Environmental Indicators & Engineering: an alternative for weighting factors

Marten E. Toxopeus, Eric Lutters, Fred J.A.M. van Houten
University Twente, Engineering Technology, the Netherlands

Abstract

Many impact assessment methods use weighing factors to agregate the different environmental effects into a single score value for the total impact caused by a product life cycle. The introduction of subjectivity in the decision process during product development, by using this kind of weighting factors, should be avoided. A more objective approach uses indicators based on laws of physics, for example the notion exergy. Construction and implementation in Simapro of an exergetic indicator is illustrated in this paper.

Keywords

Life cycle analysis, impact assessment methods, sustainability, exergy, thermodynamics

1 INTRODUCTION

Lifecycle assessments are in particular employed to analyse existing products. This implies that these assessments concern products for which everything (in the ideal situation) is known, i.e. the entire lifecycle, is established. In everyday practice however, the results of an LCA are evidently of more interest and value during the development phase of products; here adaptations are still possible to improve the product. In development, environmental impact is only one of the many criteria that play important roles. In fact, it is often not merely the (quantitative) impact that is important, but rather the relative differences between alternatives [1].

Over the years, many different solutions have been proposed to support designers with simple procedures for the estimation of the possible environmental impacts. One of these is the well-known Ecoscan program, which is a variant of Simapro [2]. Most of these types of programs apply impact assessment methods that use weighting factors to construct an environmental impact indicator. The inherent subjective character of these weighting factors drives a wedge between the practical and the more academic approaches in design. As an acceptable compromise, the use of indicators that are directly based on the laws of physics is proposed. One such possible indicator is elaborated and discussed in this paper.

2 BACKGROUND

From an historical viewpoint, it is easy to understand the introduction of weighting factors. As such, LCA's were developed to enable the analysis of products over their entire lifecycle. This implied that an environmental impact could be allocated to each different stage of a products' lifecycle. Or, as an illustrative example, the chemical and petrochemical industries could substantiate that the huge environmental pollutions of which they were accused was not necessarily the biggest contributor when compared to the contribution made by other stakeholders, such as component manufactures, users and waste handlers. Consequently, in calculating environmental impacts, it rapidly became obvious that the abstract concept of 'the environment' needed to be broken down into a number of more practical and workable effect descriptions.

The impact on each environmental effect could be determined based on relationships that were the results of scientific research [3][4]. When the different effects needed to be combined in order to calculate 'the total impact on the environment' the difficulties became apparent. Questions that had to be addressed encompassed problems on e.g. locality (e.g. global vs. regional or local impact), and ethics (e.g. impact on human health vs. change in flora and fauna). The difficulties with such issues are also illustrated by the different order levels of classification used in the different methods that have been developed over the years. A clear distinction is clearly visible in e.g. the first order level approach in the eco-indicator '95 [5] method versus the higher order level approaches of the CML '92 [6] and the eco-indicator '99 methods [7]. More information on the definition and use of weighting factors can be found in [1].

At different levels of aggregation, the influence of subjective weighting procedures on the total environmental impact becomes apparent. This can be explicated in e.g. one of the last stages where the different effects are compared to each other. Even in earlier stages this influence is visible, in determining the impact of interventions on the higher order levels of classification, for example in determining the characterisation factors for the emission of CFC-11 to the impact it has on human health. Toxicology is mainly a statistical science, especially when the interventions themselves do not seem to have a direct relationship to the final damage.

The involvement of too much domain specific knowledge during the development of the different impact assessment methods could be an explanation for the wide spread use of weighting factors. It could also explain the different approaches for handling the difficulties introduced by the order levels of classification.

3 DESIGNERS & INDICATORS

Ordinarily, the benefit of doing a full LCA [8] is to create an extensive environmental profile, analysing the lifecycle of (existing) products. An additional goal is to find possible improvements to the life cycle that will reduce the environmental impact of such products.

