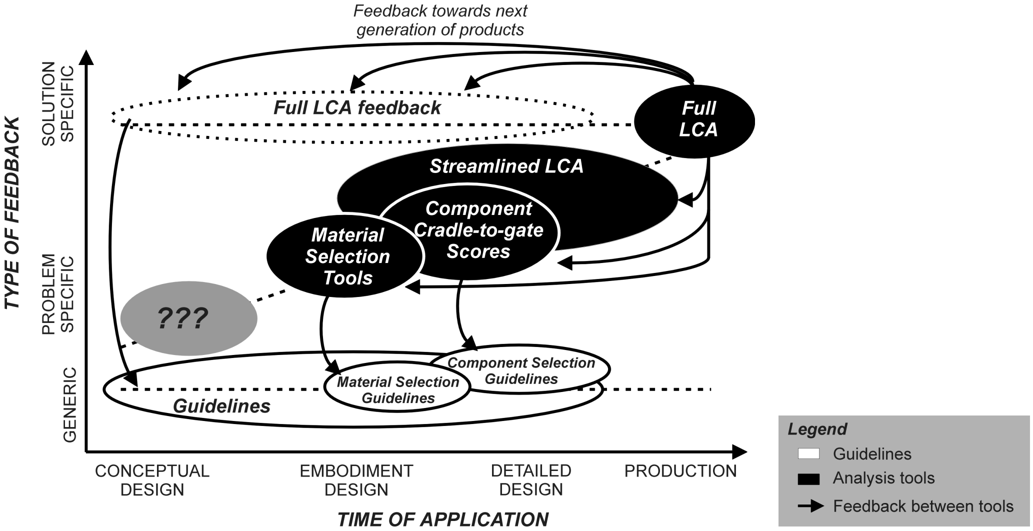

Figure 1. Categorisation of holistic LCE Tools according to type of feedback and time of application.

2. Eco-Cost Estimating Relationships (E-CER's)

Early estimation of product costs is everyday's practice in a business environment. Parametric cost estimating techniques are commonly used in e.g. aerospace industry to estimate the cost of projects and products early in the development process on the basis of Cost Estimating Relationships (CER's). CER's are mathematical expressions relating cost as the dependent variable to one or more independent cost driving variables [5], and are derived from historical, theoretical and literature data using e.g. regression analysis.

In analogy to this definition, we propose to define Eco-Cost Estimating Relationships (E-CER's) as mathematical expressions relating an eco-cost as dependent variable to one or more independent eco-cost driving variables. In this framework, eco-costs need not necessarily be expressed in monetary units such as external costs [6] or willingness to pay [7], but can be expressed by any commonly used indicator such as EcoIndicator 99 [8], a Category Indicator Score [9], or a product oriented Environmental Performance Indicator [10]. Eco-cost driving variables are chosen amongst the functional requirements, which are available early in the design process. For example, in case of a machine design, a designer will be able to give an order of magnitude for the required nominal power of the motors used in his design concept.

Figure 2 exemplifies the results for an Eco-Indicator99 based E-CER for the production of 3-phase AC motors between 5 and 75 kW, based on data from one producer [11]. The R^2 value shown in the figure is already comfortably higher than the 0,8 lower limit used in e.g. NASA cost estimation procedures [5].

Even better R^2 values can be obtained by splitting the total eco-cost according to eco-cost drivers such as the amount of individual materials, which do not necessarily follow similar types of regression curves. For example, the linear regression curve of Figure 3 can be used to estimate the eco-impact of the motor's copper parts' production. The rule-of-thumb equation m_{Copper} [kg] = P_{nom} [kW] even provides a valuable approximation within the 5kW-100kW power range, still maintaining a coefficient of determination $R^2 > 0,9$.

