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APPLICATION OF ANALYTIC HIERARCHY PROCESS FOR WEIGHTING OF IMPACT CATEGORIES IN LIFE CYCLE IMPACT ASSESSMENT

Abstract: *A usually highly controversial issue in life cycle impact assessment is the weighting of impact categories, as this is a subjective issue. The first part of the paper describes the proposed approached where analytic hierarchy process is used to calculate the weighting factors of impact categories in life cycle impact assessment. Further on, proposed approach is implemented on example where environmental impacts of material production for three products are compared. Three scenarios have been assembled with different weightings factors of impact categories and obtained results were discussed in conclusion of this paper.*
Keywords: *weighting factor, life cycle, impact category, analytic hierarchy process*

1. INTRODUCTION

The problem of comprehensive evaluation of environmental issues - which in principle depends on a number of parameters - lies in the diverse nature of those parameters and their dimensional variety. In other words, total environmental impact cannot be expressed by simply aggregating particular values of influential parameters, i.e., criteria. This is why in this area focus is placed on the development of multi-criteria analysis (MCA) and life cycle assessment (LCA) methods for evaluation of environmental impacts [1].

In the area of environment protection, multi-criteria evaluation can be employed whenever there are multiple alternatives that need to be assessed and compared - e.g., environmental loading on different locations [2], environmental assessment of products in eco-design [3] or in eco-labeling [4], municipal solid waste management and planning [5], environmental evaluation of processes in Environmental Impact Assessment (EIA) [6] or for Best Available Technologies (BAT) [7]. An example of multi-criteria evaluation of environmental loading at particular locations is presented in [2]. Here, a multi-criteria methodology was used to evaluate the need for remediation of polluted areas, taking into consideration various aspects, such as the sediment quality, economic and social aspects.

Application of MCA in LCA has been discussed in many scientific papers and some of them are mentioned in the following text. Benoit and Rousseaux [8] noticed that from a broader perspective, LCA may also be described as a multiple criteria decision aid method. Furthermore, they compared the methodology steps of multi-criteria decision-making tool with LCA. A new method was proposed in [9] for the identification of environmental impact category weights using a panel approach and a multi-criteria decision aid for use within the weighting step in Life Cycle Impact Assessment (LCIA). In [10] a application of multiple criteria decision making is presented to deal with decision conflicts often seen among design criteria in composite material selection with the help of life cycle assessment.

Hermann *et al*. [11] presented the analytical tool, called “Compliment”, which can be used to provide detailed information on the overall environmental impact of a business. “Compliment” integrated parts of tools such as LCA, MCA and environmental performance indicators. Hermann *et al*. [11] discussed about possibility to combine LCA and MCA. LCA is standardised and reproducible, whereas MCA is subjective and different results may be obtained depending on the method or perspective selected. The MCA evaluation method is generally used to weight and sum LCA results into a single index (after classification, characterisation and optionally also normalisation). Despite the loss of information that occurs when aggregating data into a single index, the weighting of midpoint impact categories and the subsequent calculation of one overall, single number score is one of the general strengths of a combination of LCA and MCA evaluation methods.

The objective of a study [12] was to propose a systematic and easy-to-use method for the determination of impact category weighting factor. Multiattribute decision making methods were evaluated for this purpose, including: the Analytical Hierarchy Process (AHP), the rank-order centroid method, and the fuzzy method. Time, area, irreversibility, and scientific uncertainty were chosen as criteria for calculating the significance of impact categories.

The following text describes the idea of the proposed approached where AHP is used to calculate the weighting factors of impact categories in LCIA. Further on, proposed approach is implemented on example where environmental impacts of material production for three products are compared. Three scenarios have been assembled with different weightings factors of impact categories and obtained results were discussed in conclusion of this paper.

2. THE PROPOSED APPROACH

According to ISO 14044, Life Cycle Impact Assessment (LCIA) proceeds through two mandatory and two optional steps: 1. Selection of impact categories and classification, 2. Characterisation, 3. Normalisation, 4. Weighting. This part of the paper focuses on the optional step of weighting. Although the characterisation is an obligatory step, according to ISO 14042, the results of a characterization step can be easily misinterpreted, as:

- A column displaying 100% can refer to very high or very low figures.
- All characterized impact category indicators tend to have different units, so even if the amounts were to be displayed, these would not have meaningful information.
- Not all impact categories are probably equally important, so there is no information on weighting.

Normalization is intended to solve the first two shortcomings by creating a uniform unit for all impact categories and by showing the relative contribution of all impact categories to the environmental problems in a region.

Normalized impact category indicator results are not all equally important, and may thus not be added to form a single score. Weighting factors are required. Weighting is a subjective step and therefore this is one of the most controversial and difficult issues in LCA interpretation. ISO 14042 does not allow weighting across impact categories for public comparisons between products.

However weighting is explicitly allowed for other applications, and thus this means it is a responsibility of decision maker to use weighting in a proper way.

