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What Ecological Indicators Really Measure – the Normative Background of Environmental Evaluation

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Ecological evaluation becomes a valuable tool for process engineering as environmental concerns must more and more be seen as defining boundary conditions for process design. Currently we see a wide portfolio of different measures that may be used to support process engineers in their design decisions. They offer however conflicting advice in many practical applications.

The primary reason for the spread in results for the same process when evaluated by different measures lays in their normative assumption. They influence what is measured and how different impacts are weighed.

The paper dissects the normative assumptions of single issue measures (e.g. Carbon Footprint and Global Warming Potential), efficiency measures (e.g. Material Input per Service Unit), thermodynamic measures (e.g. Emergy) and complex, highly aggregated measures like Ecological Footprint and the Sustainable Process Index. It can be shown that they differ widely in their normative base and consequently lead to quite different evaluation results. The paper will provide guidelines for the choice of environmental measures as well as for interpretation of the often divergent results.

1. Introduction

In the last three decades environmental concerns have begun to influence public discourse about the development pathway of global human society. On the global political level landmark accords like the Montreal Protocol limiting ozone depleting substances in 1986, the Rio Accords in 1992 framing the development Agenda for the 21st century or the Kyoto Protocol limiting Greenhouse Gas emissions in 1997 set the stage for a broad political process to reduce human impact on the environment. As industry is a major interface between human society and environment, the last decade in particular has seen a dramatic increase in publications addressing the relationship between engineering and sustainability in general (e.g. Jawahir et al. 2013) and providing guidelines for process industry in particular (e.g. Klemeš et al., 2011).

A common argument in these publications is the importance of measuring the environmental impact of industrial processes along the whole life cycle of products (De Benedetto and Klemeš, 2009). Engineering has its largest impact on the environmental performance of industry in the design phase of processes. Taking environmental concerns into consideration therefore means to integrate measures to reduce the ecological impact in processes design. This in turn requires support for engineering decisions by appropriate methods. Engineers can however only consider ecological aspects of their design if they are informed about the consequences of their design decisions and hence there must be measures of environmental impacts of industrial processes that guide engineers in their design. Consequently the number of publications presenting environmental impact measures to be applied in the process industry is rising quickly (e.g. Klemeš, 2015) as well as the provision of tools and methods to help engineers estimating the impact of their design (Bare, 2014). This growing body of literature and methods forms the basis for integrating environmental aspects into process design practice. At this point it is therefore appropriate to discuss the character and basis of these methods that will without doubt shape industrial process design in future.

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2. What environmental assessment methods used in process industry measure

The impact of human activities on the environment as well as on the well-being of creatures, including in a recursive loop human beings too, are manifold and the following list is exemplary but not comprehensive. As a global society we extract resources and change the distribution of materials in spatial and temporal terms by emitting substances at other places than where the originate and linking long-term global material storages to short term material cycles. We change the chemical composition of materials and introduce substances into ecosystems for which these substances are alien. We change the structure of landscapes and habitats, infringing on the chances of species to survive in their home habitat. We change the structure of earth's surface with consequences for natural material and energy flows. Finally we put creatures (including us) in contact with substances and energy forms (e.g. nuclear radiation) that may harm their health and reproductive capacity. It is without doubt that industrial activity contributes to all these listed environmental impacts.

In contrast, to the wide range of impacts, the measures most commonly used to evaluate environmental consequences of industrial activities concentrate on the exchange of material and energy between technosphere and the environment. The reasons for focussing on the metabolic are both fundamental and pragmatic: resource utilisation and emissions arguably lay at the basis of many other impacts caused by industrial operation; pollution degrades ecosystems, causing a loss in bio-diversity as well as direct impacts on health of humans, animals and plants while the change in global dynamic natural systems like the atmosphere or water bodies can also be linked to accumulation of substances (e.g. Greenhouse Gases). This means that by measuring the metabolic exchange between industrial processes and the environment a good part of the impact of human activity can be captured.

