Ratio, sum, or weighted sum: the curious case of BASF's eco-efficiency analysis

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Research Article

Ratio, Sum, or Weighted Sum? The Curious Case of BASF's Eco-efficiency Analysis

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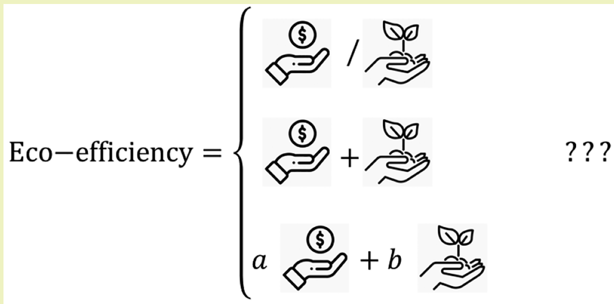

ABSTRACT: Eco-efficiency is generally defined as the ratio of an economic and an environmental variable. This interpretation is also cited in connection to its most popular implementation, known as the "BASF eco-efficiency portfolio analysis". There is, however, something strange about this. A ratio is easily visualized as a slope, but BASF's method is working with a distance, which can be formulated as a weighted sum, not as a ratio. Upon closer analysis, it further shows that the two variables receive equal weight. These findings are contradicting the ISO 14045 standard and the perception in mainstream literature. We discuss the relevance of this shift of viewpoint. We also discuss some of the extensions, namely, the socio-efficiency analysis and the SEEbalance. We finally investigate the recent changes that were introduced in the eco-efficiency method, including an eco-efficiency index, and conclude that these changes have been reported in an incomplete way, or in documents that are difficult to trace. Effectively, this means that the most popular way to calculate and visualize eco-efficiency is unverifiable, impeding its status as a science-based method for sustainable industry support. We end by sketching the path forward.

KEYWORDS: *eco-efficiency, eco-efficiency portfolio, BASF, ratio indicator, weighted sum, sustainable industry*

INTRODUCTION

The term eco-efficiency (EE) was introduced as a business strategy for "increasing value added while decreasing pollution and resource use".[1] Soon after, a more quantitative interpretation was added, in terms of the ratio of the value added and the environmental damage.[2] The World Business Council for Sustainable Development[3] likewise proposed the product value divided by environmental influence for defining EE. Such ideas were more thoroughly elaborated in subsequent articles.[4−11]

Meanwhile, an opposite approach was taken by the United Nations,[12] defining an EE indicator as "the ratio between an environmental and a financial variable". This form is also used by several subsequent authors.[13,14] In a similar style, Saling et al.[15] use the term "E/C ratio", environment divided by costs.

In the same article, however, Saling et al.[15] also mention the other form, "the ratio of economic creation to ecological destruction". A similar reversal of the definition can be found in Schaltegger,[16] who first defines EE as "the ratio between value added and environmental impact added" and who continues the same sentence with "the ratio between an ecological and an economic performance indicator". One sentence later, the author returns to "the ratio between the economic costs and the ecological benefits", after which a formula specifies "created ecological benefits/economic costs". The ISO 14045 standard for EE[17] makes a similar twist. It first defines EE in terms of an indicator as a "measure relating environmental performance of a product system to its product system value". In an (informative) appendix, the text changes to "dividing the product system value indicator by the environmental impact indicator".

These examples point to general confusion, which was resolved by distinguishing four variations:[18]

$$\mathrm{EE} = \begin{cases} \dfrac{\text{value}}{\text{impact}} & \text{(environmental productivity)} \\ \dfrac{\text{impact}}{\text{value}} & \text{(environmental intensity)} \\ \dfrac{\Delta\text{value}}{\Delta\text{impact}} & \text{(cost per unit of improvement)} \\ \dfrac{\Delta\text{impact}}{\Delta\text{value}} & \text{(environmental cost-effectiveness)} \end{cases} \quad (1)$$

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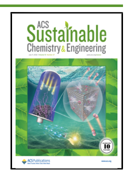

However useful all four indicators may be, embracing all of them as EE has the danger of introducing a confusion of metrics and objectives. For one, it would not suffice to report EE as a number, but it would always require a specification of which variation is used. Worse, it would not even be clear what the desired direction of progress would be. Such a conflation is, for instance, present in Schmidheiny,[19] who defines EE as the impact per unit of value, and then proudly announces that companies are raising it, whereas a decrease would be something to aim for.

