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# Deconstructing and Reconstructing the Theoretical Basis of the Ecological Scarcity Method

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**Abstract:** The ecological scarcity method (ESM) is a widely used system for assessing the environmental impact of pollutant emissions and resource extractions in the context of life cycle assessment (LCA). Its mathematical principles have been described in various reports, but not in scientific journals, which typically only quote the ESM or challenge the numerical values of the targets. It is, therefore, appropriate to carefully dissect the method and critically reassemble the resulting fragments. Our analysis introduces a substantial number of modifications, in terms of overall formulation, detail and interpretation, while it respects most of the existing numbers and is still applicable to the full range of pollutants and resources. It also yields the conclusion that, although the developers of ESM have tried to align the approach with the ISO 14040/14044 standards for LCA, this attempt has been less successful than foreseen. We finally conclude that the reference to ESM as a "distance-to-target" method further obscures the interpretation of the method.

**Keywords:** ecological scarcity method (ESM); life cycle assessment (LCA); life cycle impact assessment (LCIA); distance-to-target; weighting

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## 1. Introduction

The ecological scarcity method (ESM) is a system for assessing the combined effects of different environmental stressors in a one-number indicator. The basic idea of the ESM is that emissions of different pollutants and extractions of different natural resources use up a part of the environmental utilization space (hence the term "ecological scarcity"), as defined through established target values. The target values are mostly based on national (e.g., Swiss) laws and international agreements (e.g., via the United Nations). The ESM, then, offers a list of such target values (split by stressors, such as $CO_2$, $NO_x$, PM10, energy carriers and water) and a mathematical formula to translate these numerical values into "eco-factors", which describe the scarcity of a unit amount of a stressor. It has been developed especially for the purpose of life cycle impact assessment (LCIA), but it can also be used for other types of assessment, e.g., for measuring a region's or country's production-based environmental footprint. Within the main application domain of products, different regionalized versions are possible.

Its origins go back to a couple of Swiss projects and publications in the 1980s and 1990s [1–3]. The method has been redesigned later [4], among others in order to align it with the ISO 14040/14044 structure [5,6], distinguishing consecutive characterization, normalization and weighting steps. We refer to [7,8] for the most recent accessible description, including a more extensive historical sketch.

The method has been used extensively, especially in life cycle assessment. Google Scholar mentions (in August 2023) more than 30,000 results with the keywords "ecological scarcity method LCA", and it lists almost 200 references to [7]. We also mention various enhancements, for instance, for application to other regions than Switzerland, such as Thailand [9] and the EU [10].

Despite this apparent success, we also observe a confused understanding in the literature, including a lack of clear reporting. For instance, if the ESM is supposed to allow for an aggregation of different stressors, we would expect to see a formula of the form

$$I = \sum_{s} (w_s \cdot m_s) \tag{1}$$

where $I$ is the aggregated impact indicator, $m_s$ is the amount of stressor $s$ (measured in, for instance, kg or kg/year) and $w_s$ is the importance weight (perhaps the "eco-factor") for stressor $s$. If we further add the characterization-normalization-weighting scheme of ISO 14040/14044 [5,6], we would expect

$$I = \sum_{c} \left( W_c \cdot \frac{1}{N_c} \cdot \sum_{s} (C_{c,s} \cdot m_s) \right) \tag{2}$$

where $C_{c,s}$ is the characterization factor that measures the contribution of stressor $s$ to impact category $c$, $N_c$ is the normalization reference for impact category $c$ and $W_c$ is the weighting factor of impact category $c$.

However, if we study [7,8], no such formulas are found. By contrast, we find the formula

$$Eco - factor = \underbrace{K}_{\substack{\text{Characterization} \\ \text{(optional)}}} \cdot \underbrace{\frac{1 \cdot \text{UBP}}{F_n}}_{\text{Normalization}} \cdot \underbrace{\left(\frac{F}{F_k}\right)^2}_{\text{Weighting}} \cdot \underbrace{c}_{\text{constant}} \tag{3}$$

where $K$ is a "Characterization factor of a pollutant or a resource", $F_n$ is a "Normalization flow", for which the "Current annual flow with Switzerland as the system boundary" is taken, $F$ is the "Current annual flow in the reference area", $F_k$ is the "Critical annual flow in the reference area", $c$ is a constant with the value $10^{12}$/a ("/a" is per annum; see Section 4.2), and UBP is an "Eco-point" [7] (p. 50). The formulation and wording in [8] (p. 56) is very similar, with only minor variations in spelling and typography.

A comparison of Equations (1) and (2) versus Equation (3) now raises several questions:

- What is the role of the eco-factor in comparison to the usual characterization factors, normalization references and/or weighting factors?
- Are there anyhow impact categories in the ESM?
- Is there a summation (as in Equation (1)) or perhaps a double summation (as in Equation (2)) involved in the ESM?
- What is the role of the terms $c$ and UBP in Equation (3)?
- What happens when the "optional" term $K$ is skipped?

