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ESTIMATING THE ENVIRONMENTAL IMPACTS OF SIMILAR PRODUCTS

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1. Introduction

Performing a detailed Life Cycle Assessment (LCA) is a time consuming process, involving information that is available solely in the late phases of the design process. Therefore, LCA is in most cases too complex to be integrated as a regular constituent into product development. This especially holds true in the early phases of product development, when the "rough" estimations of the product's impact on the environment are needed in order to take advantage of the significant (and relatively cheap) improvement opportunities characteristic to early design.

Parametric estimation techniques - known from production and/or Life Cycle Cost estimation practice - have been proposed as a simplified LCA technique for estimating the environmental impacts of similar technical products based on a limited number of LCA studies. The aim of these environmental parametric estimation techniques is to establish a coupling between functional requirements (FR) or design parameters (DP) that product developers have at hand in early design phases and the environmental impact (EI) of the product. Therefore we outline methods that help to find parametric expressions in the form of EI=f(FR) or EI=f(DP) (see also [Suh 1990]). This paper presents and compares techniques for creating parametric expressions, developed at respectively *Katholieke Universiteit Leuven* and *Darmstadt University of Technology.* Though the presented techniques operate independently of the measurement method for the environmental impact (EI), the case studies use *Eco-indicator 99* throughout. Estimating the environmental impact of new designs using these expressions can provide good results on the condition that the examined range of products is similar, i.e. the products (1) fulfil the same function, (2) are based on the same solution principle, and (3) involve comparable production processes.

2. Methods

2.1 Theoretical modelling

Principle

Theoretic modelling is suited for developing parametric expressions for relatively simple components such as structural components (e.g. plates, beams) [Dewulf 2003]. In first instance, the environmental impact of a design is expressed as a function of design parameters using primarily geometric formulae: EI=f(DP). Afterwards, appropriate engineering design formulae and algorithms are used to formulate the design parameters as a function of functional requirements available earlier in the design process: DP=f(FR). Combining both equations leads to an expression of the environmental impact as a function of functional requirements: EI=f(FR).

Case study

As an example, the cradle-to-gate environmental impact of a plate can be straightforwardly calculated from the components' dimensions using geometric formulae:

$$EI_{plate,i} = t \cdot a \cdot b \cdot \rho_i \cdot EI_i \tag{1}$$

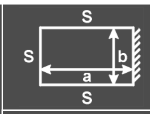
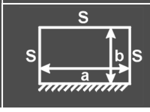
where a, b and t respectively represent the plate length, width and thickness, while ρ_i and EI_i represent the material density [kg/m³] and cradle-to-gate environmental score (e.g. expressed in [Eco-indicator 99 Pt/kg]) for material i.

The design parameters in Eq. 1 can moreover be expressed as a function of maximum loads and load conditions, thus leading to an overall expression relating environmental impact to functional parameters available truly early in the product development process. For example, in case the plate needs to be designed for optimal stiffness, the maximum deflection y_{max} of a homogeneous, rectangular plate under uniform load q [N/m²] is known to be [Young 1990]

$$y_{max} = \frac{\alpha \cdot q \cdot b^4}{E \cdot t^3}\text{, which is equivalent to } t = \sqrt[3]{\frac{\alpha \cdot q \cdot b^4}{E_i \cdot y_{max}}} \tag{2}$$

where α is a parameter depending on plate proportions and boundary conditions (See Table 1), and E is Young's Modulus of the plate material.

Table 1. Parameter α as a function of plate proportions and boundary conditions for selected cases. An S represents a simply supported edge [Young 1990]

	A	*a/b*						
		1	*1.5*	*2*	*2.5*	*3*	*3.5*	*4*
Boundary conditions		**0.030**	**0.071**	**0.101**	**0.122**	**0.132**	**0.137**	**0.139**
		**0.030**	**0.046**	**0.054**	**0.056**	**0.057**	**0.058**	**0.058**

Substituting Eq. 2 in Eq. 1 leads to a very simple parametric model for calculating the cradle-to-gate environmental impact of a plate design for optimal stiffness:

$$EI_{plate,i} = \sqrt[3]{\frac{\alpha \cdot q \cdot b^4}{E_i \cdot y_{max}}} \cdot a \cdot b \cdot \rho_i \cdot EI_i \tag{3}$$