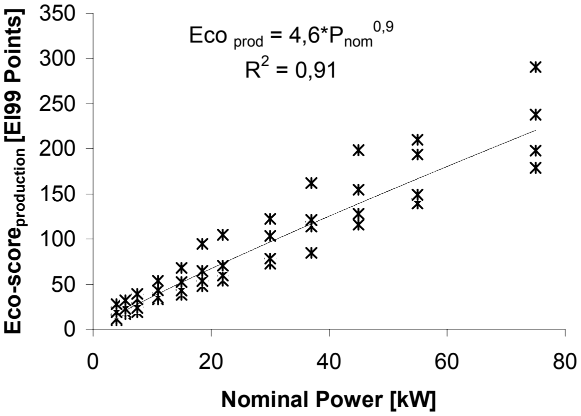

Figure 2. Eco-impact of the production of 3-phase AC motors of 5 to 75 kW. The figure is based on a one supplier survey and only takes into account material production impacts.

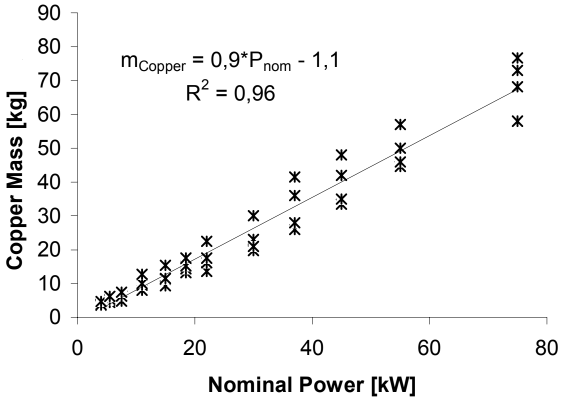

Figure 3. Mass of copper in 3-phase AC motors of 5 to 75 kW.

E-CERs are now being developed for a large number of widely used systems and components, ranging from motors to bearing systems, transmissions, construction elements, elementary hydraulic and pneumatic systems, etc. in order to be made available to designers in different companies. While the independent variables of the E-CERs are chosen to be functional parameters of the design, the required input for the designer is available both more easily as well as earlier in the design process in comparison to the materials inventory required by most ecodesign tools.

3. The importance of uncertainty analysis

E-CERs can be defined at different levels of abstraction. On a very concrete level, an E-CER can be defined covering the bearings of one specific type and one specific supplier. E-CERs of this type are typically used in a detailed design phase. On an intermediate level, an E-CER can be defined covering the bearings of one specific type but including all suppliers, thus supporting embodiment design decisions. One a high level, an E-CER can be defined covering the full range of bearings. These high-level E-CERs will be needed in the conceptual design phase.

However, while even the very low-level, supplier specific E-CERs are already subject to a certain level of uncertainty, it is clear that the uncertainty of E-CERs will increase when covering a broader range of suppliers and component types. Moreover, the eco-cost driving parameters used as independent variables for the E-CERs will also be uncertain in early design phases. Consequently, an analysis based on pure average data is an insufficient support, and the uncertainty of the analysis result needs to be calculated. For the first tests, the following, pragmatic approach is followed:

- only linear regression approximations are used: $y=a+b_1.x_1+ b_2.x_2+\dots$;
- uncertainty of the regression formula is expressed by calculating not only the optimal constant term a, but also the standard error σ of the regression. Consequently, for 68% of the input parameter combinations (X_1, X_2,...), the actual performance Y will lie in the interval $[a-\sigma+b_1.X_1+b_2.X_2+\dots\ a+\sigma+b_1.X_1+b_2.X_2+\dots]$;
- uncertainty of the input parameters can be taken into account by not only providing a most probable value X, but also a minimum X_{min} and maximum X_{max}.

Numerical methods for interval arithmetic or fuzzy arithmetic are then used to calculate both the most probable value Y and the 68% certainty interval $[Y_{min}\ Y_{max}]$. A detailed description of the underlying mathematics is, however, outside the scope of this paper.