The importance of environmental impact as a design criterion is increasing. This stresses the need to integrate the corresponding analyses in the development life cycle. However, for several reasons, it is not practical, (and in most cases not even possible) to create a full environmental profile of a product under development. Since the environment is only one of the many criteria, designers are in most cases mainly interested in obtaining an indication of the expected environmental impact. Presumably their main concern is to construct an adequate basis for selecting one among different design alternatives.

At the same time, it might seem peculiar that well-known indicators, like the CML-92, eco-indicator '95 or the eco-indictor '99, are all based on weighting factors, thus implying the use of subjective elements. Designers seem to accept these subjective elements with the justification that only relative comparisons between different concepts are required. Consequently, the absolute value of the impact is no longer an issue. Since the choice of a certain impact assessment method or a specific set of weighting factors is usually not restricted by the design process, any given indicator of the expected environmental impact could be useful in many cases.

4 AN INDICATOR BASED ON THERMODYNAMICS

One way to deal with the subjectivity introduced by employing weighting factors is to use the results of multiple impact assessment methods to reduce the influence of a certain set of weighting factors on the design decisions [1]. A different approach finds its basis in identifying indicator values in the product development cycle that are not influenced by such subjective elements.

4.1 Rationale

A few simple observations have initiated the development of such an indicator. The first obvious observation is that all interventions relate to processes, being transformations from one state to another. Additionally, many transformations need some type of energy input; this is even true for transformations that, in themselves, will not cause any emissions, nor need raw materials. Simple examples include many production processes, like bending sheetmetal components. Consequently, the substantial linkage between the impact on the environment and the consumption of energy is obvious. Nevertheless, the factual impact on the different environmental effects can not be expressed merely in terms of energy. For example the damage caused by the emission of carcinogenic substances can not be related to the amount of energy involved in the processes that produced and emitted these dangerous substances.

Furthermore, many environmental impact assessment methods consider the depletion of fossil fuels, either by trying to determine the decrease of natural reserves or by calculating the amount of fossil fuel resources used by a product's life cycle to sustain a certain functional unit.

The first law of thermodynamics states that energy can neither be created nor destroyed. This would imply that the mentioned 'consumption of energy' doen not exist; indeed, in fact there are only transitions from one type of energy into another. This requires an approach that expresses the quality of energy. Aiming at such an approach, the combination of the first and second laws of thermodynamics results in the notion exergy.

Definition of exergy

Exergy is the maximum obtainable amount of work that can theoretically be extracted from a specific energy flow in an ideal situation, whilst re-establishing equilibrium with the surrounding environment.

The formula that is probably best known to mechanical engineers for calculating the exergy content of an energy flow, uses the differences in enthalpy and entropy between that flow and its surrounding (equation 1).

$$e_x = (h - h_o) - T_o * (s - s_o) \qquad (1)$$

Of course the enthalpy (h) and entropy (s) depend on the temperature, pressure, the state of occurrence and composition of the medium. The subscript o indicates the enthalpy and entropy at surrounding conditions. Within the field of thermodynamics the surrounding conditions are often defined as:

- P_o = Surrounding pressure = 101.3 kPa
- T_o = Surrounding temperature= 25^{o}C
- No movement
- The chemical composition of the earth (water / soil / atmosphere)

Of course, a lot of discussion is possible about how to exactly define the surrounding conditions. Additionally, in practical situations, many researchers define their own specific surrounding conditions appropriate for a specific exergetic analysis. In this paper, the discussion on those specific definitions is disregarded.

It should be noted that there seems to be an interesting analogy with the concept of system boundaries in an LCA. An impact assessment method is only applied to the interventions, being the 'substances' that cross the borders of a black-box representation of a product life cycle. It is the exchange of these substances between the surrounding and the product life cycle that causes the environmental impact. Evidently, the description of 'surrounding' in an LCA corresponds to the exergetic definition of the surrounding conditions.