Rearranging Eq. 3 moreover allows for grouping the factors into a factor solely dependent on the functional parameters and a factor solely dependent on material properties:

$$EI_{plate,i} = \left(\sqrt[3]{\frac{\alpha \cdot q \cdot b^4}{y_{max}}} \cdot a \cdot b \right) \cdot \left(\frac{\rho_i \cdot EI_i}{\sqrt[3]{E_i}} \right) \tag{4}$$

In each material selection problem, the first factor will be equal for all considered alternative materials. Consequently, the selection can be based on the second factor. This factor is a material property, and is consequently available in early design phases. A material A is thus environmentally preferable for stiff plates if:

$$\left(\frac{\sqrt[3]{E_A}}{\rho_A \cdot EI_A}\right) > \left(\frac{\sqrt[3]{E_B}}{\rho_B \cdot EI_B}\right) \tag{5}$$

Note that the expression $\sqrt[3]{E} / \rho.EI$ determining the adequacy of a material for environmentally preferable plates dimensioned for optimal stiffness is similar to the expression $\sqrt[3]{E} / \rho$, derived by [Ashby 1992], which expresses the adequacy of a material for stiff and lightweight plates. This parallel is no coincidence: in both cases, minimum plate dimensions are calculated, which lead to a plate volume that is, in turn, multiplied by respectively ρ and $\rho.EI$ in order to obtain the desired property (i.e. mass or Environmental Impact score). Consequently, a wide range of formulas developed for lightweight design can be converted into formulas for environmentally benign design by replacing the (mass) density ρ by the 'environmental density' $\rho.EI$.

2.2 Predicting the growth of environmental impacts of size ranges (EIGLs)

Principle

For size ranged products similarity laws help to predict the product properties of subsequent designs (index q) based on information on the initial design (index 0) (cf. [Pahl 1996]). In analogy to so called Cost Growth Laws (cf. [Pahl 1984]), or Relative Cost Structures (cf. [Ehrlenspiel 1998], [Fischer 2003]), the Environmental Impact Growth Law (EIGL) approach (see [Dick 2003]) aims at predicting the ecological properties of size ranges. This enables a comprehensive view on environmental impacts that is independent of size.

A set of products is considered to be geometrically similar if the ratio of all lengths of any follow-up design to all lengths of the basic design is constant. The step size φ_{L_q} is a dimensionless value that sets a characteristic length L_q of a subsequent design in proportion to a characteristic length of the basic design L_0. By contrast, semi-similar size ranges only show a variation of some dimensions in the same ratio while other dimensions do not vary.

The EIGL approach is suitable when an environmental impact assessment has been carried out for the basic design 0. EIGLs are based on the assumption that the step size of the environmental impact φ_{EI_q} can be expressed as a function of the step size of a characteristic length φ_{L_q} as shown in Eq. 6.

$$\varphi_{EI_q} = \frac{EI_q}{EI_0} = f\left(\varphi_{L_q}\right) \tag{6}$$

Thus, it is possible to calculate the environmental impact EI_q of any follow-up design based on the environmental impact EI_0 of the basic design and on a closer analysis of the growth characteristic which is given by the step size of the environmental impact.

In the EIGL approach, the step size of the environmental impact φ_{EI_q} is expressed as a polynomial of N-th order (see Eq. 7). Generally, $N=3$ integer exponents x_i are sufficient.

$$\varphi_{EI_q} = \sum_{i=0}^{N} a_i \cdot \varphi_{L_q}{}^{x_i} \tag{7}$$

In the case of geometric similarity the growth shares of the polynomial expression increase with volume (with $\varphi_L{}^3$), surface (with $\varphi_L{}^2$), length (with $\varphi_L{}^1$), or remain constant (with $\varphi_L{}^0$). In general, the coefficients are positive, with the exception of some recycling processes where e.g. thermal residue recovery is credited in the environmental impact assessment.

The coefficients a_i assigned to the growth exponents x_i are determined according to the scheme shown in Table 2. The assignment to a growth property class is not always obvious since the exponents for various processes can deviate from integer values. But using rounded exponents gives mostly satisfying results.