For some methods, like the Eco-indicator 99 methodology it is possible to present the weighting problem to the stakeholders using the weighting triangle. Shortage of weighting triangle is that it is designed to evaluate only three endpoint impact categories, i.e. three damage categories in Eco-indicator 99. MCA methods can determine weight for unlimited number of criteria so it can be used for determination of midpoint and endpoint impact category weight factor.

The weighting methods can be grouped into three main categories [13]:

- Midpoint weighting methods - refer to midpoints like climate change and acidification. Here, assumptions on further empirical effects towards endpoints and their evaluation are combined in one step.
- Endpoint weighting methods - convert interventions into damages at endpoint levels. These endpoints, as in terms of damages to human health and biodiversity, are subsequently evaluated in a weighting step to aggregate these endpoint scores.
- Integrated weighting methods - are developed by economists and based on willingness-to-pay, as estimated through general panel procedures.

In this paper the proposed approach for multi-criteria weighting of impact categories has been applied on endpoint level (chapter 3), but it can be easily applied on midpoint level also. The proposed approach is based on equation (1), where the environmental impact *EI* (single score) of products is performed by multiplying the LCIA normalization results with the assigned weights:

$$EI_i = \sum_{j=1}^{m} w_j N_{ij} \ , \quad i = 1, 2, ..., n, \tag{1}$$

where:

N_{ij} - LCIA normalization results for *j*-impact categories,
wj - impact category weight factor,
m - number of impact categories,
n - number compared products.

Dimensionless values EI_i are directly proportional to environmental impact (single score) of the *i*-th product for the selected impact categories. In other words, higher values of *EI* indicate higher environmental impact, and vice versa. Based on the obtained results (*EI*), the products are ranked, allowing one to gain insight into the environmental impact of each product.

This approach uses multi-criteria analysis tool called Analytic Hierarchy Process (AHP), developed by Saaty [14], for determining the weighting factor of impact categories. The AHP method builds on the pair-wise comparison model for determining the weights for every unique criterion and sub-criterion. The AHP concept basically allows the decision makers to evaluate the importance of each selected criterion when compared to other criteria on a scale from 1 to 9, ranging from "same importance" (1) to "absolutely more important" (9). When creating a decision tree, decision-maker is allowed to first define weights of the basic criteria used for evaluation, and then he/she can define the lower level sub-criteria which precisely define the examined multi-criteria problem. Application of multi-hierarchical criteria is especially suitable in cases with multiple criteria which can be grouped into several functional classes [11]. Examples of AHP application for criteria weighting are presented in [1,12].

3. THE APPROACH IMPLEMENTATION - NUMERICAL EXAMPLE

For implementation of proposed approach in this paper, the following numerical example was chosen where environmental impacts of three products (A, B, C) are compared. In this example only the production phase for materials from which products are made is taken for LCA. Product A is produced from 3 kg of steel, B from 1kg of aluminium, and C from 0.5 kg of copper. For this comparison three scenarios with different weighting factors of endpoint impact categories were made:

- Scenario 1: with default weighting factors (1:1:1:1) for damage categories.
- Scenario 2: with weighting factors which intensify the impact of Human health and Resources damage categories.
- Scenario 3: with weighting factors which intensify the impact of Resources damage category.

For LCA of products A, B, and C SimaPro 7 software was used with IMPACT 2002+ V2.10 LCIA method [15]. IMPACT 2002+ is a combination of four methods: IMPACT 2002, Eco-indicator 99, CML and IPCC. The IMPACT 2002+ method was largely based on Eco-indicator 99, but instead of three as in Eco-indicator 99, it has four damage oriented impact categories: human health (HH), ecosystem quality (EQ), climate change (CC), and resources (R). The authors of IMPACT 2002+ suggest that if aggregation is needed, one could use self-determined weighting factors or a default weighting factor of one (1:1:1:1). They also recommend using the weighting triangle but as the weighting triangle can only assess 3 damage categories at one time, AHP was used to determine damage category weight factor.

First, materials and their quantities are selected in SimaPro 7 database for products A, B and C:

- Product A - 3 kg of Steel, low-alloyed, at plant/RER U.
- Product B - 1 kg of Aluminium, production mix, at plant/RER U.
- Product C - 0.5 kg of Copper, at regional storage/RER U.

After applying the IMPACT 2002+ LCIA method the normalisation results are obtained in dimensionless values (Table 1).

Table 1. Normalisation results (IMPACT 2002+)

	HH 10E-3[-]	EQ 10E-3 [-]	CC 10E-3 [-]	R 10E-3 [-]
Steel	0.991	0.153	0.509	0.539
Aluminium	0.998	0.137	0.892	0.756
Copper	1.59	0.683	0.092	0.102

According to previously defined scenarios 2 and 3, AHP comparison matrix are filled to represent the decision maker preferences (Table 2 and 3).