These questions are important because the ESM is on the one hand widely used and on the other hand claims to be "in accordance with ISO Standard 14044" ([7] (p. 49), [8] (p. 56)). Moreover, many authors cite an equation of the form of Equation (3), although often with small changes (e.g., [4] use for $F_n$ the same symbol $F$ that occurs in the weighting term, [10] changes "UBP" into "EU-EP", and [11] writes "EP" for this "UBP"). But all defining documents starting with [1] and ending with [8] are reports, not scientific journal articles. As such, they lack the status of scholarly work. Yet, [7] (p. 35) and [8] (p. 36) claim that it is a scientific method. They conclude this on the basis of two arguments:

- It is based on "scientific data";
- The characterization part is based on scientific methods, "for example, the climate impact of gases is assessed on the basis of the Intergovernmental Panel on Climate Change (IPCC)".

We agree with these two points, but we have another thing in mind, namely the way in which the above information is combined into an eco-factor. Equation (3) contains symbols that represent data but the formula itself must also satisfy the criteria of science. So, the discussion, if the ESM is "arbitrary or scientific" ([8], (p. 36)), is too restricted and should be broadened to a critical analysis of the scientific validity of Equation (3). After all, there are many other life cycle impact assessment (LCIA) methods that rely on scientific sources, such as IPCC. ESM distinguishes itself from other LCIA methods, such as ReCiPe [12] or IMPACT World+ [13], not by its use of scientific sources, but by its use of the eco-factor formula, given in Equation (3). The scientific status of this extra element is the main topic of the present article. An extra motivation for this focus is that several articles (such as [9,10]) summarize the ESM by giving Equation (3) a central position, suggesting that Equation (3) is the main distinguishing feature of the ESM.

In this paper, we first deconstruct the ESM in its building blocks: characterization, normalization and weighting (Section 2). In this process, we will add more precision than Equation (3) offers, including summation, subscripts and units. Then, we will pursue a reconstruction of the ESM with the more refined building blocks (Section 3). This will result in a more accurate specification of the formula of the ESM. While our original aim was to create a more unequivocal definition of the ESM, it turned out that some issues could not be resolved. So, at some points, our analysis will remain inconclusive. This might be regarded as a disappointing result, but we actually argue that this demonstrates that the principles of the ESM need to be further elaborated. The later sections (Sections 4 and 5) will analyze the differences and some other issues. We will use a precise notation, and the symbols will be introduced whenever they appear. In Appendix A, we summarize the symbols.

## 2. Deconstruction

In this section, we will step-by-step analyze the different building blocks of the ESM. We will conduct this based on [8], the ISO 14040/14044 standards [5,6] and occasionally other documents. We refer to this methodology as "deconstruction", following [14].

### 2.1. Characterization

In Equation (2), we indicate a characterization factor by $C_{c,s}$. The process of characterization then proceeds through

$$S_c = \sum_s (C_{c,s} \cdot m_s) \tag{4}$$

where $S_c$ is the characterization result for impact category $c$.

While the choice of symbols is arbitrary, it is essential for good communication to indicate the type of stressor (here $s$) as well as the type of impact (here $c$). A similar practice is followed by, for instance, [15] (p. 109).

It is remarkable that many texts indicate the stressor but do not indicate the impact category. For instance, Ref. [16] provides a formula in which the subscript for $c$ is missing, loosely speaking about the "impact categories of interest". A curious hybrid form is presented in [17] (p. 176), where $S_c = \sum_s (C_s \cdot m_s)$ is used (notation adapted). This is incomplete in so far that the characterization factor should be $C_{c,s}$ (or perhaps $C_{s,c}$). After all, the characterization factor of a particular toxic substance will, in general, be different for human toxicity, aquatic ecotoxicity and terrestrial ecotoxicity. In general, many toxic stressors do not contribute to climate change, so they will have a global warming potential of zero: $C_{\text{climate change},s} = 0$.

In the ESM, the characterization factor is indicated by a simple symbol $K$. There is no specification if $K$ differs per stressor and/or per impact category. The illustrative examples, however, suggest so. For instance, we read about "the case of greenhouse gases [with] the characterization value of 265 kg $CO_2$-eq./kg $N_2O$ for nitrous oxide ($N_2O$)" ([8], (p. 66)). Hence, we believe that K is supposed to have (at least) two subscripts, one for the stressor and one for the impact category.

We further note that characterization factors may be further refined by attaching emission compartment, region and/or time. The authors of [18], for instance, give the characterization factor four subscripts: $j$ for the impact category, $i$ for the stressor, $k$ for the location and $l$ for the emission compartment. We note that [8] discusses ESM's differentiation of regions and time on pages 56–58 but that their characterization factor does not seem to differ per region or time.

It is impossible to prescribe a generic unit because the units of the amounts of the stressor and the impact category results differ across the numerous types of flows and impacts. We will, therefore, only illustrate it with one example, for greenhouse gases. In many such cases, the stressors are quantified as mass amounts, for instance, in kg. The characterization factors are typically the global warming potentials, expressed in kg $CO_2$-eq/kg. The resulting impact score is then kg $CO_2$-eq.

### 2.2. Normalization

According to ISO 14044 [6], normalization processes a characterized result by relating it to "some reference information". ISO's text is somewhat unclear about the details. It states that the characterized result is divided by "a selected reference value". Many texts interpret this as a division of a characterized result by another characterized result:

$$T_c = \frac{S_c}{N_c} \tag{5}$$

where $N_c$ is the normalization reference, expressed in impact terms. See, for instance, [18] and [15]. But the ISO text itself may be read as suggesting something different because all examples of reference values are formulated as "inputs and outputs", and these terms refer to stressors rather than to impact categories. In other words, the text might be read as using $\frac{S_c}{M_s}$, where $M_s$ is the reference flow of stressor $s$.