Table 2. Calculation scheme for determining the environmental impact contributions a_i to the basic design

		Environmental impact EI_{ij} [Pt.] of process j, growing with $\varphi_L^{\,i}$					
j	process	i=3	i=2	i=1	i=0		
1	steel production	0.20253					
2	chamfering			0.00004			
3	electroplating (chrome)		0.01176				
4	paper production				0.00086		
…	…	…	…	…	…		
	$EI_i = \sum_j EI_{ij}$	0.31567	0.02014	0.00116	0.07560	0.41257	$\sum_{i=0}^{3} EI_i = EI$
	$a_i = \frac{EI_i}{EI}$	0.76513	0.04882	0.00281	0.18324	1.00000	$\sum_{i=0}^{3} a_i = a \overset{!}{=} 1$
	φ_{EI}	$= 0.766\,\varphi_L^3$	$+ 0.049\,\varphi_L^2$	$+ 0.003\,\varphi_L$	$+ 0.183$		

Case study

The EIGL approach has been validated with various case studies, e.g. a commercially available DC motor series which varies in length while the diameter remains constant. The step size of the environmental impact is traced in Figure 1 as a function of the step size of the charcteristical length for the motor example. Both axes are logarithmically scaled.

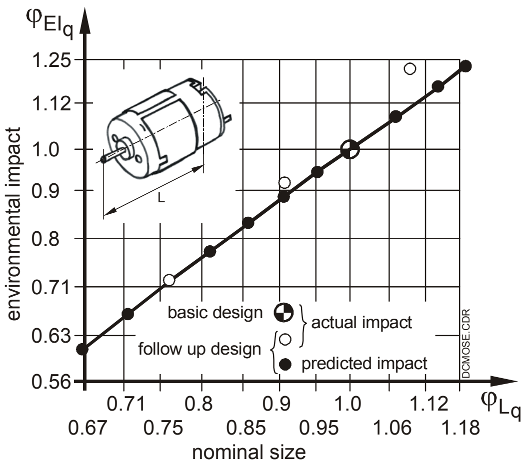


Figure 1. Relative environmental impact diagram of the examined DC motor series[1]

The deviation between the actual impact and predicted impact is partly due to lacking homogeneity in the design of the motors and partly due to uncertainties resulting from the attribution of processes to growth properties.

[1] Altogether four models have been assessed using *Eco-indicator 99*. Strictly speaking, one reference assessment and one complementary control assessment would be sufficient for the application of the method. The assessment covers the material production, manufacturing, recycling, and disposal stage.

2.3 Deriving empirical regression functions (E-CERs)

Principle

A commonly used parametric cost estimating technique in aerospace and naval industries is using Cost Estimating Relationships (CER's) [Brundick 1996]. CER's are mathematical expressions relating cost as the dependent variable to one or more independent cost driving variables, and are derived from historical, theoretical and literature data using e.g. regression analysis. In analogy to this definition, [Dewulf 2003] proposed to define Eco-Cost Estimating Relationships (E-CER's) as mathematical expressions relating an eco-cost (or any other environmental indicator) as dependent variable to one or more independent eco-cost driving variables. The latter variables are chosen amongst the functional requirements, which are available early in the design process.

Case study

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. Therefore, the required nominal power is considered to be the functional requirement and consequently the independent eco-cost driving variable for the cradle-to-gate *Eco-indicator 99* E-CER derived in Figure 2. The coefficient of determination R^2 shown in the figure is already comfortably higher than the 0.8 lower limit used in e.g. NASA cost estimation procedures. Statistical hypothesis tests can be used to assess the validity of adding extra eco-cost driving parameters, such as the number of poles.