Part of the confusion can be explained by reflecting on the idea of efficiency denoting "the relation between output and input",[16] which Meier[20] concisely writes as

$$\text{efficiency} = \frac{\text{benefit}}{\text{burden}} = \frac{\text{outputs}}{\text{inputs}} \tag{2}$$

If we take a manufacturer's point of view and consider economic value as the output and environmental capital as the input, we indeed can think of EE in terms of economic value divided by environmental impact. This then represents the desire to make more value with less impact, in-line with the Factor Four movement.[21] If we, however, start from the idea of improving environmental performance, the change of environmental impacts is the output and the cost is the input. Therefore, it can make sense to use a different definition if we wish to keep the convenient rule that a higher EE is preferable. Taking into account that logic, the first and fourth variations of eq 1 are in agreement with the eco-efficiency concept, whereas the second and third variation are more in agreement with eco-inefficiency. Note that this logic is not at all universal; there are authors who define EE in such a way that a lower value is better.[22]

Next, consider a third point of view: the customer, who can be either a consumer or a business client. Most of us like to have products that are both economical and environmentally friendly. This means that not the ratio of value over impact and neither the ratio of impact over value are leading, but rather that we aim to minimize the sum of value[23] and impact, probably including a weighting of the two.[23] Hence, we try to minimize

$$\text{value} + \text{weight} \times \text{impact} \tag{3}$$

where weight is the weighting factor for environment vis-à-vis economy. [In this presentation, we have chosen to rephrase a weighted sum $a \times \text{value} + b \times \text{impact}$ as $\text{value} + \frac{b}{a} \times \text{impact}$ because it requires one weighting factor $\left(\text{weight} = \frac{b}{a}\right)$ instead of two (a and b).] This can be converted in a quantity that we desire to maximize in different ways. Two such ways are

$$\text{EE} = \begin{cases} -(\text{value} + \text{weight} \times \text{impact}) \\ \dfrac{1}{\text{value} + \text{weight} \times \text{impact}} \end{cases} \tag{4}$$

Here, we have maintained the left-hand side to represent EE, although the quantity is not a ratio between an output and an input. Instead of the sum of the value and the impact, other mathematical forms are possible as well. Joachimiak-Lechman et al.,[24] for instance, propose a product of the two dimensions:

$$\text{EE} = \frac{1}{\text{value} \times \text{impact}} \tag{5}$$

Saling et al.,[15] with whom we are already familiar when they defined EE as a ratio, also consider such a form when they write that "alternatives having the same product of economic and ecological assessment are deemed equally eco-efficient". Their next sentence, "alternatives with the lowest factor in the defined comparable system are the most eco-efficient ones", then suggests a form similar to that of Joachimiak-Lechman et al.[24]

Neglecting weighting for a moment, the above customer-oriented schemes could, in the spirit of Meier,[20] be written as

$$\text{efficiency} = \begin{cases} -(\text{economic burden} + \text{environmental burden}) \\ \dfrac{1}{\text{economic burden} + \text{environmental burden}} \\ \dfrac{1}{\text{economic burden} \times \text{environmental burden}} \end{cases} \tag{6}$$

Perhaps, we should interpret Vercalsteren et al.[25] also in that way when they write that "the most eco-efficient option has simultaneously the lowest cost and the lowest environmental score". Piccinno et al.,[26] despite the fact that they did not define EE in a precise way, probably have the same in mind when they reject "over-proportional" and "under-proportional" options, favoring "proportional" ones.

Coming back to weights, the ratio forms of EE forms do not include a weighting of environment vis-à-vis economy. The joint consideration of environmental impact and economic value usually requires a trade-off and, therefore, needs to include a subjective priority setting, typically as a weighting. When a portfolio of product alternatives is assessed in terms of an environmental and economic score, a profit seeker may give more weight to the economic indicator than an environmentalist, and the two persons may come up with a different final ranking, even though they agree on the underlying facts. The definition of EE as a ratio of the two scores does not include a weighting or other subjective element, but results in an objective ranking of the alternatives in the portfolio. Although an objective approach is certainly attractive, the paradox of the disappeared subjectivity deserves to be studied.[27] This is all the more puzzling because the ISO 10445 standard[17] claims that "the eco-efficiency method includes a weighting of environmental impacts and costs". The standard also discusses situations in which "more weight will be put on the environmental performance of the studied alternatives". This suggests that a ratio-based EE indicator would assume the form