This ambiguity of dividing by an impact metric or a stressor metric is at the heart of one of the problems in understanding the ESM procedure. Documents that report normalization references typically perform both (see, e.g., [19,20]). They define a system, for instance, Japan in 2020, collect information on the various stressor flows ($M_s$), and then calculate the characterized reference values ($N_c$). Mathematically formulated, they calculate

$$N_c = \sum_s (C_{c,s} \cdot M_s) \tag{6}$$

for every impact category $c$. These texts apparently interpret ISO's phrasing with a nuance: the normalization references are not the inputs and outputs, but they are the characterized and aggregated versions of those inputs and outputs. This nuance is, however, not detectable in Equation (3), partly because no indices for stressors and impact categories have been added.

ESM, like most LCIA systems, uses a defined region and year for the normalization reference. For ESM, the region is Switzerland, but the year is not specified ([8], (p. 42) speaks of the "environmental pressure in a region (in this case Switzerland) per year", but obviously the pressure is not the same for every year). Clearly, an operational method should include this specification, as it will affect the results. Especially for distinguishing retrospective or ex ante studies, the time frame may matter.

The issue of units is also worth discussing. Annual flows and "per year" amounts have units like kg/year. The characterization factors are the same as before, so the normalization reference $N_c$ at the impact level will be in per year units too, for instance, kg $CO_2$-eq/year. The normalized result $T_c$ will then be expressed in year. For the ESM, we do not know the situation because normalization results are not reported as such.

### 2.3. Weighting

ISO 14044 [6] specifies that weighting can be applied to either characterized or normalized results. Because the ESM includes a normalization, we will concentrate on this second form. Weighting then converts normalized results to a common metric, allowing further aggregation into a single number. Technically, this uses

$$I = \sum_c (W_c \cdot T_c) \tag{7}$$

The issue of the unit depends on the units of the weighting factors $W_c$. In the case of ESM, [8] (p. 56) defines the weights to be "a dimensionless quantity". If then, following the logic of the previous section, $T_c$ is expressed in year, the weighted result $I$ is also expressed in year.

For the weighting factors, [8] (p. 56) use "the ratio of current to critical flow". This presents a complication because weighting factors are—following the ISO standard—defined for impact categories (we use the notation $W_c$ to refer to the weighting factor for impact category $c$) but the term "flow" is typically associated with the stressor level (pollutant emission or resource extraction). An expression like $W_c = \left(\frac{F}{F_k}\right)^2$ would make no sense because we need to add subscripts at the righthand side, either for the impact category ($c$) or for the stressor ($s$). The examples in [8] give a mixed picture in this respect. For global warming, the weight is derived at the impact level, in terms of the amount of $CO_2$-eq ([8], (p. 74)). On the other hand, for PM2.5 and PM10, the weight is derived at the emission level ([8], (p. 87)). For reasons of ISO compliance, we will follow the first route. We note that the mixing of the individual stressor level and the characterized and normalized impact level may be regarded as introducing an inconsistency.

The approach then easily fits the general scheme:

$$W_c = \left(\frac{Y_c}{Z_c}\right)^2 \tag{8}$$

where $Y_c$ is the current impact level and $Z_c$ is the critical impact level. If both are expressed in kg $CO_2$-eq/year, the resulting weighting factor is indeed dimensionless. The current impact level is clearly the result of the current stressor levels:

$$Y_c = \sum_s (C_{c,s} \cdot y_s) \tag{9}$$

where $y_s$ is the current flow at the stressor level.

The critical impact level $Z_c$ is formulated in terms of impacts, not in terms of individual flows. For instance, targets are formulated in terms of $CO_2$-equivalents, not in terms of individual greenhouse gases.

## 3. Reconstruction

If we assemble the three elements, characterization, normalization and weighting, together, we obtain

$$I = \sum_c \left( \underbrace{\left(\frac{\sum_s (C_{c,s} \cdot y_s)}{Z_c}\right)^2}_{\text{Weighting}} \cdot \underbrace{\frac{1}{\sum_s (C_{c,s} \cdot M_s)}}_{\text{Normalization}} \cdot \underbrace{\sum_s (C_{c,s} \cdot m_s)}_{\text{Characterization}} \right) \tag{10}$$

Singling out all terms except the life cycle inventory result $m_s$ as the eco-factor $w_s$, we construct

$$I = \sum_s (w_s \cdot m_s) \tag{11}$$

where we have introduced the eco-factor with a single index $s$ as

$$w_s = \sum_c \left( \underbrace{C_{c,s}}_{\text{Characterization}} \cdot \underbrace{\frac{1}{\sum_s (C_{c,s} \cdot M_s)}}_{\text{Normalization}} \cdot \underbrace{\left(\frac{\sum_s (C_{c,s} \cdot y_s)}{Z_c}\right)^2}_{\text{Weighting}} \right) \tag{12}$$

Here, we have also adjusted the order of the terms to better correspond with that of Equation (3).