4.2 Exergy and LCA

The notion exergy can accordingly be quite useful for determining several aspects related to product life cycles. For example, the efficiency of a system is ordinarily more important than the actual amount of energy needed for that system. In other words, the efficiency determines how much energy is needed to sustain the desired functional unit. In analysing product life cycles it is often easier to determine the waste of energy, rather than the actual efficiency. Since the quality of an energy flow determines how useful it is, the exergetic content of an energy flow determines if energy is wasted.

As an example, exhaust cooling water with the same temperature as the surrounding will still contain energy (just like the inlet flow of cooling water), but the exergetic value will be zero by definition. Meaning no 'energy' is wasted by the cooling water outlet.

Exergy is not only useful to describe efficiencies but also to determine other environmental issues. For example, the depletion of all resources (although often focused on fossil fuel) should be incorporated in impact assessment methods. Already the CML '92 impact assessment method addressed the depletion of biotic and abiotic resources. Since the actual resources are unknown, the amount of exergy needed to exploit these resources from the earth can be used as an indication of depletion.

As another example: many consider the availability of fresh water to be the next big issue for future conflicts; economic, social and even environmental. The exergetic requirements for production of drinking water could be a way to determine the availability of fresh water.

4.3 Exergetic Lifecycle Assessment

It is clear that the notion exergy can be a useful tool in the analysis of a product life cycle. A more far-reaching step is to consider the use of an exergetic LCA. Based on the observations in section 4.1, the results of exergetic lifecycle assessments may function as an indication of the foreseeable environmental impact.

An exergetic lifecycle assessment considers exergetic effects instead of environmental effects, whereas the principles of lifecycle analysis are still applicable. There seems to be no direct need to adjust or expand the goal definition and inventory as defined in the ISO14041 [9].

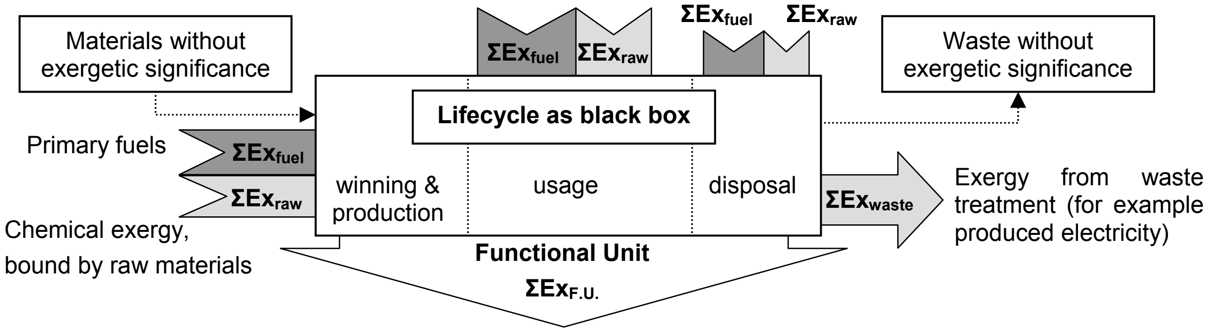

Figure 1: Basic principle of an exergetic lifecycle analysis.

Figure 1 shows the basic principle of an exergetic lifecycle analysis. The impact assessment method can be based on the eco-indicator ’95 method. Instead of characterising the different interventions to the environmental effects, the charactersiation step is used to determine the exergetic value of the interventions. For each substance (either raw material or emission) the chemical exergy can be determined [10]. In section 5 an example of the application of this method in Simapro is discussed.

Exergy indicator

From figure 1, an exergy indicator can straightforwardly be constructed. This indicator is simply the difference between the exergy going into the lifecycle process and the exergy remaining available after the lifecycle, eq. 2.

$$Ex_{ind.} = \overset{\swarrow}{\sum} Ex_{fuel} + \overset{\swarrow}{\sum} Ex_{raw} - \overset{\nearrow}{\sum} Ex_{waste} - \overset{\nearrow}{\sum} Ex_{f.u.} \tag{2}$$

The values of the variables depend on the characterised contribution made to the categories by the different exergy flows. However, it makes more sense to plainly relate the value of each exergy flow to an equal characterisation factor.