From the pragmatic point of view energy and material flows may be measured easily and influenced considerably by engineering decisions. This makes them prime targets for design approaches to reduce the ecological impact of industry. Besides that the direct impact of industrial design on structural impacts on the environment as well as on the actual health of living beings cannot be evaluated with the same level of clarity as its metabolic impact. Impacts like habitat loss and changes in the natural functions on a landscape scale as well as many health issues are systemic and may not easily be traced to a single industrial source or technical design feature. This means that the clear cause-effect relationship that can be seen in between process design and material and energy flows exchanged with the environment is much more blurred for these structural impacts. As these impacts are much harder to evaluate and may not be linked to individual design decisions they are usually less present in the discourse about environmental impact of process industry.

In terms of the system boundaries the emerging consensus is that environmental impacts shall be measured along the whole life cycle of a product. This vertical integration of all processes leading up to a certain product, even including the use and end-of-life phase is necessary to avoid shifting the responsibility for impacts along the value chain. By evaluating always the whole life cycle design decisions have to be taken in a systemic way, reducing the impact of the whole value chain. This avoids that a seemingly positive decision at a certain process step may cause increased ecological impacts somewhere else in the life cycle and hence increase the ecological burden caused by providing the product or service.

3. Normative aspects of measuring ecological impacts

At first glance the problem of measuring and evaluating the impacts of industrial processes on the environment seems to be a straight forward natural science problem: here are natural systems which are the object of all natural science research and there are human induced perturbations to these systems. All waht is needed is to measure the consequences of these perturbations and see to it that they do not cause natural systems to reach an undesirable state. There are however two fundamental problems that do not allow a purely natural science solution to this task:

- The definition what exactly is the "undesirable" state of natural systems that has to be avoided is normative: nature answers to man's perturbations according to the laws of nature, which might put an evolutionary end to ecosystems and species, the human race included. There is no "natural" limit to what consequence evolution might come in answer to human impacts, but there are certainly resulting states of the environment that we do not want. The decision however what are desirable and less desirable states of the environment are therefore normative decisions taken by humans, guiding decisions by humans.
- There is no "absolute" knowledge in science about the functions of natural systems. Natural science is a process of intersubjective discourse about our reality and knowledge therefore progresses. This means that we have to take normative decisions on what to focus on and what limitations on the

> assumed changes in the disturbances of natural systems we allow. Even if we assume to have solid estimates of “planetary boundaries” that we must not transgress in order to avoid uncontrollable disturbances in natural systems (Steffen et al. 2015), there is still no scientific solid “proof” of those limits as there is no experiment conceivable to reach these limits. This would violate our first normative assumption that we avoid natural states that are “undesirable”. We therefore have to obey a “safety distance” from these limits, the way how we define this limitation is again normative.

This means that whenever we measure and evaluate ecological impacts, we have to put up with the fact that we do so on the basis of normative concepts. These concepts define the focus of our measures as well as the way we use these measures to evaluate environmental impacts as the basis of our decisions.

4. Normative basis of environmental evaluation methods

The following paragraphs will briefly discuss normative concepts that lay at the base of some frequently used environmental evaluation methods. This analysis is exemplary and has the objective to raise the attention of users of such measures and environmental indicators to the implications of the normative concepts on which they are built on. From the view point of the authors there is no ”right” or “wrong” normative concept. We are however of the opinion that knowledge of the normative basis of environmental measures and indicators is a necessity for any engineer using them to support his or her decision.

There are two particular aspects that require normative assumptions in such measures: On the one hand the focus of the measure as this explains what particular aspect of the interaction between human society and the environment is covered by the measure. On the other hand the way a measure or index aggregates different impacts in its evaluation, as this defines the evaluation function of such measures and indicators. Aggregation to a single indicator/measure in particular increases the decision support capacity as it provides clear ranking of alternatives. It is however always based on a normative concept that “weighs” different impacts against each other. It goes without saying that even not distinguishing between different aspects (e.g. by assigning them the same weight) is a normative concept!