## 4. Comparison with the ESM-Form

When we compare the reconstructed form (Equation (12)) with the one by ESM (Equation (3)), we observe a superficial similarity: the eco-factor consists of a characterization factor, the reciprocal of a normalization reference and the squared ratio of a current and a critical level. Despite this, there are a few notable differences:

- The presence of two subscripts;
- The absence of the constant;
- The absence of the term UBP;
- The removal of the term "optional" for characterization;
- The occurrence of the characterization factor inside the normalization and weighting term.

Below, we will discuss these differences.

### *4.1. The Role of Stressors and Impact Categories*

The original ESM formula specifies how to calculate an eco-factor using terms like characterization factor, normalization flow, current flow and critical flow, but it does not specify which of these are stressor-specific. In some examples, we find subtle differences, for instance, [8] (p. 74) gives stressor-specific characterization factors for global warming, while the same page gives an impact-specific critical flow. We argue that an unambiguous understanding of the mechanism of the ESM would benefit from a more precise formulation of the general formula, which includes the addition of subscripts for stressors (here: $s$) and impact categories (here: $c$).

In general, the precise choice of impact categories is not clear in the ESM. Although ISO 14044 [6] states that the selection of impact categories is a mandatory element in an LCA study, [7] mentions the term only in their generic chapter on LCA and never in the details of the ESM. Moreover, [7] (p. 22) provides two examples of such impact categories, namely "greenhouse gases" and "nitrogen oxide". These two deviate markedly from the more usual choices, such as global warming, acidification, eutrophication, etc. [12,13]. We also observe that pages 64–65 provide a figure and table which contain items that resemble such impact categories, but their naming and number is not consistent and, moreover, never mentioned in relation to the term "impact category". For instance, we see 11 items in the figure and 14 in the table, including unusual ones like "impact potential" and "2000-watt society primary energy resources". The result is that a simple question such as "which impact categories are covered in the ESM?" is hard to answer. Hence, any study using ESM will have a problem in complying with ISO's requirement to report the impact categories addressed.

### *4.2. The Constant*

The original ESM formula contains the term $c$ which "serves to obtain readily representable numerical quantities". Its value is set to be $10^{12}$/a. The "a" in this expression is explained to be "annum" ([8] (p. 241)), which is Latin for year.

The choice of the term "annum" and its abbreviation "a" is a bit unfortunate, as it is certainly non-standard. The official SI-unit for time is the second, abbreviated as s [21]. The system of prefixes allows for expressions such as millisecond and kilosecond, and a number of non-SI units (minute, hour and day) is seen as well [21]. The use of the prefixes should allow for an easier communication of very large and very small numbers. Indeed, we typically express a land distance as 250 km rather than 250.000 m. In that respect, a constant is not needed per se. The value of $10^{12}$ would be covered by the prefix tera (T).

The use of a dimensional constant in physical relationships is of course a different matter. The gravitational force, for instance, is usually expressed as $F = G\frac{m_1 m_2}{r^2}$, where $G$ is approximately $6.67 \cdot 10^{-11}$ N·m$^2$·kg$^{-2}$. The purpose of this constant is to connect the units kg and m with the unit N. In the present case, there is no such issue, so it seems that the constant is more a curiosity than an essential element of the ESM.

We also read ([8] (p. 50)) that $c$ "takes account of the temporal dimension that remains from the quantitative units". We discuss the relevance of this in the following subsection.

*4.3. The UBP*

The original ESM formula contains the term "UBP". The authors of [7] (p. 248) describe it as "Eco-point (unit for the ecological scarcity assessment method)", and on some other pages we find "the unit of the assessed result" and "EP = UBP". The authors of [7] (p. 50) further provide examples like "21 UBP per gram $SO_2$" and "460 UBP per gram $CO_2$-equivalent". UBP is clearly supposed to play a role comparable to the kilogram, the meter or the joule. This is, however, a dubious point.

Scientists, in general, communicate their results in SI units. These include the base units (such as kg and m), the derived units (such as $m^2$ and m/s) and the derived units with dedicated names (such as Hz = $s^{-1}$ and J = N·m). A small number of non-SI units has been declared to be acceptable as well, for example, the litre and the hour.

All such units have been defined in a clear and reproducible way. For instance, the meter is "the length of the path travelled by light in vacuum during a time interval of 1/299792458 of a second" and the kelvin is "the fraction 1/273.16 of the thermodynamic temperature of the triple point of water" [21]. Such definitions serve to calibrate measuring equipment across time and space, but they also allow for the flawless communication of results.

Probably, the developers of the ESM found it necessary to introduce a new unit, just like Hz and the J were introduced as shorthands for $s^{-1}$ and N·m. But in the documents of the ESM, we were not able to find a reproducible definition of the UBP. Such a definition could read like "1 UBP is the number of lives lost due to the emission of 1 kg of substance X under conditions Y". After all, the meter is not simply the unit of length, but a quantified unit of length: 1 m is the length of the path that light travels in Z second.

