LIFE CYCLE IMPACT ASSESSMENT
A DAMAGE-BASED WEIGHTING METHOD FOR ENVIRONMENTAL IMPACTS

Ola ERIKSSON Ph.D[1]
Mauritz GLAUMANN Ph.D[1]
Getachew ASSEFA Lic. Eng.[2]

1 University of Gävle, Department of Technology and Built Environment, Building Quality, Södra Sjötullsgatan 3, SE 802 57 Gävle, Sweden, ola.eriksson@hig.se mauritz.Glaumann@hig.se

2 Royal Institute of Technology, Department of Chemical Engineering and Technology, Industrial Ecology, Teknikringen 42, SE 100 44 Stockholm, Sweden, getachew@ket.kth.se

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Summary

This paper describes the conceptual framework for a damage value-oriented weighting method for endpoint problems. It is developed with the aim to be transparent, and with a minimum of subjective features. Calculations of external environmental impacts are based on data for material- and energy flows, emission factors, and characterisation of emissions into contribution to environmental impact categories. These environmental impact values are then weighted by using damage values (total number of DALY (Disability Adjusted Life Years)) for each type of problem. Estimations of the number of persons possibly affected by a problem caused by emissions have been made and multiplied by the severity for each affected person. The category weight is the sum of all damage values in an impact category. This approach has several advantages: (1) A clear distinction between the characterization step and valuation step of the LCA, (2) A knowledge driven method where an improvement in quality and reliability of information and data used can be easily introduced to the framework. The method also suffers from some disadvantages: (1) As in other weighting methods, forecasts about the future in terms of scenarios do always mean an uncertainty and (2) Local and regional environmental problems are extrapolated to global effects, which means that uncertainties are introduced.

1. Introduction

1.1 Background

During the past ten years several tools for environmental assessment of buildings have emerged. Among them two types are discernible; criteria systems and tools more or less based on life cycle assessment. Criteria systems in the building sector normally contain a number of areas that are assessed as important in terms of environmental impact. For each area a scoring system has been developed with a scale ranging from less to greater environmental impact. Such methods are BREEAM (Great Britain) (BREEAM, 2005), GBTool (Canada) (Green Building Challenge, 2005), LEED (USA) (LEED, 2005), EcoProfile (Norway) (Byggforsk, 2005) and Miljöstatus (Sweden) (Miljöstatus, 2005).

Since the late 1990’s methods for environmental assessment of buildings based on LCA have been developed for the building sector. Most of these methods have aimed to be used for selection of building design and building material during the planning phase. Within life cycle assessment different weighting methods based on different basis for valuation are used.

EcoEffect (Assefa et al, 2005) is a life cycle based method aimed to be used in planning, construction, and administration of buildings as a decision support tool for taking measures in delimiting the environmental impact. This means all types of negative impact (disabilities or damages) on humans and environment today and in the future.

1.2 Problem

None of the criteria systems known to us have developed or used a systematic weighting method – either no weighting has been made, else it has been based on own judgements. Generally, weighting methods in LCA tools are difficult to adopt due to their complexity. Weighting methods applied in LCA are often hard to interpret or suffer from poor transparency and adapted for a specific application (not possible to generalise).

Comparisons of activities or products based on subjective weighting are not suitable for publishing (ISO, 2000).

1.3 Aim

The purpose of this paper is to present the principles behind a weighting method for environmental impact developed by the EcoEffect project group.

2. Method

The basis for the weighting in EcoEffect is an anthropocentric world-view; environmental problems will sooner or later end up as problems to humans. Therefore all environmental impacts are transformed to end point problems to humans and these have to be quantified in terms of "suffering" for individuals and groups of people at present and in the future. End point problems are also called category end points (ISO 14040) which means any kind of physical or psychological impact on humans. This means that a decrease in the environmental impact leads to less damages/disabilities for humans. By "damages or disabilities" is meant both physical and psychological disabilities. Environmental impact is calculated with respect to the risk for negative impact on humans and the severity if it occurs, see equation 1.

$$EI = p * s \tag{1}$$

EI = Environmental Impact

p = The Probability for humans being affected

s = The severity if the impact occurs

Impact on individuals on a building property is called internal environmental impact, whereas impact on humans outside the premise - caused by its use - is called external environmental impact. In this paper the method for assessment of external environmental impact is described. For description of the method behind assessment of internal environmental impact, see Westerberg et al (2005).