4.1 Efficiency oriented measures

A large group of measures used to identify environmental performance of human activities are based on the concept of efficiency. This concept is based on the normative assumption that using less input of resources (or energy) to obtain the same output also uses less environmental services and has therefore automatically a lower environmental impact. Whereas first law efficiency measures (rating the energy efficiency) are a longstanding tool to evaluate engineering design and also double as a rough estimate for environmental performance, other efficiency measures have gained interest as explicit environmental measures. This is particularly true for material intensity (Lettenmeier et al., 2009). The normative assumption in applying material efficiency is that every human action has an environmental impact and that knowledge about cause-effect of the particular influence of individual substances is not known apriori. The more mass is however moved to generate a certain product or service, the deeper is the human intervention in the ecosphere. This is seen as a measure for the ecological impact. This measure is particularly used in many eco-design applications.

A characteristic of material intensity is its close relationship with technological progress: the more technologically advanced a certain product is, the less is usually its material intensity. The reason for this technology affinity of material intensity measures is the fact that reducing mass to produce a certain product or provide a certain service is an intrinsic engineering design principle.

Besides linear efficiency measures that relate the output of a technological system to its energy or material input, second law efficiency measures evaluate the efficiency of utilising the quality of an energy or material input. The most advanced measure of this type is Emergy (Odum, 1996). The general normative assumption of these measures that are based on the thermodynamic concept of exergy is that reducing quality loss of the flow of energy and substance through human society is a basis for reducing man’s impact on the environment. This kind of efficiency evaluation leads intrinsically to utilising resources and energy in interlinked cascades, reaping as much societal benefit from high quality resources as possible before they are degraded to a form no longer utilisable. This concept of evaluating the quality loss of flows through technological and societal systems can easily be linked to the concept of natural income by using solar irradiation as the reference for all processes (Ulgiaty and Brown, 1998).

4.2 Problem oriented measures

Problem oriented environmental measures are currently the most utilised evaluation approaches. Examples for this group are the Carbon Footprint/Global Warming Potential (ISO, 2013) and various other measures like the Water Footprint (Hoekstra and Chapagain, 2008) to name just two of the more well known measures. There is an already large and growing body of literature that reports of applying such measures, especially the Carbon Footprint, to process engineering. This ranges from evaluating renewable energy systems (Perry et al., 2008) to the management of energy systems (Klemeš and Pierucci, 2008) to the evaluation of complete regional biomass supply chains (Lam et al., 2010). A good overview of various measures in this group is provided by (Čuček et al., 2012).

The basic normative concept of this group of measures is that there are different, incommensurable ecological problems where human impact risks to disturb nature in a way that leads to undesirable consequences. For every of these problems a predominant, mostly metabolic cause-effect chain is identified and the measures are constructed in a way that allows the user to evaluate the cumulative impact of the exchange of material and/or energy between technosphere and ecosphere triggered by the activity in question. The user of these measures can then evaluate different alternatives according to their contribution to this particular environmental problem and can minimise the impact by reducing the exchange flows that are identified as causes for it.

As an example, the Carbon Footprint focuses on the effect of the accumulation of trace gases in the atmosphere on global warming by changing the irradiation balance of our planet. The Carbon Footprint aggregates all emissions of gases that have the potential to change this balance from the production system in question and expresses this cumulative impact in kilograms of carbon dioxide that would cause the same change.

Like all problem oriented measures, the Carbon Footprint pursues a reductionist approach to environmental evaluation. It focuses on a particular problem (global warming) from the point of view of a particular cause-effect argument (changes in the irradiation balance). Other factors that might contribute to the same problem are not considered in the evaluation. In the case of global warming for example, there is considerable scientific evidence that the change in land cover by reducing wetlands and forest areas and increasing sealed areas in settlements and agricultural fields contributes significantly to climate change (Ripl, 1995). Although this cause would contribute to the same environmental problem it is left out of consideration in the Carbon Footprint.

The focus on a particular environmental problem if not balanced by other considerations can lead to controversial results: From the view point of Carbon Footprint, increasing the share of nuclear energy will reduce the impact of energy provision. This may however increase other environmental and health risks. This requires the inclusion of more than one problem oriented measures into the evaluation of the ecological performance of a certain human activity. Here we face two more normative decisions in environmental evaluation with this type of measures:

a) The choice of the environmental problems to be involved in the evaluation and
b) The way these measures are weighed if an aggregation is necessary.