Table 2. AHP comparison matrix for damage category (scenario 2)

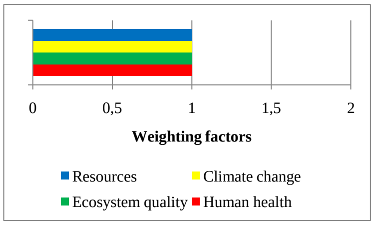
Incons=0.05	HH	EQ	CC	R	w
HH	1	3	3	2	0.443
EQ	1/3	1	3	2	0.183
CC	1/3	1/3	1	3	0.096
R	1/2	1/2	1/3	1	0.278

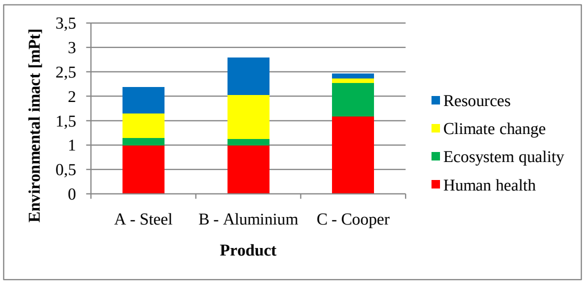
Table 3. AHP comparison matrix for damage category (scenario 3)

Incons=0.08	HH	EQ	CC	R	w
HH	1	1/2	3	1/2	0.219
EQ	2	1	2	1/2	0.273
CC	1/3	1/2	1	1/2	0.125
R	2	2	2	1	0.383

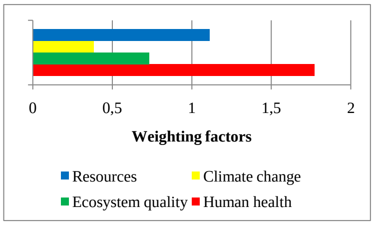
Considering that the sum of default weighting factors for IMPACT 2002+ (1:1:1:1) is equal to 4, and that the sum of AHP obtained weights is equal to 1, the AHP obtained weights were multiplied by 4 thus making the single score results mutually comparable (Figure 1). The single score results for three scenarios were obtained when calculated damage category weight factor and normalisation results were taken and included in equation (1).

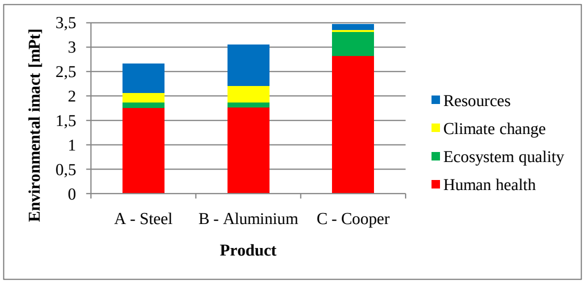
Scenario 1



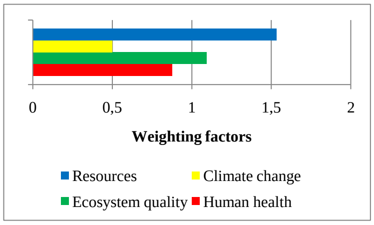


Scenario 2





Scenario 3



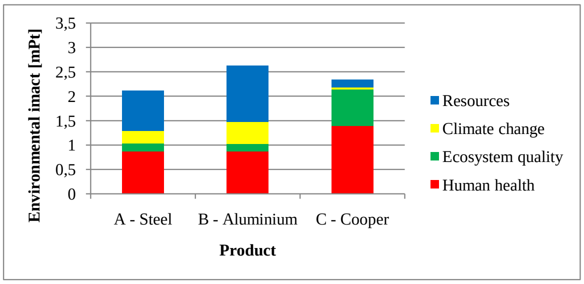


***Figure 1.** Damage category weighting factors sets for three scenarios (figures on the left side), comparison of three materials environmental impacts for production - single score results (figures on the right side)*

4. CONCLUSION

In the first scenario weighting set is default and product B outranks products C and A (B>C>A). Nevertheless, when weighting factor of damage category changes, environmental impact changes also. In second scenario applied weighting set resulted in larger environmental impact of C product, C outranks B and A (C>B>A). Although, the environmental impacts of damage categories and total environmental impact changes in third scenario change, the products have same rank as in first scenario (B>C>A).

Cooper has a largest environmental impact because only small amount of cooper (0.5 kg) produce almost similar environmental impact as larger amounts of steel (3 kg) and aluminium (1 kg). Product A in all three scenarios has the lowest environmental impact because its material, steel has a much lower environmental impact compared to aluminium and cooper.

The proposed approach for determining of weighting factors of impact categories in LCIA was well implemented in the presented example and thus proven its functionality. Default weighting factors of impact categories are not always the best solution, because of the complexity of problems in LCA. Further research should focus on developing a representative set of criteria for weighting of impact categories in LCIA. Furthermore, more research should be done on midpoint level to investigate the impacts of midpoint weighting factors on LCA single score results.

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