The probability for a disability/damage of a certain type to occur, eq. 1, is dependent on the physical characteristics of the assessed building, i.e. is based on data for the building. A damage value has been defined for the relative significance of different types of damages. This has nothing to do with the building, just the type of problem. The damage value, which describes the severity for a damage/disability, concerns the group of people that assumingly are affected by the problem. To distinguish this damage value from the one used for internal environmental impact, the term group damage value is used. The damage values are used as basis for weighting between different end point problems. For each type of problem a group damage value may be calculated. It is expressed as the number of affected persons multiplied by the average severity per individual. The procedure is illustrated in Figure 1:

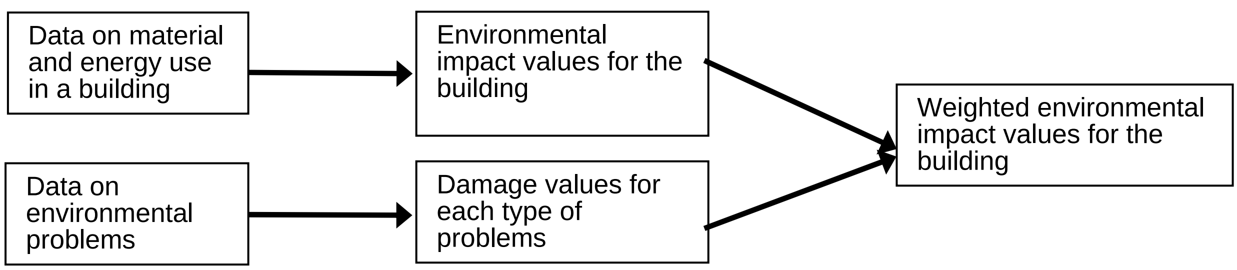

Figure 1 The principles for calculation of the environmental assessment.

2.1 Identification of End Point Problems

Environmental impact is to a large extent caused by activities meant to fulfil human needs and desires. Estimation of the number of individuals that may be affected, immediately or with some time delay, due to emissions depends on the type of emission and its magnitude. To clarify the connections between need/service and environmental impact a cause-effect chain is constructed, see Figure 2.