$$\text{EE} = \frac{\text{value}}{\text{weight} \times \text{impact}} \tag{7}$$

But it is immediately clear that even though a weighting factor would affect the EE value, the resulting ranking of products will be unaffected by the weighting factor. [Likewise, the claim[6] that such a ratio "emphasizes the trade-off between economic and environmental aspects of production, giving equal emphasis to both", is wrong. A ratio-based EE indicator comprises no trade-off and no weighting.[27]] The absence of weighting in the product form is understandable with the same logic, as

$$\text{EE} = \frac{1}{\text{value} \times \text{weight} \times \text{impact}} \tag{8}$$

will not affect the ranking or decision either.

The output-divided-by-input scheme[20] is carried further by taking thermodynamic efficiency as a vantage point and requiring that EE not only is a ratio between output and input but also is dimensionless, as well as bounded between 0 and 1.[28]

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As an example, industrial processes due to second-law inefficiency operate according to

$$E_{in} = E_{out} + E_{loss} \tag{9}$$

where E is, for instance, energy. This then serves to define the thermodynamic efficiency of the process as

$$\text{efficiency} = \frac{E_{out}}{E_{in}} = 1 - \frac{E_{loss}}{E_{in}} \tag{10}$$

Clearly, indicators of the type value/impact or impact/value are, in general, not dimensionless (typical units are, for example, $/kg CO_2 or kg CO_2/$), and they are not restricted by the values 0 and 1. Huysman et al.[29] distinguish in this way "level 1" and "level 2" efficiencies.[30] It should be mentioned that some authors[31] normalize the numerator and denominator, effectively using forms like "normalized value" divided by "normalized impact" or variations thereof. Such indicators are dimensionless, but not necessarily bounded between 0 and 1.

Altogether, it appears that there is a wide choice of options: value/impact, impact/value, value × impact, value + impact. Each of these may apply to different decision situations.[14,32] We summarize the different interpretations in Table 1. In addition, there are approaches in which EE is not a number, but a strategy for the "simultaneous study of economic and environmental impacts",[33] or where eco-efficiency is used as a synonym for environmental friendliness.[34,35] We also mention a recent review,[36] which discerned various qualitative and quantitative approaches. We finally mention a bibliometric analysis,[37] which in its title and abstract promises to study eco-efficiency, but which has a so much wider scope that it actually overlooks many important contributions to eco-efficiency while emphasizing other subjects. (For instance, it mentions papers by Tone, Rebitzer, and Textor as the top-three cited papers, but none of these contain the word "eco-efficiency".)

Table 1. Summary of Quantitative Eco-efficiency Interpretations[a]

interpretation	references
$\frac{\text{value}}{\text{impact}}$	2−10, 15−17, and 20
$\frac{\text{impact}}{\text{value}}$	12−17, 19, and 22
value + impact or $\frac{1}{\text{value + impact}}$	23, 25, and 26
value × impact or $\frac{1}{\text{value} \times \text{impact}}$	15 and 24−26

[a]Some of the references include weights or normalizations.

Many of the articles mentioned reside in the theoretical domain of science. There is, however, one approach that stands out prominently as the dominating approach to EE, not only in the theoretical literature but also in the practice of industrial consultancy. We are referring to the EE portfolio, pioneered by Saling et al.[15] It is "a 20-year success story",[38] and "more than 600 studies in the fields of agriculture, chemical industry, construction, energy and fuels, food and feed, and household and personal care" have been carried out.[39] Because the main originators refer to it as the "the BASF eco-efficiency analysis",[38,40] we will do likewise in the present article. One of the hallmarks of the approach is the use of a graph (sometimes colored with a green-red or green-yellow-red diagonal gradient), separating products with high EE from products with low EE. This is referred to as the portfolio plot[15] or the eco-efficiency portfolio.[40] As an example, we refer to Figure 1, as well to many publications in which the EE portfolio is applied.[22,25,26,41−44]