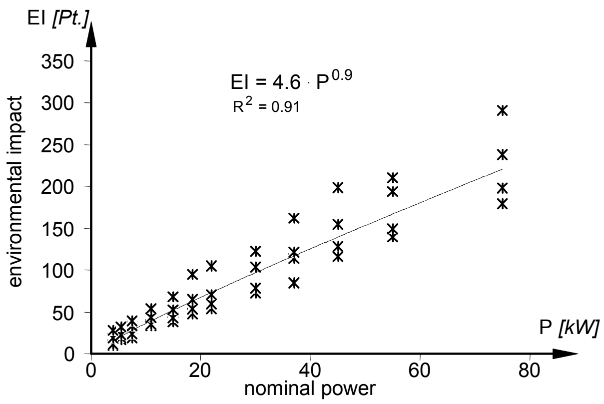


Figure 2. Cradle-to-gate *Eco-indicator 99* score for 3-phase induction motors of 5 to 75 kW[2]

3. Comparison

This part of the paper points at the fundamental similarities and differences between the approaches and investigates the utilisation situations of the individual techniques.

A first difference is the time needed for creating the parametric expression, and - linked to this - the profile of the person responsible for creating the parametric expressions. While theoretic modelling and EIGLs can be used within a reasonable time span, a relatively large time investment is needed for creating regression based E-CERs. However, it must be noted that the largest time investment is needed to gather the life cycle inventory data for the first specimen of a product range, while the LCA of similar products only requires the collection of relatively easily accessible data such as the bill of materials.

Second, the complexity of the products which can be described by the parametric expressions varies. Though an understanding of the causal relationship between the independent variables in the

[2] The figure is based on a one supplier survey and only takes into account material production impacts. Similar E-CERs can be derived for other life cycle stages of the motor, such as for use phase energy efficiency [Dewulf 2003].

parametric expressions (i.e. the design parameters) and the dependent variable (i.e. the environmental impact) is crucial for developing adequate parametric expressions, this prerequisite is only stringent for the theoretic modelling approach, followed by the EIGLs, and less stringent for the regression based E-CER approach.

Third, the applicability range for the parametric expressions is determined by the products itselves. Since EIGLs are created based on a single product, the applicability will be very much specific. In case of E-CERs, on the other hand, products involving multiple solution principles and production processes can be used to create one single parametric expression. The latter expression allows the user a first, though very rough, estimation of the product's environmental impact before essential choices in the design process have been made. It is however obvious that the uncertainty on this parametric expression will increase significantly, and needs to be taken into account while using the expression.

4. Conclusions

This paper proposed parametric estimation techniques as a simplified LCA technique for estimating the environmental impacts of a range of similar products based on a limited number of LCA studies. The aim of these environmental parametric estimation techniques is to establish a coupling between functional requirements (FR) or design parameters (DP) that product developers have at hand in early design phases and the environmental impact (EI) of the product. Three approaches, developed at two universities, were compared: theoretical modelling, Environmental Impact Growth Laws (EIGLs), and Eco-Cost Estimating Relationships (E-CERs). Strengths and weaknesses of the approaches are investigated. The paper is a first step towards the creation of an integrated approach for providing early environmental impact estimation techniques for product developers.

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References

Suh, N. P., "The Principles of Design", New York: Oxford University Press, 1990.

Dewulf, W., "A Pro-Active Approach to Ecodesign. Framework and Tools", PhD dissertation, Katholieke Universiteit Leuven, 2003.

Young, W., "Roark's Formulas for Stress & Strain", 6th ed., New York: McGraw-Hill, 1990.

Ashby, M., "Materials Selection in Mechanical Design", Oxford: Butterworth Heinemann, 1992.

Pahl, G., Beitz, W., "Engineering Design. A Systematic Approach.", 2nd ed., Berlin: Springer, 1996.

Pahl, G., Rieg, F., "Kostenwachstumsgesetze für Baureihen (Cost Growth Laws for Size Ranges)", Munich: Hanser, 1984.

Ehrlenspiel, K., Kiewert, A., Lindemann, U., "Kostengünstig Entwickeln und Konstruieren (Cost Effective Development and Design)", 2nd ed., Berlin: Springer, 1998.

Fischer, J. O., Götze, U., "Design to Cost. Software Application for Relational Cost Tables." (in German), Konstruktion, 11/12-2003.

Dick, M., "Environmental Impact Growth Laws", PhD seminar, Darmstadt University of Technology, 2003.

Brundick, B., "Parametric Cost Estimation Handbook", Arlington: US Navy, 1996.

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