As an illustration, Figure 4 presents the results of fuzzy arithmetic calculations supporting material selection for a beam mounted on a train. Input parameters of the E-CERs were the estimated length of the beam, the estimated load conditions, and the travelling distance of the train. Output parameter is the Eco-Indicator'99 score for the different alternatives. On the left-hand side, the "fuzzy" result of the calculations is presented. For the reader who is not familiar with fuzzy set representations: the most probable Eco-Indicator score for the different solutions can, for each alternative, be read in abscise at the point where the ordinate reaches 1 (ca.. $2.5*10^4$ for the red curve). The interval covering the potential solution range for each alternative, taking into account the uncertainties, can be found in abscise between the values corresponding to a "0" value in ordinate, e.g. ca. $[1*10^4\ \ 11*10^4]$ for stainless steel (RVS).

Due to the accumulation of uncertainties, the left-hand side figure merely adds any value in comparison to the calculation of the average scores for each alternative. On the right-hand side figure, however, the effect of the uncertainty on the input parameters was largely eliminated. This was done by calculating, for each set of input parameters not merely the eco-indicator scores, but the ratio of the eco-indicator score to the eco-indicator score of a reference alternative (in this case the steel alternative) using the same input parameters. From this figure, one can conclude that, for any combination of input parameters, steel will perform better than PVC and Aluminium, which in turn perform better than stainless steel (RVS).

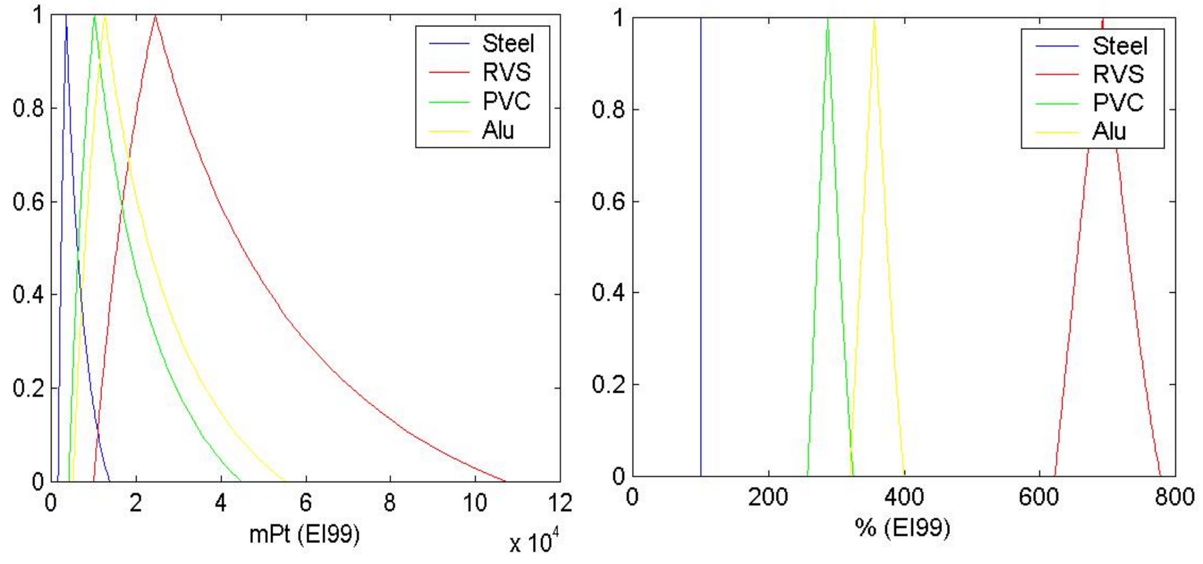

Figure 4. Example of fuzzy arithmetic results for a material selection case. In the left-hand side figure, uncertainties of the input parameters accumulate and prevent the user to draw conclusions. In the right-hand side figure, the effect of these uncertainties is reduced.

4. Eco-PaS

E-CER's form the core of the Eco-PaS (Eco-efficiency Parametric Screening) tool, presented in Figure 5. Eco-PaS supports the estimation of eco-impacts based on the functional parameters available in the concept development phase. It is based on the following principles:

- A design is usually conceived as an innovative *combination of standard solutions to elementary functions*. For example, the elementary function "illumination" is fulfilled by a selection out of the standard "lighting system" solutions.
- The system requires *input* in terms of functional descriptions and constraints (called Functional Parameters) instead of technical parameters.
- The system returns *output* in terms of *quantified eco-efficiency performance indicators*, even in the early conceptual phase.
- The system uses a *convergent approach*: all solutions are considered to be viable candidates unless proven inappropriate.