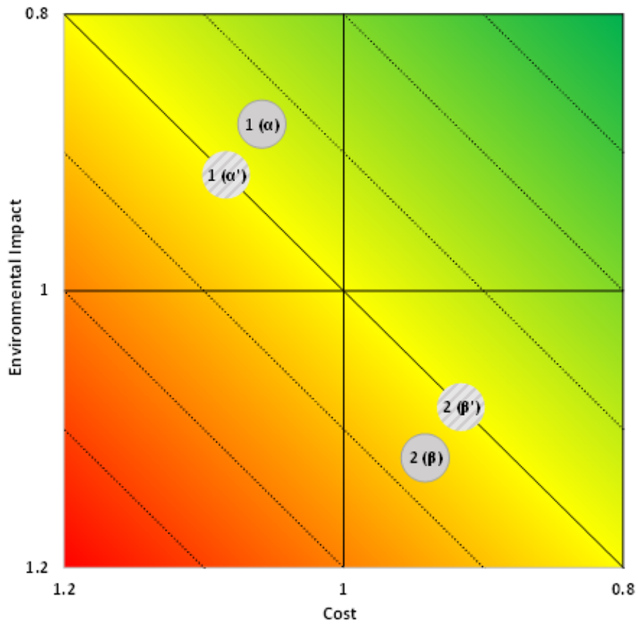

Figure 1. Eco-efficiency portfolio plot, as suggested by Kicherer et al.,[31] adding colors and dashed lines.[39] The solid circles denote the "preliminary" portfolio positions ($PP_{C,\alpha}$, $PP_{E,\alpha}$) for α = 1 and α = 2; the dashed circles denote the "improved" positions ($PP'_{C,\alpha}$, $PP'_{E,\alpha}$). For consistency with Kicherer et al.,[31] the labels α (for product 1) and β (for product 2) have been added as well. Note that the original source uses the labels α' and β' to indicate the "improved" coordinates of products 1 and 2.

Because of its popularity, the question of the interpretation of EE in the BASF approach is of more than academic interest. In another publication[45] the method has been analyzed in terms of its compliance with the "independence from irrelevant alternatives" principle. It was shown that adding or removing irrelevant alternatives (products that are inferior from both an economic and environmental point of view) may lead to rank reversals of the relevant alternatives. In this article, we will study the method from another angle, namely, the choice of EE principle and the presence or absence of weighting. Although one might argue that a method that has been around for 25 years and that has served many decisions and customers is not in need of a critical analysis, we still feel that there is such a need. As we will see below, the description of the method suffers from incompleteness, inconsistencies, and a lack of traceable sources, even though a recent article by Grosse-Sommer et al.[39] claims that it is "a robust basis to support sustainability assessments".

In the next section, "Description of BASF's Eco-efficiency Analysis", we will objectively describe the main features of the BASF EE portfolio. In the third section, "Critical Analysis of BASF's Eco-efficiency Analysis", we critically analyze the description in terms of sense and sensibility. In the fourth section, "Eco-efficiency as a Weighted Sum", we zoom in on the weighting issue. In the fifth section, "Recent Developments", we analyze some recent developments. Finally, we report the conclusions of our analysis. Most of the mathematical proofs are in the appendices that are available as Supporting Information.

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DESCRIPTION OF BASF'S ECO-EFFICIENCY ANALYSIS

The BASF EE analysis consists of a number of steps,[15,40] including the following: (1) Per product, the calculation of a number of environmental impacts (global warming, energy consumption, toxicity, etc.); (2) per product, the calculation of life cycle cost; (3) per product, the normalization and weighting of environmental impacts based on, among others, societal weighting factors, resulting in a one-number environmental impact; (4) per product, the combination of the cost and the environmental impact in a portfolio plot; (5) the ranking of all products in the portfolio plot.

In this article, we will focus on the last two steps: the EE portfolio and the ranking of products. We will assume that a one-number cost value and a one-number environmental impact score have been calculated for each product, in the spirit of earlier work.[15,40] Our analysis will then start with the description, based on Kicherer et al.,[31] which is by far the most detailed exposition of these last two steps that is known to us. We will slightly adapt notation to make the analysis more systematic and add a few symbols; see Table 2 for an overview.