This indicator disregards the distinction between renewable and non-renewable sources. It only gives an indication of the total amount of exergy needed to sustain the functional unit by this particular product life cycle. This indicator in itself seems usable to support design decisions; the alternative with the lowest exergetic indicator value would be preferable from an energy point of view. Additionally, this alternative will very likely also cause the least environmental impact. In the next section the construction of an indicator is discussed that is based on exergy and expresses a level of sustainability.

Exergy & Sustainability

One of main goals in taking into account the environmental impact during product development is to reach a higher level of sustainability in products. Here, the definition of sustainability as given by Brundland is used; “To satisfy our current needs without limiting future generations in satisfying their needs” [11]. As a result of the intention to create more sustainable products, one of the first principles for developing product life cycles is to decrease waste of material and energy, to use resources as efficiently as possible in order to minimise resource depletion. Associated with this concept of sustainability is the distinction between renewable and non-renewable sources. A resource can be considered to be renewable, only if the resource can (and will) be reconverted to its original state; i.e. the state it was in before the start of the product life cycle in which it was involved. Consequently, the wood used for the production of a table can only be considered renewable as long as the same amount of wood is grown back during the lifecycle of that table. The same is valid for the use of renewable energy sources. By definition, there is no depletion of renewable sources, and therefore the use of renewable sources is considered to be sustainable.

From an exergetic life cycle viewpoint this implies that for renewable sources, the same amount of exergy, stored in the same energy carrier is available before and after the product lifecycle. From a thermodynamic viewpoint, a process without exergy loss, i.e. a reversible process, can be considered to be sustainable as well.

It is extremely important to note that the use of renewable energy sources does not automatically mean that a corresponding process is sustainable as well from an environmental position. For example, the use of a wood fired furnace still creates emissions of NOx since this is also a temperature dependent process using natural and harmless components from the atmosphere (the temperature initiated reaction between nitrogen and oxygen). Nevertheless, within product life cycle analysis, sometimes the assumption is used that closed loop processes (like the use of renewable sources) should be treated as sustainable. The impacts caused by the use of these resources are considered to be of a higher order and it depends on the level of detail whether or not those will be accounted for within the analysis. By applying these kinds of assumptions, information about the origin of the exergy source (renewable or non-renewable) could be translated into a classification of sustainable (closed loop) and non-sustainable environmental impacts.

4.4 Exergetic sustainability

An indicator to express the relative differences of environmental impacts caused by the design alternatives is of interest to product developers. By applying the notion exergy, such an indicator can be constructed without using weighting factors. It is important to determine a number of basic principles of such an indicator on beforehand.

Firstly, a higher value of the indicator should mean a more sustainable alternative. This implies that the distinction between non-sustainable and sustainable exergetic effects is clearly valued. The exergetic impact assessment method described earlier already makes this distinction. It can be initiated in the inventory phase and be expanded in the characterisation phase. For example the characterisation factor for biomass as a raw material can be expressed as an exergetic contribution to the sustainable or renewable exergy effect, while crude oil will only have a contribution factor to the non-sustainable exergy effect, even without the need to make such a (obvious) distinction in the inventory. Although crude oil originates from biomass through a natural process, the amount of crude oil to be ‘produced’ during any product lifecycle is negligible, as calculated by Cornelissen [12].

A second principle is that merely the (additional) use of a sustainable exergy source does not automatically increase the indicator value. Incinerating biomass within the system boundary of a coal fired power plant, without actually transforming the heat into electricity should not increase the level of sustainability of this hypothetical power plant. In fact it is at best a form of wasting renewable exergy without increasing the overall impact. This immediately implies that the efficiency in which the exergy is used should influence the indicator value.

Since this proposed indicator mainly addresses the relative differences between design alternatives, there is no need to express it in absolute units. On the contrary, the indicator value should be characterised by efficiencies. Thus a 100% score indicates absolute exergetic sustainability, while 0% expresses no exergetic sustainability at all. This also implies that the indicator value should preferably be dimensionless.