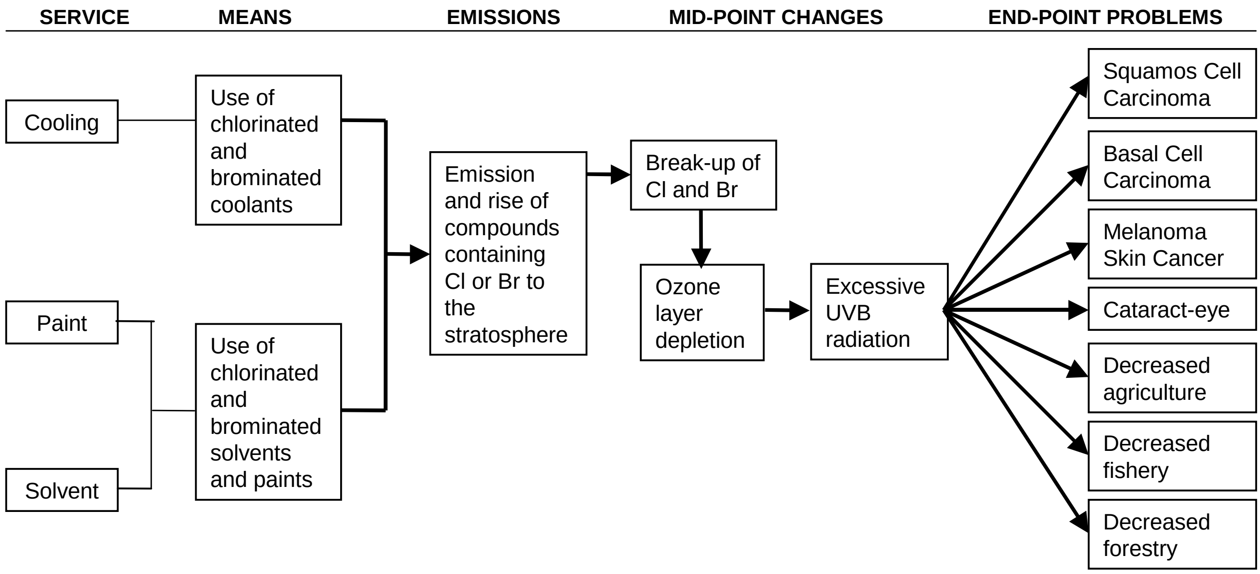

Figure 2 Example of a cause-effect chain from service to problem for an impact category, in this case Stratospheric Ozone Depletion.

Cause-effect chains are used to identify the consequences of environmental changes and end point problems for calculation of damage values. The cause-effect chain shows how the method takes the course of events into concern and what potential damages that are known and which are included in the calculations of damage values. As many end point problems as possible should be included. The number of affected and the average severity for each affected individual are estimated for each type of category end point in the cause-effect chain.

It must be emphasized that needs often can be fulfilled in different ways, causing different emissions and thus damages. Known or potential consequences may however be hard to quantify. The figure shows the simplification of reality as it is taken into account when calculating group damage values. Description of each impact category included, the problems connected to each category, choice of category indicators, estimation of the number affected, calculation of damage values etc. is found in Glaumann et al (2005a).

2.2 Estimation of the Number of Affected Individuals

Estimation of the number of people that will be affected by a certain end point problem is perhaps the most uncertain part of the entire environmental assessment methodology. The number of affected of a certain end point problem depends on

- The total amount of emissions contributing to the impact category
- How influential the substances are
- Which concentrations humans are exposed to

There are different ways to estimate the number of affected persons. The most natural way is to estimate how many people are affected today and from historic development try to extrapolate the trend for the future. The number of affected is normally expected to follow the development of the emissions. For some end point problems other scientists (e.g. Steen 1999) have explained the connections between emissions and impacts. They can be used to calculate group damage values, e.g. emission of x amount of a certain substance decreases the crop harvests with y %. If pollutants released from different processes would be evenly distributed globally, and the concentrations where they are dangerous were known, the amount of affected could be calculated. If this amount is known for a certain year, the next question is if it can be expected to increase or decrease for the following years and for how long time the impacts will last. Concerning the duration time, estimations have been made for the majority of the environmental problems in Bernes (2001).

2.3 Damage Values

A damage value represents the relative severity for a specific disease/damage or disability that affects one or more persons. How severe this is can be described by the extent of suffering/disability during the disability time and by the reduction of expected lifetime. A system has been developed by WHO, World Health Organisation (Murray and Lopez, 1996) for description of these two consequences. The system called DALY (Disability Adjusted Life Years), is originally developed to measure “burdens of disease” for populations (e.g. within regions or nations) aimed to serve as basis for prioritisation and allocation of financial resources within health- and medical care. A prerequisite to be able to calculate burdens of disease is that statistics for diseases are available, i.e. deaths due to different diseases, average life times and a disability weight for each disease. One advantage with use of damage values as weights instead of direct weighting of the categories is that the damage values do not change with the number of problems within a category. Instead there will be one unique value for each type of problem. The more end point problems included in an impact category, the larger becomes the damage value.

When calculating the burden of disease for a specific disease, the time frame is normally one year for which statistics on number of diseased and dead people is known. But in this case the external damage value should include both those who suffer from disability and those who die prematurely during the whole duration of the problem. For an end point problem emanating from an environmental impact with a duration time of several centuries, e.g. global warming, the calculation of the group damage value should account for the average lifetime of the affected people as well as the duration of the problem itself. The calculation is presented in equation 2:

$$gdv_i = t * DALY = t* (YLD + YLL) = t * (n * dw * dt + m * yl) \qquad (2)$$

gdv_i = group damage value for the end point problem i [years]
t = duration time for the end point problem in the category [years]
YLD = Years Lived Disable (average time for disability) [years]
YLL = Years Lived Lost (average shortened lifetime) [years]
n = number of ill/harmed persons []
dw = disability weight [0-1]
dt = average disability time per person [years]
m = number of premature death due to affection during the year, []
yl = average number of lost years per person [years]

For environmental problems where DALYs are not available, disability weight, lost years and number of affected persons for a specific year has to be calculated. A simplified method to obtain disability weights has been developed within the project (Glaumann et al, 2005b).