The core of the system is the Functional Eco-Efficiency Assessment making use of E-CER's. Both the direct variant (cf. Figure 2) resulting in eco-cost indicators as well as the indirect variant (cf. Figure 3) resulting in intermediate eco-cost drivers are possible. In the latter case, the intermediate eco-cost drivers are typically technical parameters such as the mass of individual material types, which are then easily converted into eco-cost scores using the widely-used eco-cost material lists. Moreover, in some cases it is possible to derive the relationship between the functional parameters and the eco-cost using theoretic instead of empirical modelling. For example, in case of structural components, elementary formulas from construction engineering are available to calculate the mass (with related eco-cost) of a beam in function of length and load conditions for different design alternatives (Cf. the example in the previous section).

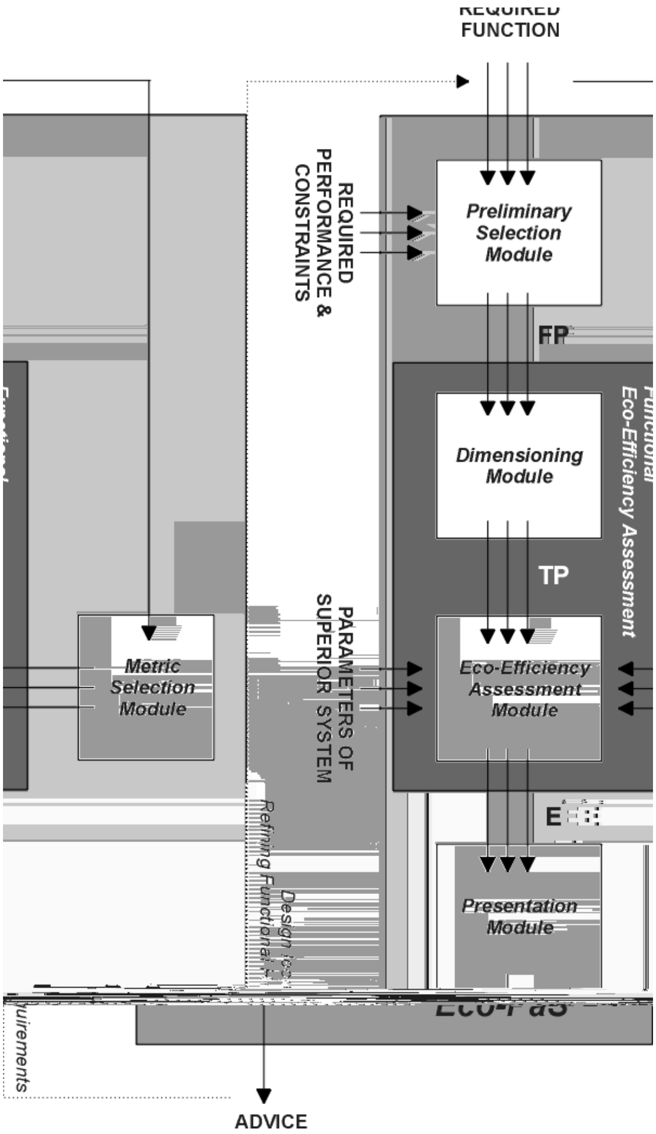

Figure 5. Principle of the Eco-PaS (Eco-efficiency Parametric Screening) system for Eco-Efficiency (E^2) estimation based on functional parameters (FP) and intermediate technical parameters (TP).