For a better understanding, the different life cycle phases of a product are ignored. A product life cycle is simply considered to be a black-box process, with input and output, as represented in figure 2.

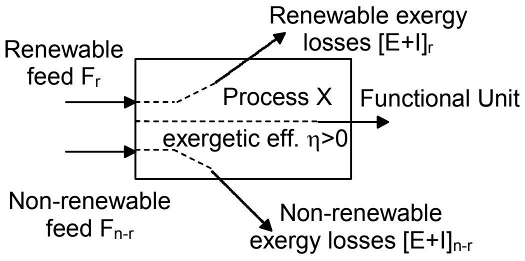

Figure 2: Product lifecycle represented as a process

The subscripts r and n-r indicate renewable and non-renewable exergy flows; exergetic emissions are depicted with a capital E, and the losses due to irreversibility are depicted with a capital I. Depending on the defined functional unit, the exergetic efficiency can be zero or higher. In most cases a product life cycle is not actually an energy process that will have an exergetic output. However, a power plant for example will have an exergetic output in the form of electricity during its lifecycle, consequently, its efficiency will be higher than zero; therefore, it can be represented as an energy process. Conversely, product life cycles without an exergetic output in the functional unit will be represented as service processes. The following sections will describe situations to express the importance of this distinction

Product lifecycles as energy processes

First of all, consider the energy process. Based on the previously described assumptions, the proposition is made that the impacts caused by renewable sources are negligible compared to the impacts caused by non-renewable sources. Also, the overall process efficiency will be higher than zero. Figure 3 illustrates the consequences of these assumptions.

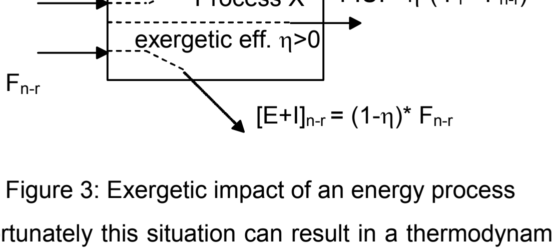

Figure 3: Exergetic impact of an energy process

Unfortunately this situation can result in a thermodynamic impossibility. It is therefore necessary to include the amount of the renewable exergy flow that contributes directly to the functional unit. In order to solve this problem an additional category has to be introduced, called apparent exergy feed (F_{app}). This apparent exergy can be calculated by equation 3.

$$F_{app} = [E+I]_{n-r} + F.U. = F_{n-r} + \eta \cdot F_r \qquad (3)$$

The energy process can now be schematically represented as given in figure 4. The efficiency will differ from the original representation, due to the rebalancing of the process to avoid thermodynamic inconsistencies. To avoid miscommunication about efficiencies the term exergetic eco-efficiency (η_{eco}) is proposed.

$$\eta_{eco} = \frac{F.U.}{F_{app}} = \frac{\eta \cdot (F_{n-r} + F_r)}{F_{n-r} + \eta \cdot F_r} \qquad (4)$$

From equation 4, it is clear that a 100% score will represent sustainability. Additionally, the indicator values the efficiency with which both non-renewable but also renewable sources are used. In other words, wasting renewable sources is still a waste. Futhermore, since both the functional unit as well as the apparent feed exergy will be expressed in the same units, this exergetic eco-efficiency is dimensionless.

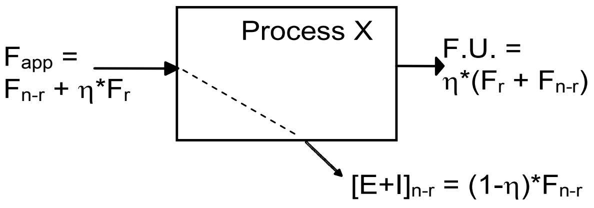

Figure 4: Rebalanced energy process

Product Lifecycles as a service process

In contrast to the energy process representation of a product lifecycle as discussed above, the so-called service process will not contain an exergy producing functional unit. Most products can be classified as service process variants. A general service process can be presented as shown in figure 5.