Perhaps we can use the ESM formula as defining the UBP. To conduct this, consider Equation (3). It contains an optional characterization factor and let us take the unit kg $CO_2$-eq/kg for this. The next term is the reciprocal of the normalization flow, which will be kg $CO_2$-eq/year. The weighting factor is a squared ratio of two flows, which yields a dimensionless number. Finally, we observe the presence of a constant with unit year$^{-1}$. Altogether this gives the eco-factor the unit kg$^{-1}$. The authors of [8] (p. 76) express eco-factors for greenhouse gases in UBP/g, So, the UBP is, in fact, a unit corresponding to a dimensionless quantity: it is not a unit at all. Instead of writing that the eco-factor of methane is 12 UBP/g, we may better write that as 12 g$^{-1}$.

A final point is that the explicit incorporation of the term "UBP" in an equation is highly unusual. Just consider the case of Ohm's law: $V = IR$. We challenge the developers of ESM to show a textbook on electricity in which Ohm's law is stated as $V = IR \cdot \text{volt}$ or as $V = IR \cdot 1 \cdot \text{volt}$. Units are part of the explanations ("where V is the potential difference in volt"), but not of the relationships.

*4.4. LCIA Steps: Optional or Mandatory?*

In Equation (3), the characterization is stated to be "optional", while the normalization and weighting are not. This is an intriguing reversal of the principles of ISO 14040/14044 [5,6], where characterization is mandatory, and normalization and weighting are optional. It is, therefore, of interest to study and discuss how this precisely works in the ESM.

The authors of [8] (p. 68) write that "a characterisation may be applied if the corresponding environmental impact played a key role when the target was set". This, if for instance, the case for greenhouse gases where the target, is defined as 7829 kiloton $CO_2$-eq/year, and no targets are set on the stressor level. We interpret this as follows:

$$w_s = \begin{cases} \sum_c \left( \underbrace{C_{c,s}}_{\text{Characterization}} \cdot \underbrace{\frac{1}{\sum_s (C_{c,s} \cdot M_s)}}_{\text{Normalization}} \cdot \underbrace{\left( \frac{\sum_s (C_{c,s} \cdot y_s)}{Z_c} \right)^2}_{\text{Weighting}} \right) & \text{(case1)} \\ \underbrace{\frac{1}{M_s}}_{\text{Normalization}} \cdot \underbrace{\left( \frac{y_s}{z_s} \right)^2}_{\text{Weighting}} & \text{(case2)} \end{cases} \quad (13)$$

Case 1 is the ISO compatible case discussed so far: stressors contributing to a common impact category are characterized (using $C_{c,s}$), next normalized by an impact category-specific normalization reference ($N_c = \sum_s (C_{c,s} \cdot M_s)$)) and finally weighted by an impact category-specific weighting factor ($W_c = \left( \frac{(\sum_s (C_{c,s} \cdot y_s))}{Z_c} \right)^2$).

Case 2 is outside the ISO structure: it does not involve impact categories and there is no characterization step. But there is a normalization, working at the stressor level ($n_s = M_s$) and a weighting at the stressor level ($w_s = \left( \frac{y_s}{z_s} \right)^2$).

With this subdivision in two cases in mind, we can try to analyze which stressors fall in case 1 and which in case 2. For some pollutants, it is easy. $CO_2$, for instance, is a clear case 1 stressor, contributing to the impact category of global warming. And CFC-11 also belongs to case 1, contributing to ozone depletion. Ammonia ($NH_3$), on the other hand, is a case 2 stressor, for which stressors-specific normalization and weighting factors are used. So far, the situation is clear, albeit not in agreement with ISO.

However, for several other stressors this is not as straightforward as it sounds. We mention a few complications. HCFC-22 is both a greenhouse gas and an ozone-depleting substance. For the eco-factor, the largest result is used (page 76). Page 43 argues that consideration of both impacts would lead to a double-counting. The ESM, therefore, decides to use "only the most stringent target" in such situations. Apparently, we need to change the description of case 1 in that respect:

$$w_s = \max_c \left( \underbrace{C_{c,s}}_{\text{Characterization}} \cdot \underbrace{\frac{1}{\sum_s (C_{c,s} \cdot M_s)}}_{\text{Normalization}} \cdot \underbrace{\left( \frac{\sum_s (C_{c,s} \cdot y_s)}{Z_c} \right)^2}_{\text{Weighting}} \right) \quad \text{(case1)} \quad (14)$$

Another complication is presented by the carcinogenic pollutants (benzene, dioxins, furans and polycyclic aromatic hydrocarbons). There are characterization factors available for the strength of these substances in contributing to an unnamed impact category. But the critical level is not defined at the impact level, but at the individual stressor level. These critical stressor levels ($z_s$) are next characterized to compute a critical impact level. Thus, we find a third option

$$w_s = \max_c \left( \underbrace{C_{c,s}}_{\text{Characterization}} \cdot \underbrace{\frac{1}{\sum_s (C_{c,s} \cdot M_s)}}_{\text{Normalization}} \cdot \underbrace{\left( \frac{\sum_s (C_{c,s} \cdot y_s)}{\sum_s (C_{c,s} \cdot z_s)} \right)^2}_{\text{Weighting}} \right) \quad \text{(case3)} \quad (15)$$

The third and final complication that we discuss is CO. CO is most famous as a toxic pollutant, but it also contributes to global warming. No critical flow is available for CO, but the ESM has derived one by combining its GWP and the critical flow of greenhouse gases [8] (p. 88). The mathematics is probably

$$w_s = \underbrace{\frac{1}{M_s}}_{\text{Normalization}} \cdot \underbrace{\left(\frac{y_s}{Z_c / C_{c,s}}\right)^2}_{\text{Weighting}} \quad \text{(case4)} \tag{16}$$

This yields an eco-factor of 1.6, which is much smaller than the values for less toxic substances, such as $NO_x$ (33) and $NH_3$ (44). We believe that ESM's reliance on critical flows is the cause of this and perhaps similar aberrations.