Both decisions clearly depend on the intentions of the evaluator. Whereas normative decision a) depends on the environmental focus of the evaluator, decision b) ranks the importance of the environmental issues the evaluator places on individual problems. This may either be done by valuating the distance to defined goals (Sikdar et al., 2012), where the choice of goals again is subject to normative considerations, or by directly weighing the individual measures. It is clear that multivariant objectives (e.g. Čuček et al., 2011) in all cases reflect a normative decision, even if the measures included are weighed equally.

4.3 Sustainability based measures

Besides measures that refer to particular environmental problems the group of ecological footprints are explicitly based on the normative concept of strong sustainability (Ekins et al., 2003). This concept requires that human activity must be based on natural income of solar radiation and does not allow for substitution between different kinds of capital, in particular substitution between natural and economic capital. As natural income of solar radiation is inherently linked to the surface area of our planet as the basic resource to convert this income into useful services for society, ecological footprints measure human impact in the area required to provide a certain service or product. The normative assumption of these measures is therefore that all production systems compete for area as the resource to sustain human society based on natural income. The ultimate goal for a sustainable society is therefore to live within its natural budget, i.e. to use not more area as is available on our planet.

Within the group of ecological footprints there are still differences in how this normative assumption is operationalised. The Ecological Footprint according to (Rees, 1992) evaluates human activities under the condition that sustainability is already achieved. It therefore assumes that energy is already provided in a sustainable way, using biomass derived energy as a substitute for all energy forms that are not explicitly provided from renewables. This Ecological Footprint evaluates the area of productive land that is necessary to support the resources consumed by society. This operational assumption has the consequence that the measure does not take emissions into account and cannot effectively distinguish between different energy provisions systems as sustainable energy provision is already assumed to be sustainable.

The Sustainable Process Index SPI (Narodoslawsky and Krotscheck, 1995) in contrast builds on two principles to evaluate the area necessary to embed all flows generated by a production system sustainably into the ecosphere: Flows induced by the production system in question

- Must not change global natural material cycles (e.g. the global carbon cycle) and
- Must not change the natural quality of local soil, water and air compartments.

Using these operational principles, the SPI strongly discerns between renewable and fossil resource use (applying principle 1) and evaluates the impact of emissions (by applying principle 2). As a consequence of the different operational assumptions the Ecological Footprint according to Rees generally evaluates the impact of human activities more lenient than the SPI, with the latter rating production systems based on fossil resources and the use of nuclear power as particularly unsustainable.

5. Guidelines for using environmental measures taking their normative basis into account

The previous section made it clear that there is no way to avoid normative assumptions when evaluating human activities and in particular production systems ecologically. This is a general statement and applies to all evaluation methods as the very act of evaluating implies the employment of normative principles.

At this point it is essential to note that applying normative principles does not render the outcome of evaluation any less useful: we need to evaluate to decide and in engineering we need measures to guide our design decisions. What is however necessary is that whenever we use ecological evaluation methods in our decision processes, we must be aware of their normative character and follow some rules in their application as well as in relating our judgement to other stakeholders. These guidelines are:

- Define the normative framework to which decisions are oriented; this requires the establishment of an explicit, clearly stated and well-argued goal for the activities that are subjected to any evaluation, including what is within and outside the responsibility of the actors.
- Deduce from this normative framework the evaluation method whose normative basis conforms best to the defined normative framework.
- Explain the normative framework and the reasoning why the evaluation method was chosen whenever relaying evaluation results to third parties.
- When comparing different evaluation results on the same subject, make sure that the normative framework of the evaluations are commensurable. If this is not granted, comparisons make no sense!

6. Conclusions

Ecological evaluations are intrinsically built on normative assumptions. This fact does neither infringe on their usefulness for supporting decisions nor on the necessity to use environmental measures in engineering practice in order to guide technological development towards less environmental impact. It does also not diminish their scientific credentials as only good scientific operationalization of normative principles leads to useful ecological measures.

The normative basis of environmental measures adds to the responsibility of those using these decision support instruments. It requires from them awareness of the fact that they build their judgements and decisions on normative principles. From this awareness follows that anyone using environmental measures has the obligation to define the normative framework to which he orients his activities. It remains in the responsibility of the evaluator to choose an environmental measure that reflects this framework and make this decision and the arguments leading to it explicit.

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