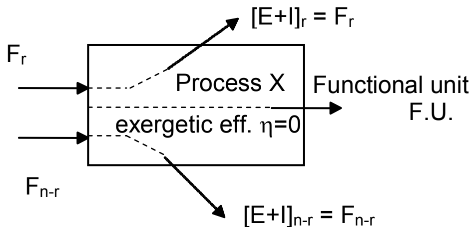

Figure 5: Representation of a general service process

The concept of the new indicator can also be applied to service processes and is basically consistent with the calculations in the former section. However, according to the definition of a service process the new indicator can not be interpreted as an efficiency since it will not be a dimensionless value. It rather expresses the non-renewable exergetic unit consumption (κ_{n-r}) required to sustain the functional unit by that particular product.

By definition the exergy of the fulfilled functional unit of a service process is negligible. However, the product (or the desired output) of a service process is defined in a functional unit (f.u.). The exergy entering the product life cycle is therefore completely transformed into exergetic emissions and losses due to irreversible processes. If the same propositions are applied, and the calculations in the former section are taken into account, then the results of κ_{n-r} can be presented as:

$$\kappa_{n-r} = \frac{F_{n-r}}{F.U.} \tag{5}$$

Although the non-renewable exergetic unit consumption is not dimensionless, this value can still serve as a basis for comparison, given that the different alternatives should be compared on the same f.u.

In order to create an exergetic impact assessment method in Simapro, it is essential to adopt the assumption that exergy emissions and exergy losses originating from renewable sources are assumed to be negligible compared to the effects caused by exergy from non-renewable sources.

5 EXERGETIC LCA WITH SIMAPRO

To be able to test whether the proposed concepts regarding exergetic life cycle assessment are useful within actual design cases, a new impact assessment method has been implemented using Simapro. While developing a new impact assessment method it is important to understand and incorporate the interactions between the users, the database and the impact assessment method, as represented in figure 6.

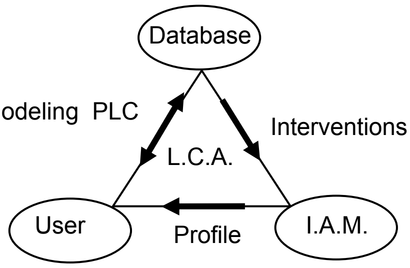

Figure 6: Interactions between users-database-I.A.M.

5.1 Reference

In addition to the assumptions already discussed, it is important to use existing data as much as possible. Another important ‘constraint’ is the possibility to analyse (computer) models of a product life cycle against their environmental impact as well as on their exergetic impact, without the need for adjusting the models themselves. These two issues imply that the product lifecycles are modelled using the existing datasheets available in the Simapro libraries. As a result of this, the table of interventions will contain the traditional substances used in the characterisation phase of environmental impact assessment methods.

5.2 Exergetic impact assessment method

The eco-indicator ’95 constitutes the basis for this new impact assessment method. The familiar environmental effects are replaced by three exergetic effects.

Renewable exergy

The renewable exergy effect describes all substances containing exergy from known renewable sources. For some substances it is easy to determine the renewable origin based on their names. The general assumption is used that all substances with a biotic origin, like wood or biomass as well as energy sources with a sustainable background like hydropower and solar energy, should be considered to stem from a renewable source. Some substances even contain additional information expressing a sustainable or renewable source. The list of interventions contains for example several CO_2-substances, including ‘CO_2 biogenic’. Due to the nature of the classification method within the datasheets this is only applicable to the raw material category.