Table 2. Summary of Notations

symbol	meaning
$\alpha \in \{1, 2, ..., j\}$	product index
NF_C or $NF_{C,\alpha}$	"normalized" cost (of product α)
EI or EI_α	"normalized" environmental impact (of product α)
PP_C or $PP_{C,\alpha}$	"preliminary" cost (of product α)
PP_E or $PP_{E,\alpha}$	"preliminary" environmental impact (of product α)
PC' or PC,α'	"improved" cost (of product α)
PE' or PE,α'	"improved" environmental impact (of product α)
$R_{E,C}$	environment to cost relation (of product α)
d or d_α	distance (using "preliminary" coordinates) to the diagonal line (of product α)
d' or d'_α	distance (using "improved" coordinates) to the diagonal line (of product α)
EE* or EE^*_α	eco-efficiency (using "normalized" coordinates) (of product α)
EE or EE_α	eco-efficiency (using "preliminary" coordinates) (of product α)
EE′ or EE'_α	eco-efficiency (using "improved" coordinates) (of product α)
w^*	environment to cost weighting in "normalized" units
w	environment to cost weighting in "preliminary" units
w'	environment to cost weighting in "improved" units
$\bar{x}$	average value taken over all values of a variable x

Let the portfolio consist of j products, labeled as $\alpha = 1, 2, ..., j$, and let the economic value (or cost) of "product α" be given by $NF_{C,\alpha}$ and its environmental impact by EI_α. [The original text writes about "product α" and later mentions a second product, β. But it also uses "1, 2, 3,..." to indicate products. Here, we choose to resolve this by using α as an index, which can assume the values 1, 2, 3, ...] Each product α therefore defines a point $(NF_{C,\alpha}, EI_\alpha)$. These coordinates are transformed into "preliminary" positions $((PP_{C,\alpha}, PP_{E,\alpha})$, which are transformed in a second step into "improved" positions in $(PP'_{C,\alpha}, PP'_{E,\alpha})$. [We will consistently write "preliminary" and "improved" in quotation marks because that is the terminology used by Kicherer et al.[31] For lack of a better term, the original variables will be referred to as "normalized". In a next section, we will question the issue of what actually needs to be "improved" here.] The details of these transformations are provided in Appendix 1 of the Supporting Information.

Figure 1 shows, for two example products, the "preliminary" positions as well as the "improved" positions. The figure is a replication of Kicherer et al.'s (ref 31) Figure 2, enriched with the colors and dashed lines as suggested by others.[39,40,46]

Kicherer et al.[31] informs us that "the most favorable products are located in the upper right corner, whereas the least favorable will be lower on the left side". For example, they conclude that "both products have a similar eco-efficiency" because their "distance from the diagonal line" is equal. Other authors[39,40] make comparable statements.

The axis labels of Figure 1 speak of "Cost" and "Environmental Impact" (because the original Figure 2 of Kicherer et al.[31] does so), so it is not *a priori* clear if the drawing contains the "normalized" metrics (NF_C and EI), the "preliminary" metrics (PP_C and PP_E), or the "improved" metrics (PP'_C and PP'_E). On the basis of the authors' conclusion that the two products have an equal preference, we conclude that the graph is primarily intended to indicate the "improved" positions, PP'_C and PP'_E, although it, probably for illustrative purposes, also contains the "preliminary" positions, PP_C and PP_E. The "normalized" positions are not visualized by these authors.

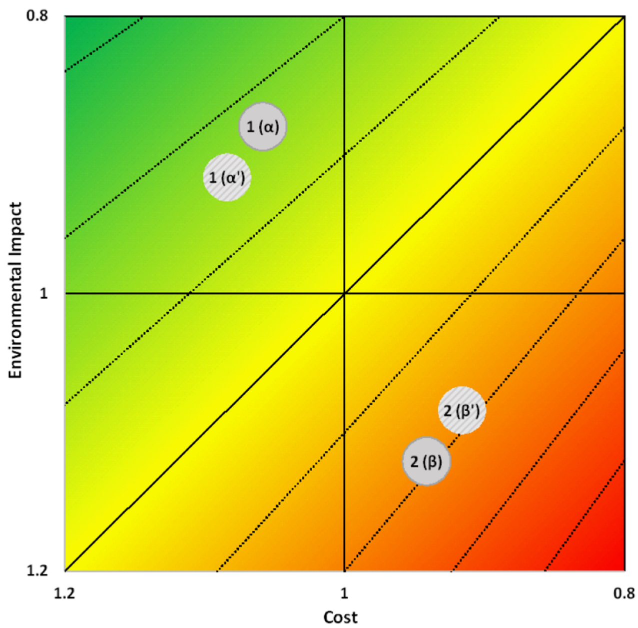

Figure 2. Same EE portfolio plot as in Figure 1, but now with the colors and lines redrawn to reflect the definition of EE as environmental impact divided by cost. The lines correspond, from top to bottom, to slope values of 0.7, 0.8, 0.9, 1.0 (the solid line), 1.1, 1.2, 1.3, and 1.4. The lines are not parallel; they converge in (0, 0). The angle (φ) of the lines decreases with increasing slope, according to $\varphi = \arctan(1/EE')$, where EE′ is the ratio-based eco-efficiency. Mind that the impact axis is vertical, whereas a slope as value/impact would assume a horizontal impact axis.

