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Materials selection with several sizing variables taking environmental impact into account

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ABSTRACT

In two recent papers by the authors in Materials and Design it was shown how efficient materials optimisation can be performed in realistic design cases with several sizing (geometrical) variables. In the present paper this analysis is expanded to take environmental impact into account. Two approaches are considered for the materials optimisation. In the first one, the environmental impact is considered as a constraint and the solution in found with the help of a control area diagram (CAD). In the second approach trade-off values for the environmental impact are used. The approaches are applied to a pressure vessel where the geometry is defined by four geometrical variables. Four pressure vessel steels and three aluminium alloys are used in the analysis. Merit indices and merit exponents are systematically used to solve the material optimisation problem. As expected the optimum material is strongly dependent on the chosen target functions and constraints. It is demonstrated that the two approaches for materials optimisation give identical results.

1. Introduction

In material selection the environmental consideration is one of several important aspects that have to be considered. Other aspects are the production methods, the function, the market demand, the design, the cost and the total lifetime of the product [1]. Two of the first to take into account environmental impact in materials selection were Ashby [2,3] and Holloway [4]. Ashby compares the impact on the environment from the material, the manufacturing, the transport and the use of the material. The next task is to improve that part that influences the environmental impact most. For a refrigerator the major impact comes from energy lost by conduction through the walls. Then a merit index for this property is helpful to improve the effectiveness of the refrigerator [2]. Holloway showed [4] that it is possible to use material charts, developed by Ashby [5] to find a more environmentally friendly material. The damage to the environment arises from the production of the material, the manufacturing of the product, transport of the product, the use of the product and finally from the disposal of the product. It is possible to reduce the impact if the product or material could be recycled. We use resources to produce a material and to manufacture the product. These resources could be minerals, water, electricity, etc. Then there are emissions when producing and transporting the material and the product. Emissions are also connected to the use of the product. Examples of such emissions are CO_x, NO_x and SO_x to the air that gives rise to global warming, ozone depletion and toxicity.

Ideally a full life cycle analysis (LCA) should be performed for each of the considered materials in the selection process to minimise the environmental impact [6]. In several studies LCA analyses have also been a part of materials selection methods. One such method is the multi-criteria decision making model (MCDM). This method includes engineering analysis and life cycle simulation. In a paper by Huang et al. [7] material selection for PC housing was performed using this model. The input in this model is function and performance requirements together with material attributes. The parameters are the weight and shape/dimension of the component. The parameters are then used as input in the four life cycle processes. (1) Materials extraction and processing, (2) manufacturing, (3) usage and (4) recycling. This results in a total life cycle environment impact and a life cycle cost using eco indicator.

Vogtländer et al. [8] used an end-of-life concept. They considered five different parameters. (1) The eco-costs of recycling, (2) eco-benefit of recycling, (3) economical cost of recycling activities, (4) market value of recycling activities and (5) market value of recycled materials.

In a paper by Emolaeva et al. the LCA methods were applied to analyse the environmental impact. Their case study was a floor panel in a concept car. They applied structural optimisation to determine the geometry and weight for the different materials. Then they used SimaPro [9] for the LCA using the Eco-99 indicator. In the actual selection process an objective function given by Eq. (1) was used:

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$$c = \sum_{i=1}^{n} \alpha_i c_i \tag{1}$$

where α_i are the weighting and c_i are the material indices. The result from the LCA can here be used as a material index. The optimal material is the one with the lowest value of c.

To perform a full LCA is time consuming and costly. Ideally only a few materials/processes will be possible candidates. Then an LCA is performed for these chosen situations. This was illustrated in a paper by Giudice et al. when selecting material for an automobile brake disc [6]. They used a similar approach as in Eq. (1) where the total environmental impact descend from the material itself, the manufacturing, the use and end-of life.

There is a serious problem in applying an equation like (1). It involves the use of weight factors in the optimisation. These factors are difficult or impossible to select in a way that is valid for a range of materials and conditions. The same difficulty appears if weight factors are applied in other parts of the LCA. In materials selection there are established ways of avoiding these difficulties. After preselection of materials, a de-selection process (also called discriminating search) should be used. In this step, discriminating properties (for examples those related to manufacturing such as machinability and weldability) are identified and requirements are formulated for them. The materials that do not satisfy the discriminating requirements are eliminated [10]. The important technical aspect of this is that if the discriminating part has been performed correctly, all the remaining materials should be possible to apply for the component in question. Then in the optimisation phase the best of the remaining materials in some respect is identified. For this purpose a target function is chosen. If more than one target function should be optimised at the same time this can be handled with what is now often called trade-off [11–13]. This technique will be described in detail below. In this way the use of less well defined weight factors is fully eliminated.