Non-renewable exergy

All other substances in the raw materials category are allocated to the non-renewable exergy effect. This implies that the specific chemical exergy value is determined for all raw materials of interest. Depending on their origin the characterisation factors determine how much exergy value per unit of mass is allocated to the two exergy effects. The assumption that the raw materials do not contain any physical exergy (due to temperature or pressure differences) is justified by the proposition, inherent to the theory of life cycle assessment, that raw material substances are considered to be imported into the product life cycle directly from nature. Obviously all other substances from the raw material category that do not contain any chemical exergy receive a characterisation factor of zero for both effects.

Exergetic emissions

Since the origin of many substances within the other classification categories - emissions to air, water and soil - can not be determined, a third exergetic effect is created. This effect consists of the exergy content of emitted substances. This can be either of a physical nature, like the emission of heat by cooling water, or chemical exergy bound to emitted substances such as methane or hydrogen. The actual characterisation values are again based on the exergetic content of these interventions. The exergetic emission effect describes the waste of exergy due to dissipation. This effect does not account for exergy losses due to irreversible energy transformations within the black box of the product lifecycle model.

Exergetic normalisation

The exergetic effects can very well be normalised in a similar manner to norms currently used in impact assessment methods. Unfortunately, data is not available for the average impacts on these three effects caused yearly by the average European citizen. Since the units for the three described effects are already identical, there is no necessity to translate the specific units for each effect into a common unit in the normalisation step. Untill there is more specific data available to determine normalisation factors for the different effects, the current method ignores this step by using a factor one for all effects.

Exergetic evaluation

The underlying goal for developing and implementing this exergetic life cycle assessment method, is to avoid the need for subjective weighting factors. Also ISO 14042 [13] dissuades the use of weighting factors.

On the other hand, to support the decision process in product development cycles, an indication of the expected impact of different alternatives is probably welcomed by designers. Assuming that renewable exergy sources are preferred over non-renewable sources, the renewable sources are disregarded. This is supported by the common assumption of negligible impacts caused by closed loop processes. Since exergetic emissions already imply the input of (non-)renewable exergy, it is acceptable to use only this effect as an indication of the different performances of the design alternatives.

In order to implement this approach in Simapro, a conjuring trick is required: the three effects are expressing in terms of extreme weighting values: renewable exergy:

0, non-renewable exergy: 0, exergetic emissions: 1. By switching the weighting factors between non-renewable exergy and the exergetic emissions the indicator will actually be able to express the non-renewable exergetic unit consumption ($\kappa_{n\text{-}r}$) of paragraph 4.4.

5.3 Applying the new method to design cases

The exergetic impact assessment method implemented in Simapro, has been tested to see if the results are acceptable in product development. Over several years, teams of students were asked to compare the results of this new method to their results obtained from traditional environmental impact assessment methods. The teams tackled very diverse design problems, ranging from business products to consumer product with specific demands. They were also encouraged to construct their own personal set of weighting factors to be used instead of the default factors in the eco-indicator ’95 method.

Although the design cases were imaginary and the level of detail often was restricted by a limited amount of time, the results were promising. As expected, there was no clear numerical relation between the eco-indicator ’95 single score values and the values for the exergetic emissions. But in most cases similar design decisions would have been made by the teams whether they used the eco-indicator 95 method or the new exergy impact method. During the interviews to evaluate their design projects, the students confirmed the hypothesis that they would rather use the exergy method to support their design decisions than the eco-indicator ’95 method. They even admitted to have adjusted their personal weighting factors in favour of their preferred alternatives. However, the results of the exergy method could hardly be manipulated. In general, it appeared that the aspect of introducing subjective elements such as weighting factors did not appeal to the students. The prospect that weighting factors constructed by others (perhaps even at a different point in time) might influence their decisions, almost made them reconsider the idea of taking into account environmental impact as a design criterion.

6 CONCLUDING REMARKS AND OUTLOOK

It is important to emphasise that the presented thermodynamics based indicators can not be considered as replacements for the traditional eco-indicators. This is caused by absence of a clear numerical relationship between the exergy requirements and the actual environmental damage caused by the interventions. When performing a quantifiable environmental LCA of a product or products, an impact assessment method tuned to the environmental impact should be used. If environmental indicators based on weighting factors are used to compare the performance of different design alternatives, the use of the exergetic indicators, like the exergetic eco-efficiency (η_{eco}) or the non-renewable exergetic unit consumption ($\kappa_{n\text{-}r}$), might be preferred.