For each external end point problem a group damage value is calculated. The group damage value is supposed to reflect the relative severity of the studied problem in comparison to other environmental problems. The group damage values for each problem within a impact category is then summed up to a group damage value for the impact category. This value is used as a weight and is then multiplied by the environmental load value of the same impact category for the building, thus ending up in a weighted environmental load value (see Figure 1). The weighted environmental load values for all impact categories considered constitutes the environmental assessment in EcoEffect. They have the same unit and may therefore be added to each other. By performing this calculation for each problem it is possible to show the calculations and data in a table/spreadsheet for the sake of transparency.

The external impact is caused by emissions of pollutants and depletion of resources. Emissions may cause damage to human beings and the nature. Resource depletion covers the current exploitation of natural resources that might cause scarcities in the future, thus ending up in more or less severe consequences for future generations. The following two chapters explain the method behind the environmental assessment of emissions and resource depletion.

2.4 Environmental Assessment of Emissions

In life cycle assessment calculation of the contribution from different emissions to each impact category, the characterisation step, has been shown by different researchers (e.g. Wenzel et al, 1996). For each impact category a reference unit is used, e.g. CO_2-equivalents for global warming. In reality emissions may contribute more or less to an impact category depending on the circumstances. The equivalents are generally calculated as giving maximum effect; hence the term “potential” is used for the different impact categories (e.g. Global Warming *Potential*). The calculation of environmental impact from emissions is shown in Figure 3 (it refers to the simplified picture in Figure 1).