In materials selection Eco-indicators are often used to handle LCA. The purpose of an Eco-indicator is to take as many types of environmental impacts into account as possible and transform them into a single value for materials for conventional production processes. All types of environmental analyses are associated with difficulties of finding accurate data for how for example emissions affect the environment, which means that high precision can never be expected. It is also quite tedious to update Eco-indicators with the most modern and precise information. As in all LCA, environmental impact during transport, use of material, recycling, etc. have to be handled in a case specific way. To some extent this can be taken into account with help of trade-off. This is analysed in the present paper. Examples of commonly used Eco-indicators are, EPS2000 [14]; EDIP97 [15]; CML2001 [16]; Eco-indicator 95 [17] and Eco-indicator 99 [18], where the digits state the year the method was developed. In the development of Eco-indicator 99, a number of systematic steps have been taken to avoid the difficulties with the use of weight factors. For that reason, Eco-indicator 99 was chosen in the present paper.

In a paper by Mohite and Zhang, Eco-indicator 99 was applied to identify the environmental impact for material used for computer drives [19]. In two papers by Huang et al. materials selection in green design uses the Eco-indicator 99 when evaluating the environmental impact for a reading lamp and an air-conditioner [20,21]. In their models they employ a multi-objective decision making model where the material life cycle cost and environmental impact are used as constraints. Their result provides useful guidelines in green design. In work by Ribeiro et al. [22] the Eco-indicator 99 was used for selecting different materials for an automotive break system including both steel and plastics. The Eco-indicator 99 is not only applied for metals [23] and polymers [24], it can also be defined for non-engineering materials as wood as described by Bovea and Vidal [25]. In a paper by Ljungberg [1] the political and culture aspects of producing sustainable products are discussed among many other considerations. Bovea and Gallardo [26] compared the results of materials selection with five different Eco-indicators (EDIṔ97, CML 2000, EÍ95 and EPŚ2000). They concluded that the choice of Eco-indicator has significant impact on the result.

There are three general ways in which environmental impact can be taken into account in materials selection. The first one is to consider the environmental impact as a de-selection property. This is not suitable, however, since the impact depends on the volume or weight of the component, which is characteristic for sizing properties. Thus, the impact should be considered in the optimisation part. Usually, the environmental impact is not the main target function in the optimisation. Then there are two alternatives: the impact can be handled as a constraint or it can be taken into account with the help of trade-off. Both alternatives will be considered in detail in the present paper.

In materials selection in real engineering cases typically several sizing variables (geometric variables) are involved. Most papers and textbooks considering materials optimisation, only take into account a single sizing variable. In materials optimisation, ranking of materials with the help of merit indices play a central role. To remove this limitation with a single sizing variable, a new technique based on control area diagrams (CAD) has been developed recently [27,28]. In the present paper this technique will be expanded to cover environmental impact. In a CAD it is possible to see what sizing parameters that are limiting the optimal geometry for a given case. As an environmental constraint the total impact calculated from the Eco-indicator 99 are used. In the optimisation several geometrical parameters are allowed to be varied, and the CAD will give information what parameter is to be changed for an optimal solution. Then it is possible to include several geometrical variables to see what parameter should be changed in the optimisation.

2. Material data

The methodology for the Eco-indicator 99 can be summarised as 5 steps [23]. In step 1 an inventory of all the flows in the life cycle of the product is done. In step 2 the inventory result are divided into the three groups "Resources", "Land Use" and "Emissions". Step 3 is to do damage models for these flows according to damage to "Human health" the "Ecosystem" and to Resources". In step 4 these categories are weighted and in the final step they are summarised to a single indicator, the Eco-indicator 99 (will be called EI-99 in the paper). One has to keep in mind that the Eco-indicator today only includes the measurable effects that are known today and can be completely changed tomorrow. Therefore these indicators have to be continuously developed to include all the new findings.

To calculate the environmental impact the values from the Eco-indicator 99 are used [9,29]. The eco-points are only to be used as comparison between different materials. For materials their units is points/kg. The total environmental impact for a product is given in points. The data that is used is the total impact from carcinogenicity, respiratory (from inorganic compounds), climate change, ecotoxicity, acidification, land-use, minerals and fossil fuels, see Table 1. The list also includes respiratory effects from organics, ionising radiation and ozone layer depletion, but since these effects are less than 10^{-3} points/kg they are not included in the table. The total impacts is the sum of all separate impacts and are given in points per kilo, but could easily be transformed to point per unit volume of a material instead. With this simple transformation it is possible to use the environmental impact as a property on a control area diagram (CAD) [27,28].