### *4.5. Characterization as a Basis for Normalization and Weighting*

Finally, we observe that our reconstruction contains the characterization factor three times: for characterization itself, for determining the normalization reference and for determining the weighting factor. Recognition of the role of $K$ in Equation (3) in normalization (through $F_n$) and weighting (through $F$) is essential for consistency and updating reasons. If $K$ changes or is regionally differentiated, this should also permeate in $F_n$ and in $F$. We reiterate the fact that in the regionalized eco-factor [8] (p. 57), there is a region index for the normalization and weighting but not for the characterization.

## 5. Discussion

We finish our analysis by raising a few more general points, including the interpretation of the ESM as a "distance-to-target" method and the necessity of confirming to ISO standards.

### *5.1. Is ESM a Distance-to-Target Method?*

The ESM is generally described as a distance-to-target (DtT) method [7,11,22]. The authors of [10] (p. 1702) describe DtT as an approach in which "environmental impacts are weighted according to their distance from the current environmental situation to a defined target". We argue that the ESM is not based on a distance. Distances can be defined in different ways, but according to the generally accepted axioms [23], they always satisfy a number of properties. Let $A$ and $B$ be two objects and let $d(A, B)$ be their distance (or metric). Then the usual axioms stipulate that

1. $d(A, B) \geq 0$ for every two objects $A$ and $B$ (non-negativity);
2. $d(A, A) = 0$ for every object $A$;
3. $d(A, B) = d(B, A)$ for every two objects $A$ and $B$ (symmetry);
4. $d(A, C) \leq d(A, B) + d(B, C)$ for every three objects $A$, $B$ and $C$ (the triangle inequality).

These axioms can be easily illustrated as follows: (1) the distance between Aberdeen and Bristol is not negative; (2) the distance between Aberdeen and Aberdeen is zero; (3) the distance between Aberdeen and Bristol is equal to the distance between Bristol and Aberdeen; and (4) the distance between Aberdeen and Cambridge does not exceed the distance between Aberdeen and Bristol plus the distance between Bristol and Cambridge. When $A$ and $B$ represent scalar numbers, a convenient distance is

$$d(A, B) = |A - B| \tag{17}$$

For instance, when Alice is 25 years old and Bob 19, their age-distance is 6 years. When $A$ and $B$ are vectors in an $n$-dimensional space, there are more options, such as the Euclidean distance

$$d(A, B) = \sqrt{\sum_{i=1}^{n} (A_i - B_i)^2} \tag{18}$$

or the Manhattan distance

$$d(A,B) = \sum_{i=1}^{n} |A_i - B_i| \tag{19}$$

We note that the validity of these axioms is sometimes debated [24] but, in general, they hold firmly.

The DtT-weighting of the ESM uses the form $d(A,B) = \left(\frac{A}{B}\right)^2$ and, as such, satisfies the first axiom but not the other three axioms. We, therefore, reject the interpretation of a "distance". Rather, we argue that the name "ratio-to-target" (RtT) or, even better, "ratio-to-target squared" (RtT2) would have been more appropriate.

Labeling the ratio as a distance is, by the way, not a specific feature of the ESM, but has been conducted more often in LCIA. For instance, Ref. [25] defines DtT as based on a ratio, and [26] discusses a "distance-to-target factor", which also is a ratio: $\frac{current}{target}$. However, historically, the term "distance-to-target" was used for another principle as well. The authors of [27] provide an example in which the weight can mathematically be expressed as $\frac{current-target}{target}$. Although, that form is also not acceptable as a distance; it has the interesting feature of satisfying the second axiom. The authors of [27] use still another form: $current - target$. This form, which is also used in [28], also satisfies the second axiom. Both forms, however, can yield negative values, violating the first axiom. Altogether, we conclude that the term "distance-to-target" is not only mathematically confusing, but it is also interpreted in different ways in the literature. As such, we recommend the use of another term. We suggest ratio-to-target squared for this.

### *5.2. Options for Break-Down*

The ESM according to Equation (11) combines different stressors into one overall score, using eco-factors. While this can be convenient, we note that there are several situations in which a less aggregated result may be desirable. This includes the case of optimization, in which an analyst wants to use an LCA to find out what is the major issue in a product system. But it can also follow from ISO's requirement, which stipulates that "weighting ... shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public". Instead, in such cases, "the comparison shall be conducted category indicator by category indicator" [6] (p. 23).

The problem is that Equation (11) allows for a disaggregation by stressor but not for a disaggregation by impact category. That is only possible when (11) is rewritten as $\Sigma_c$. Now, we observe that Equation (10), actually, is of that form but that it does not contain a simply identifiable form of the eco-factor. The mathematical reason is that that the eco-factor, according to (12), is a per-stressor quantity, involving an aggregation over impact categories rather than a per-impact category quantity, involving an aggregation over stressors. There is no simple way to solve this problem.