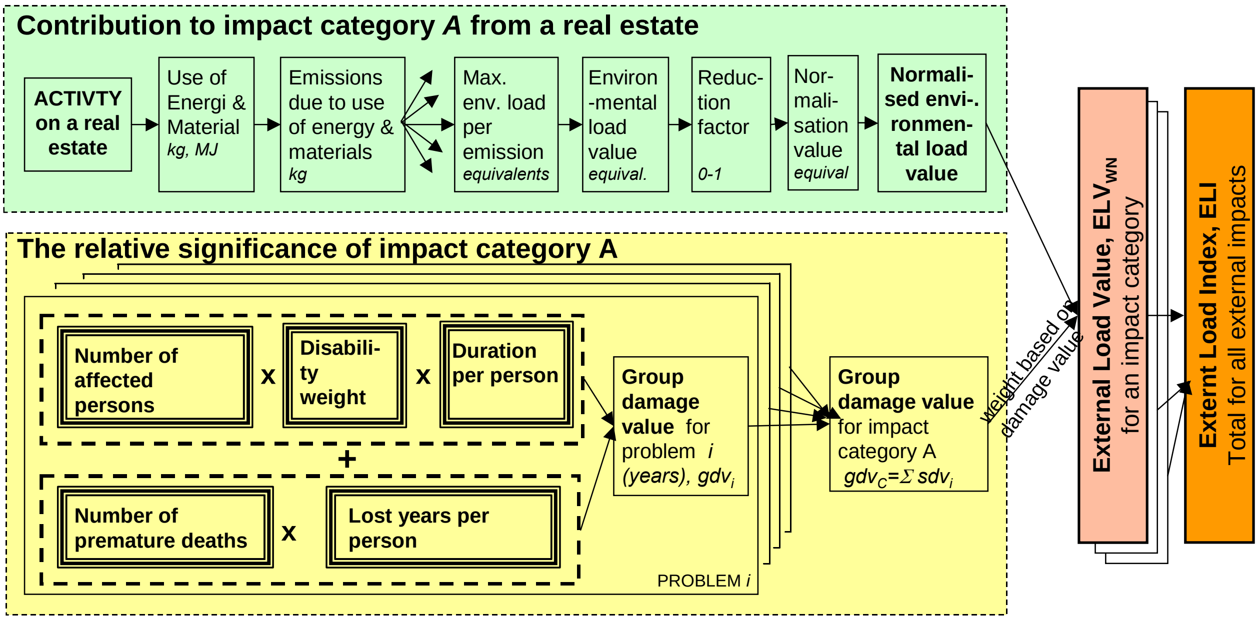

Figure 3 Calculation of environmental impact from emissions.

The lower box shows the group damage value calculation as described in the previous chapter. The upper box shows calculation of the environmental load value for a specific impact category. The impact categories in EcoEffect are mainly based on EDIP (Wenzel et al, 1996) and depicted in Table 1.

Table 1 Emission- and waste categories in EcoEffect.

Emissions to air and water	Waste and hazardous waste
Global Warming Potential	Building and demolition waste
Eutrophication Potential	Hazardous waste
Acidification Potential	Slag and ash
Depletion of stratospheric ozone	
Formation of ground-level ozone	
Human toxicity	
Ecotoxicity	
Ionizing radiation	

Using eq. 1 as a basis, the calculation of the normalised weighted environmental load value, shown in the box to the right in Figure 3 can be calculated as:

$$ELV_{NW} = p * s = (EL * R)/N * \Sigma gdv_i \qquad (3)$$

ELV_{NW} = *normalised weighted external environmental load value for a building*

p = *the probability that the environmental impact will cause an impact on human beings*

s = *the severity of the impact of the category compared with impacts from other categories*

EL = *the maximum environmental load value for a category due to emissions caused by a building*

R = *Reduction factor related to local conditions*

N = *Normalisation value*

gdv_i = *group damage value for an end point problem within the category*

The probability that an impact will occur, **p**, is assumed to be proportional to the reduced load value (EL*R).

The severity, **s**, of a category is the added group damage value for the impact category, i.e. the calculation in the lower box in Figure 3.

The maximum environmental load, **EL**, is calculated in equation 4:

$EL = \Sigma (m_i * e_j * EF_j)$ (4)

EL = *maximum environmental load related to emissions, [equivalents]*

m_i = *amount of energy or material used in the building [kg or MJ]*

e_i = *emission contributing to an impact within the category per unit of* m_i

EF_i = *effect factor (characterisation factor) for the substance*

The amount of energy and material, $\mathbf{m_i}$, refers to the entire life cycle of the building, i.e. the construction, operation and demolition phases. It is however impossible to tell the life of a building in advance. Therefore a comparison period of 50 years is used in EcoEffect. This is to give the operation phase a significant influence to the total load that should cover a life cycle. That means amounts of energy and material during the construction and demolition phases are included as they are whereas annual amounts during the operation phase are multiplied with 50.

Emission values, $\mathbf{e_i}$, are collected from life cycle inventories.

The reduction, **R**, should be made with respect to the distribution of the emissions as to link damages to emissions. In practice it is hard to tell where emissions come from and where they go, as many emissions can occur in different places. In the current version of EcoEffect the reduction factor has been set to 1 for all impact categories, i.e. no reduction is made.

The normalisation, **N**, is introduced in order to provide information about how much the building is contributing to the assessed problem and also to give the different environmental loads the same dimension, which makes them possible to compare and be weighted together. Normalisation can be made with respect to local, regional, national or global figures. For the obviously global impacts, climate change (global warming) and stratospheric ozone layer depletion, global normalisation values have been used. Elsewhere national or regional values are more appropriate. In EcoEffect values from Sweden and Denmark have been used. The chosen normalisation values have great importance for the assessment result. If, for example, normalisation values from an area with intense use of coal and oil are used, the normal value per capita becomes high, making the consequences of oil use in a building look small.