As illustrated in section 5, it is possible to use existing LCA software tools and databases to apply the proposed exergetic life cycle assessment method. Although the calculation structure in Simapro does not allow the more complex calculations for the exergetic eco-efficiency, the ‘abuse’ of weighting factors as described in section 5.2 is useful, since the energy process representation is simply a special variant of the general service process representation, which is valid for all product lifecycles.

The presented method implemented in Simapro can be elaborated by a more specific allocation of the raw material exergy over the renewable and non-renewable sources. A first step could be to determine the actual ‘sustainability’ percentages of the different raw materials. For example, the use of hydropower is currently considered to be 100% sustainable and thus is fully allocated to the renewable exergy effect. However, the lifecycle of the hydro power plant itself will not be fully sustainable. Therefore the characterisation factors can specify that a certain percentage of this raw material is to be allocated to the renewable sources while the remaining exergetic intervention is allocated to the non-renewable sources. An even better improvement for the exergetic impact assessment method is to adjust and extend the databases themselves, by including more additional information about the origin of certain interventions.

Although the product lifecycle is treated as a simplified process, the presented indicators can even be applied to far more complex systems. It is quite possible to extend the exergetic cost calculation method by Valero [14] to include these concepts and the distinction between renewable and non-renewable exergy sources in the exergetic cost allocation, as illustrated by Sewalt [15].

REFERENCES

[1] Lutters, D., Toxopeus, M.E., Houten, F.J.A.M. van; Combined assessment methods for decision support in product development, Proceedings of LCE2006, Leuven; 2006

[2] Simapro 6.0.4 LCA software; PRé Consultants b.v., Amersfoort, The Netherlands; 2004

[3] Air Quality Guidelines for Europe; WHO Regional Office for Europe, Copenhagen; 1987

[4] GLOBE, The Environment in Europe: a Global persective; report no. 481505001; GLOBE, RIVM, ISRIC, RIZA, DWG, WHO, Sept. 1992

[5] Goedkoop M.J.; De Eco-indicator 95, Final report; NOH report 9523; PRé Consultants b.v.; Amersfoort (NL); July; 1995; ISBN 90-72130-77-4

[6] Heijungs, R, et al; Environmental Life Cycle Assessment of products (Guide & Backgrounds). 1992; Leiden, Centre of Environmental Science; 1992

[7] Goedkoop M.J., Spriensma, R.; The Eco-indicator 99, A damage oriented method for Life Cycle Impact Assessment. Methodology report; Amersfoort; 1999

[8] ISO14040; Environmental management -life cycle assessment- principles and framework; 1997.

[9] ISO14041; Environmental management -life cycle assessment- goal and scope definition and inventory analysis; 1998.

[10] Szargut J., Morris R.D., Steward F.R.; Exergy analysis of thermal, chemical, and metallurgical processes; Springer-Verlag; 1988.

[11] Brundland ea; World Commission on Environment and Development, Our Common Future; Oxford University Press, Oxford, England; 1987.

[12] Cornelissen R.L.; Exergie, De Maatstaf voor de vernieuwbaarheid en duurzaamheid van het gebruik van brand- en grondstoffen; Enschede; 2000.

[13] ISO14042; Environmental management -life cycle assessment- life cycle impact assessment; 2000.

[14] Valero A., Lozano M.A., Munoz M.; A general theory of exergy saving I. on the exergetic cost, AES-Vol. 2-3, New York; 1986.

[15] Sewalt, M.P.G., Toxopeus, M.E., Hirs, G.G.; Thermodynamics Based Sustainability Concept; Int.Journal Applied Thermodynamics, Vol.4 (No.1), pp 35-41; March 2001