### *5.3. What Is the Role of the ISO Standards?*

We have seen that the ESM has tried to adopt the ISO framework of characterization-normalization-weighting ([8] (p. 47): "the aim is to largely comply with [ISO's] prescriptions"; [8] (p. 48): "it can be composed of the following three elements in accordance with ISO Standard 14044"). We also concluded, based on the same ISO standards, that there are a number of points of divergence:

- There is no clear definition of impact categories in the ESM;
- The characterization is only optional in ESM, while it is mandatory for ISO;
- No separate characterization or normalization results are computed, complicating ISO's clause 4.4.3.4.3 which states that "indicator results or normalized indicator results reached prior to weighting should be made available together with the weighting results";
- It allows for the use of normalization and weighting at the level of stressors.

Altogether, it appears that the attempt to cast the ESM in an ISO conformal structure has not been too successful. We pose the question: is this a problem? We think it is not.

ISO standards are partly based on science, but they are not scientific, and they certainly should not be a guide for science. All typical hallmarks of scientific products (referencing previous work, discussing weaknesses of earlier approaches, peer review and flexibility in adapting to new insights) are not part of the ISO 14040/14044 standards. As such, they cannot be considered as contributions to the science of LCA. Rather, they can be seen as reflecting a fossilized consensus.

This view is perhaps unorthodox in the world of LCA. For some reason, the ISO standards have received a status as if they contain scientific, unchangeable and untouchable truths. We highlight two statements that demonstrate this:

- LCA can be made "as scientific as possible" through "strict adherence to the ISO standards of the 14040 series" [29];
- The ISO standards "represent the constitution of LCA and should, therefore, be respected and protected by everyone" [30].

These authors, and among them many others, maintain that scientific work must conform to the ISO standards, rather than the other way around.

We believe that the failed attempt to refurbish the ESM in an ISO format only complicates things. If the developers of ESM had not tried to impose a characterization-normalization-weighting structure, instead keeping the straightforward original form of [1–3], many of our critical points would be resolved.

### *5.4. What Is the Added Value of the ESM?*

Comparison of the usual LCIA form (Equation (2)) and the ESM (Equation (12)) helps us to appreciate what is unique in ESM. Like several other LCIA systems, ESM provides characterization factors for a number of impact categories, as well as normalization references. But in contrast to most other systems, ESM also provides weighting factors, and it does so on the basis of a "distance-to-target" principle: $W = \left(\frac{current}{target}\right)^2$. That is the most important novelty, and we should appreciate and assess that element.

The question now is if the proposed weighting is scientifically defendable. After all, we have seen that [8] describes the ESM as "scientific", but this analysis was restricted to the data sources and the characterization factors and did not cover the weighting nor the formula. The authors of [8] (p. 27) devote a few words to this question: "the design of the calculation formula [is] value-based but can be justified on the grounds of plausibility". The justification is pretty limited; it consists of just three sentences on page 42: "Weighting expresses the relationship between the current quantity of an environmental pressure and the tolerated target quantity set out in environmental legislation. The weighting factor is squared. This means that if the current quantity of an environmental pressure is greater than the tolerated target amount, this is clearly noticeable in the result." Page 56 adds a bit to this: "The ratio of current to critical flow is squared. The effect of this is that a major exceedance of the target value (critical flow) is weighted over-proportionately, and if the current flow is substantially lower than the critical flow, it is weighted under-proportionately. This means that the higher the current pollution already is, the more strongly every additional emission is weighted."

We would describe these sentences rather as a description or explanation than as a justification. One critical issue is that subjective values that are supposed to be reflected in the weighting procedure are missing. As [31] puts it: "where are the values?" We also note that ISO 14044 ([6]) states that weighting factors "are based on value-choices and are not scientifically based". This is to some extent contradicting the ESM, in which, on the one hand, the targets are described as based on legislation and policy ([8] (p. 25)), but, on the other hand, it has been admitted that these targets are based on scientific knowledge ([8] (p. 37)).

Another point of critique is the use of a ratio ($\frac{current}{target}$) and not a distance-type indicator ($current - target$ or $\frac{current-target}{target}$) and the use of a square rather than another form (e.g., a third power or e to the power of the ratio). A scientific analysis would at least discuss the various options. We point to [32] (pp. 921–922) for a discussion in which a squared term was extensively discussed, although in another context.

Weighting environmental impacts is about using social preferences. There is no objective, scientific set of weighting factors: they necessarily depend on opinions, cultural biases and political colors. But that does not mean that "anything goes". The field of muti-criteria decision theory [33] offers many science-based methods to include social preferences. The ESM would benefit from embedding Equation (3) in such established theories, instead of relying on non-scientific ISO standards.

### *5.5. Limitations of This Study*

In this paper, we studied the clarity and consistency of the theoretical description of the ESM. We did not address:

- If the data that are used in [7,8] or in further elaborations, such as [9–11], is of sufficient quality;
- If the entire ESM-principle, including the squared ratio-to-target weighting factor, is a sound procedure for the impact assessment step;
- If the idea of using regional targets is compatible with global supply chains.

Obviously, the fact that the current ESM contains a number of scientific elements does not guarantee that the overall approach is scientific. A study of that would require a much longer analysis, and the chain is as strong as the weakest link.