CRITICAL ANALYSIS OF BASF'S ECO-EFFICIENCY ANALYSIS

In this section, we will critically examine the procedure, with a focus on the EE concept used.

A first observation is that although the procedure seems to rely on the "distance from the diagonal line", no formula for this

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distance is provided and no values of the actual distances in the example are given. In Appendix 2 of the Supporting Information, we give a more precise interpretation of this distance.

A second observation is that, despite the reference to EE as "the ratio of environmental impact per monetary unit earned", Kicherer et al.[31] do not provide an explicit calculation of EE. The determination of the optimal products seems to have been made by graphical inspection: the closer a point is to the right upper corner, the higher its eco-efficiency. This has grown into the usual practice, as demonstrated by Zhang et al.,[44] who report that "there are two methods to express eco-efficiency: via a numeric value and a two-dimensional diagram, and the last one is the most frequently used method". Indeed, these authors give a formula for EE, but they do not use it to calculate EE values.

A third issue is that our speculation on the definition of the EE value in Appendix 2 can be confronted with Kicherer et al.'s (ref 31) phrase that EE is the "ratio of environmental impact per monetary unit earned". This statement is again not fully clear because both environmental and monetary variables show up in three forms: "normalized", "preliminary", and "improved". Here, we will assume that the "improved" coordinates are intended to define EE. That form has a simple geometric interpretation in Figure 1: It indicates the slope of the line passing through the point defined by product α and the point (0, 0). A product at (1, 1) would have a slope, and therefore an EE value of 1, and so would a product at (2, 2). A product in the left upper corner has a smaller slope, and therefore a higher EE value, and a product in the right lower corner has a larger slope, and therefore a smaller EE value. Consequently, this definition of EE would change Figure 1 into Figure 2. Clearly, product 2 has a lower ratio-based eco-efficiency than product 1.

This observation raises a serious issue. The statement that EE is the ratio of environmental impact to cost and the statement that the upper right corner corresponds to the highest EE are incompatible. Either EE is highest in the upper right corner, in which case it is not impact divided by cost, or it is impact divided by cost, in which case it is highest in the upper left corner. The choice between the two principles of EE determines if products 1 and 2 have the same eco-efficiency value or if product 2 surpasses product 1.

Next, we analyze the statements that EE is a ratio in more detail. As discussed, to Kicherer et al.[31] it is "the ratio of environmental impact per monetary unit earned", which is

$$\mathrm{EE}'_{\alpha} = \frac{\mathrm{PP}'_{\mathrm{E},\alpha}}{\mathrm{PP}'_{\mathrm{C},\alpha}} \tag{11}$$

But to Saling et al.,[15] which we consider to be their precursor, it is "the ratio of economic creation to ecological destruction", which is in our notation

$$\mathrm{EE}'_{\alpha} = \frac{\mathrm{PP}'_{\mathrm{C},\alpha}}{\mathrm{PP}'_{\mathrm{E},\alpha}} \tag{12}$$

As mentioned in the Introduction, the choice between what is the numerator and what is the denominator of the EE ratio depends on the purpose of the analysis. Obtaining the most valuable product with the least impact requires maximizing $\frac{\mathrm{PP}'_{\mathrm{C},\alpha}}{\mathrm{PP}'_{\mathrm{E},\alpha}}$. But achieving the highest environmental improvement with the least cost requires maximizing $\frac{\mathrm{PP}'_{\mathrm{E},\alpha}}{\mathrm{PP}'_{\mathrm{C},\alpha}}$. Given the opposing views of Saling et al.[15] and Kicherer et al.,[31] it is worthwhile to investigate this more in-depth. Saling et al.[15] explicitly mention the customer as pivotal: "The concrete (final) customer benefit is at the heart of the analysis" and the analysis is focused on the "calculation of total cost from (final) customer viewpoint". As discussed in the Introduction, the customer point of view would call for a minimization of cost and a minimization of environmental impact, and a ratio between the two will not do the job. A sum, possibly with weights, is an appropriate method in such decision situations. Kicherer et al.[31] are less consistent about their target. On the one hand, they also mention cost, not sales or value. On the other hand, they speak about "the ratio of environmental impact per monetary unit earned", suggesting they take a producer perspective.