2.5 Environmental Assessment of Resource Depletion

A problem for future generations is that the assets of natural resources are becoming increasingly smaller. How severe the problem is depends on a range of issues. Parameters that can be mentioned are the size of the resource, the magnitude of the decrease, the possibility to substitute the substance (substitutability), the recycling possibility and the regeneration time (for renewable resources).

The magnitude of the depletion depends on the current rate of exploitation in comparison to the total stock, the so-called supply horizon. In practice, as the stock decreases the price per unit will increase and make the resource less available for an increasing population. For many of the natural resources exploited from the earth crust the cost of exploitation will continuously rise as the easy accessible resources are used first. As all extraction processes demand energy, the development of the energy prices will also have an impact on the natural resources availability. To some extent these problems will be solved by improved technology.

Substitutability is understood as the possibility to substitute a decreasing resource with another that is not scarce. For instance, Copper can in many applications be substituted by Aluminium that is more common in the earth crust. Fuels are to a high extent substitutable to each other, but phosphorus for fertilizing of soils cannot be substituted.

With a better possibility to recycle, the time for use of a resource is extended. The possibility of recycling depends on many factors, ideally materials should not be mixed or blended with each other and in the case of metals thin layers or films and alloys are less recyclable. Fuels cannot be recycled at all.

In the current version of EcoEffect resource depletion is calculated as in equation 5:

$DPV = \sum(m_i * w_i / N_i)$ (5)

DPV = *depletion value*

m_i = *used amount of pure natural resource [kg/person]*

w_i = *depletion weight*

N_i = *normalisation value [kg/person]*

The categories for depletion and the corresponding category references in EcoEffect are at present (units in kg): Copper (metals), Oil (fuels), Sand (minerals) and Wood (biomass). For each category the other resources within the category have been given a weight relative the reference resource. The following weighting aspects have been used:

- Scope: Supply horizon, change of exploitation rate
- Severity: The market value of the annual exploitation, energy demand for production of tradable goods
- Recycling possibility: Recovery time, energy demand for recycling

In the end the weighting aspects have been given weights with respect to how important they are for the availability for future generations. Finally the reference substances have been compared with each other where Copper has been set as base reference with the weight 1. The weighting method applied is Analytic Hierarchy Process (Saaty et al, 1979), i.e. another method than for emissions and waste.

3. Discussion

An environmental assessment of a building property or a building should be able to support discussions and prioritisations of environmental concern. In EcoEffect the decision basis is the potential number of affected people and how seriously they are hurt. With this approach a local problem affecting few people during a limited time period is not seen as important as a global problem affecting many people during a longer time period. We believe that this is fair and reasonable but the question is how this relates to how we understand the world, and our possibilities to take action. If local problems for a limited time period should be put more focus to, discounting has to be applied. A suggestion for how to discount environmental problem has been developed in the project, but due to limited space not presented here.

In the calculations of group damage values, all individuals are supposed to be evenly affected during the total duration time. It is fair to believe that people may get accustomed to some of the environmental problems and thus the experienced problem decreases. In other words, the reference state of the environmental impact (a state where there are no problems) may change over time. In this method the reference year is 2000, whereas the problems relate to the ones experienced in 2000, and also the ones foreseen for the future. The duration time for an environmental problem is accounted for until the conditions either have gone back to “normal” or until a new equilibrium is reached.

One of the strengths with the method is that the principles for the calculations are clear and legible to anyone that wants to use the method. Another is that the figures and data can be updated without affecting the method itself. The knowledge-based method of searching for damages and their reasons also adds gradual knowledge about the environmental problems and their relation to our own life style and consumption. It should also be noted that there is no need for high accuracy when calculating the group damage values as the magnitude varies a lot.

The method also suffers from some weaknesses. One is that the calculations of the group damage values are performed as if one person is suffering from only one type of problem at a time. In reality many people will be affected by several environmental problems simultaneously. This problem is not solved so far. Also, estimating the number of affected people from a certain type of environmental impact introduces uncertainity. Some expected damages of today are even hard to prove yet, as climate change, and to make predictions for the future increases the uncertainties even more. Different scenarios can be chosen but none of them is more certain than the other. Therefore the results have to be interpreted with caution – they do always represent estimations with a significant uncertainty.

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