## 6. Conclusions

We have shown that the ecological scarcity method, as described in [7,8], lacks a scientific foundation and is moreover so inaccurately described that it is likely to generate misunderstanding. Although it is endorsed in a selected number of policy contexts, its scientific acceptability is currently low and is at risk of being surpassed by other impact assessment methods. It is, therefore, in need of a number of clarifications and improvements. While we appreciate the use of a mathematical structure rather than only words or examples, the formulation falls short in several ways. A more accurate rendering of the formula than Equation (3) is

$$w_s = \begin{cases} \max_c \left( \underbrace{C_{c,s}}_{\text{Characterization}} \cdot \underbrace{\frac{1}{\sum_s (C_{c,s} \cdot M_s)}}_{\text{Normalization}} \cdot \underbrace{\left( \frac{\sum_s (C_{c,s} \cdot y_s)}{Z_c} \right)^2}_{\text{Weighting}} \right) & \text{(case1)} \\ \underbrace{\frac{1}{M_s}}_{\text{Normalization}} \cdot \underbrace{\left( \frac{y_s}{z_s} \right)^2}_{\text{Weighting}} & \text{(case2)} \\ \max_c \left( \underbrace{C_{c,s}}_{\text{Characterization}} \cdot \underbrace{\frac{1}{\sum_s (C_{c,s} \cdot M_s)}}_{\text{Normalization}} \cdot \underbrace{\left( \frac{\sum_s (C_{c,s} \cdot y_s)}{\sum_s (C_{c,s} \cdot z_s)} \right)^2}_{\text{Weighting}} \right) & \text{(case3)} \\ \underbrace{\frac{1}{M_s}}_{\text{Normalization}} \cdot \underbrace{\left( \frac{y_s}{Z_c / C_{c,s}} \right)^2}_{\text{Weighting}} & \text{(case4)} \end{cases} \quad (20)$$

where the four cases apply to different types of stressors, e.g., case 1 for greenhouse gases, case 2 for $NH_3$, case 3 for carcinogenic pollutants and case 4 for CO. Perhaps there are even more cases: we did not analyze the situation for every stressor.

Further, while the developers have tried to fit the existing ESM in the ISO 14040/14044 structure, they have failed to achieve this goal. This is not necessarily a problem because there is no place for a rigid voting-based structure in the realm of science. But it would be fairer if they would not suggest having achieved the goal (for instance, in [8] (p. 55), when the eco-factor formula is stated to be "in accordance with ISO standard 14044").

The inclusion of a constant ($c = 10^{12}$ year$^{-1}$) has been rejected in our analysis and so has been the fate of the pseudo-unit UBP. Its implications are as follows: the current eco-factor of "21 UBP per gram $SO_2$" will change into "$21 \cdot 10^{-12}$ year per gram $SO_2$" or perhaps "21 picoyear per gram $SO_2$" or "27.6 microsecond per gram $SO_2$". Its interpretation is straightforward: of the yearly available environmental utilization space, an emission of 1 g of $SO_2$ uses up 27.6 microseconds.

In the introduction we raised a number of questions, about the relation between the eco-factor and the usual LCIA set-up, about the presence of impact categories, about the summation(s) in the ESM, about the terms $c$ and UBP and about the status of the optional term $K$. We believe that all these issues have been clarified by using a much more transparent and explicit formulation as in Equation (20). We also think that future writers should refrain from using the distance-to-target interpretation because the ESM does not comply with the mainstream axioms of a distance.

Overall, we recommend that the developers of ESM reconsider their description on the basis of our critical deconstruction and reconstruction and, also, question the need to operate within the ISO constraints.

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## Appendix A

**Table A1.** Symbols adopted in this paper, with their counterparts in [7,8], when available.

| Symbol in This Paper | Meaning | Example Unit | Symbol in [7,8] |
|---|---|---|---|
| $s$ | stressor (pollutant or resource) | - | |
| $c$ | impact category | - | |
| $m_s$ | LCI result for stressor $s$ | kg | |
| $S_c$ | characterization result for impact category $c$ | kg $CO_2$-eq | |
| $T_c$ | normalization result for impact category $c$ | year | |
| $I$ | weighting result | year | |
| $C_{c,s}$ | characterization factor for stressor $s$ and impact category $c$ | kg $CO_2$-eq/kg | $K$ |
| $n_s$ | normalization reference of stressor $s$ | kg/year | $F_n$ |
| $N_c$ | normalization reference of impact category $c$ | kg $CO_2$-eq/year | $F_n$ |
| $M_s$ | annual flow of stressor $s$ | kg/year | $F_n$ |
| $y_s$ | current level of stressor $s$ | kg/year | $F$ |
| $Y_c$ | current level of impact category $c$ | kg $CO_2$-eq/year | $F$ |

**Table A1.** *Cont.*

| Symbol in This Paper | Meaning | Example Unit | Symbol in [7,8] |
|---|---|---|---|
| $z_s$ | critical level of stressor *s* | kg/year | $F_k$ |
| $Z_c$ | critical level of impact category *c* | kg $CO_2$-eq/year | $F_k$ |
| $w_s$ | weighting factor for stressor *s* | - | |
| $W_c$ | weighting factor for impact category *c* | - | |
| $w_s$ | eco-factor for stressor *s* | year/kg | *Eco-factor* |

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