In this respect, a later contribution by Saling[47] is of interest. Its Figure 4.2 shows a portfolio plot with the "reduction of environmental impact" horizontally and the "improvement of product functions vertically". Remarkably, it argues that "the lower [the reduction of environmental impact] is, the better the product is due to its environmental impacts". We can dismiss this as a typo, taking "environmental impact" for the horizontal variable, leaving out the word "reduction". But even more remarkable is that the figure contains a symbol X that indicates the angle of the line connecting (0, 0) and the point defined by the product. The text then adds that "tan X expresses the eco-efficiency". This clearly points to a ratio-based definition (see Figure 2), and it contradicts the sum-based definition in terms of the "perpendicular distance above the diagonal line in the direction of the upper right-hand quadrant", which is featured at another page of the same source.

■ ECO-EFFICIENCY AS A WEIGHTED SUM

We observed that the EE portfolio method uses the distance to the diagonal line to measure EE. The distance to the diagonal line, as derived in Appendix 2 of the Supporting Information, is equal to

$$\mathrm{EE}'_{\alpha} = \sqrt{2} - \frac{1}{2}\sqrt{2}\,(\mathrm{PP}'_{\mathrm{C},\alpha} + \mathrm{PP}'_{\mathrm{E},\alpha}) \tag{13}$$

Apart from a constant $(\sqrt{2})$ and a factor $\left(\frac{1}{2}\sqrt{2}\right)$, the EE indicator is basically the sum of the ("improved") cost and the ("improved") environmental impact. In other words, BASF's eco-efficiency principle is based on a sum of cost and environmental impact, even though the method is described to be ratio-based. As mentioned in the Introduction, a sum indicator may be more appropriate than a ratio-based method, depending on the goal of the analysis. The reader should therefore not *a priori* consider our result as a sign of disapproval. But the fact remains remarkable that a method that claims to be ratio-based turns out to be sum-based. As far as we know, the observation that BASF's eco-efficiency is sum-based rather than ratio-based has not been made before. Instead, many articles cite the ratio definition and then uncritically use the sum-based portfolio plot. We speculate that the discrepancy has remained unnoticed because the portfolio method relies on a graphical interpretation, without the actual calculation of EE values. If EE values had been calculated, the analysts would probably have noted the inconsistency.

Once the implicit EE indicator has been recognized as a sum, the follow-up question is how cost and environmental are weighted, if at all. The term $\mathrm{PP}'_{\mathrm{C},\alpha} + \mathrm{PP}'_{\mathrm{E},\alpha}$, deduced from the diagonal lines with slope −1, shows that the cost and environmental impact receive equal weight when expressed in "improved" coordinates. It is interesting to find out what that

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implies for the "normalized" coordinates. The analysis of Appendix 3 in the Supporting Information shows that the implicit weighting in the sum-based EE portfolio amounts to an environment-to-economy weighting, in "normalized" units, which is exactly 1. In other words, it uses just $NF_{C,\alpha} + EI_{\alpha}$, without any weighting. This is a remarkable conclusion, which deserves a closer study.

According to Kicherer et al.,[31] the variable $NF_{C,\alpha}$ expresses (life cycle) cost of product α divided by the GDP per capita of the country. As such, its dimension is persons ("Inh"). In a similar style, EI_{α} is the environmental impact of product α, also expressed relative to the country's total, per capita, so also in persons. An equal weighting of $NF_{C,\alpha}$ and EI_{α} amounts to calculating a total score as $NF_{C,\alpha} + EI_{\alpha}$ for each product α. This equal weighting means that a relative deviation from the per capita environmental impact is equivalent to an equally sized relative deviation from the per capita cost. Being 5% better on economy than the country's average is exactly the same as being 5% better than the country's average on environment.