Auxiliary modules of Eco-PaS include:

1. a preliminary selection module: the starting point of the method is the exact and abstract definition of the function required, e.g. illumination of a surface, as well as the definition of the required performance and the constraints, such as the required illumination [lux] and color. These constraints and performance requirements are referred to as *functional parameters*. The first input ("function required") serves as the basis for the Eco-PaS system to consult a database with known solution principles. A selection of technically feasible solution principles is then provided by an expert system, but can be modified through user intervention. This part of the system is indeed not aimed at replacing, but at supporting the designer: a wide range of potential solutions is offered in order to widen the viewpoint of the user from his habitual pattern of thought and experience. In case of the illumination example, different types of lamps or lamp-luminaire combinations will be proposed. In case of a bearing principle selection problem, plain bearings, air bearings and roller bearings can be proposed;

2. a metric selection module, allowing for selecting appropriate eco-efficiency performance metrics. In ideal situations, attention has been paid to eco-efficiency aspects when defining and formulating requirements, such that eco-efficiency constraints form an integral part of the functional description. In that case, the selection of an appropriate eco-efficiency metric has occurred throughout the inverse supply chain, or is even part of sector wide industry standards. An example is the proposal for an eco-efficiency metric and for product oriented environmental performance indicators for the rail vehicle industry as proposed in [10]. In many cases, however, eco-efficiency constraints are rather vague, and a holistic LCA/LCC based metric is chosen. A thorough description with respect to eco-efficiency indicator selection is, however, outside the scope of this paper;
3. a presentation module. The results of the Eco-PaS can be presented in a number of ways. A direct result of using the system in a design situation is, of course, a comparison of the estimated environmental impact of different feasible design solutions for specified functional constraints. A prototype software implementation of the model provides the results as shown in Figure 6. Towards future implementations, statistical information about the solution range as well as sensitivity analysis should be implemented to increase acceptability, as indicated in the previous section. Another option is to graphically represent for which combinations of functional parameters the different solution principles are appropriate (i.e. for example more than 20% better than the other solutions).

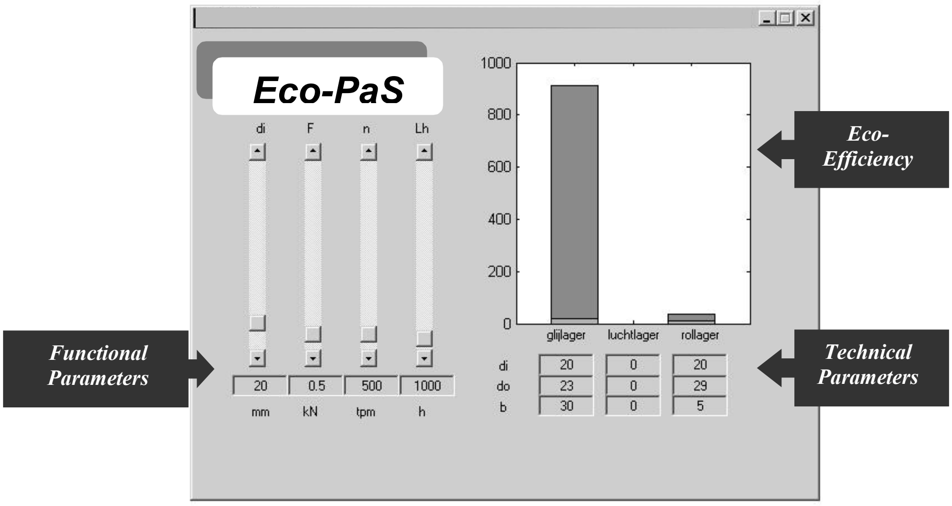

Figure 6. Output of the Eco-PaS Prototype Software.

5. Conclusion

The E-CERs and the Eco-PaS tool described and illustrated in this paper allow to estimate the environmental impact of technical solutions based on functional parameters available in an early stage of the design process. Design concepts, described as functional blocks that are subject to functional requirements, are translated into technical parameters. These technical parameters are, in turn, used to assess the eco-efficiency of the solution. Main advantage of the system is the sufficiency of input in terms of functional requirements rather than the materials inventory needed by typical LCA applications. However, to increase the acceptability and usefulness of the system, the application of statistics and sensitivity analysis is needed.

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