A natural question is if this equal weight is on purpose, or if it is a mere artifact of a mathematical procedure. The descriptions by the originators are ambiguous about a weighting between economy and environment. Saling et al.[15] write about "the assumption that ecology and economics have the same importance in a sustainability assessment", and Shonnard et al.[40] use a similar phrasing ("ecology and economy are equally important"). This suggests that the weights are equal on purpose. However, these two texts also state that the method contains "weighting factors that are related to the relative importance of economic versus environmental effects in a particular study", that there is "a final weighting step...that takes into account whether the environmental or cost impacts are more influential", and that a "determination of relative importance of ecology versus economy" is one of the steps in EE analysis. Saling[47] also notes that "the eco-efficiency method includes a weighting of environmental impacts and costs". He refers to Kicherer et al.[31] for the description of this "final weighting step...which takes into consideration whether the environmental or cost impacts was more influential". Remarkably, Kicherer et al.,[31] which is by far the most explicit text about the portfolio method, does not discuss such a weighting. Summing up, several of these texts state that there is a weighting of economy and environment and some texts refer to this as an equal weighting. That would be compatible with the term $PP'_{C,\alpha} + PP'_{E,\alpha}$ and/or $NF_{C,\alpha} + EI_{\alpha}$, but it would be incompatible with the claim that eco-efficiency is a ratio of the two terms, and as such the issue of weighting is enigmatic.

As mentioned, Kicherer et al.[31] do not calculate eco-efficiency ratios of the products in the portfolio. However, they do calculate a ratio: an "environment to cost relation for a complete project", indicated by $R_{E,C}$. It is indeed a ratio of environmental impact/cost, but not for individual products in the portfolio; instead, it applies to the average product in the portfolio:

$$R_{E,C} = \frac{\overline{EI}}{\overline{NF_C}} \quad (14)$$

In the example, $R_{E,C} = 0.48$, which is also a dimensionless number, because both the cost and the environmental impact are expressed in the same unit ("Inh"). Despite its interpretation in terms of "costs are more important than the environmental impact by about a factor 2", its role is not very clear. Its main function is to change the "preliminary" positions into "improved" positions, but why the "preliminary" positions apparently need to be "improved" into "corrected figures" is not clear. Also, the argument of being "based on the geometric theorem of Pythagoras and on the cathetus theorem" is not clear. [The "geometric theorem of Pythagoras" is the well-known relation $a^2 + b^2 = c^2$ between the hypotenuse (c) and the two other sides (a and b) of a right triangle, which are sometimes referred to as the two catheti. The "cathetus theorem" is less known. It states that the two right triangles with sides a, h, q and b, h, p, which are formed by creating a line of length h from the right angle perpendicular to the hypotenuse, splitting c into p and q, satisfy the relations $cp = b^2$ and $cq = a^2$.[48] The description by Kicherer et al.[31] mentions that these two theorems form the basis of the step from "preliminary" to "improved" positions, but no further explanation or proof is given.] The text states that this would provide "a balance between environmental impacts and costs", but the actual idea behind this balance is not explained or motivated. In the last, concluding section of the work, a scenario analysis is performed to analyze "the influence of $R_{E,C}$ on the result in the portfolio presentation". This is an intriguing formulation as it suggests that $R_{E,C}$ is set by the analyst. That impression is false: $R_{E,C}$ is the result of the portfolio values, so the sentence basically says that we seek to analyze the influence of the portfolio values on the portfolio presentation.

The final part of Kicherer et al.[31] contains two example projects that are supposed to shed more light on the role of $R_{E,C}$. In one project "the environmental impact is more important ($R_{E,C} = 2$)", whereas in the other project "the costs are much more relevant there than is the environmental impact ($R_{E,C} = 0.5$)". Apparently, $R_{E,C}$ is an indicator of the importance of environment vis-à-vis cost. The question of whether the cost is more important than the environmental impact or vice versa seems to be answered by the composition of the project, not by external preferences on how important the environment is intrinsically. And because the project portfolio may comprise irrelevant alternatives, the earlier critique[45] is of interest, also with respect to this environment-to-cost relation $R_{E,C}$. Kicherer et al.[31] announce in their abstract "a statistical evaluation of the $R_{E,C}$ factor based on the results of different eco-efficiency analyses", and their introduction adds that they have "used this method for over 300 projects, thus allowing a statistic evaluation of the practical relevance of normalized environmental impacts to costs". The main text, however, does not offer such statistics.

It is interesting that not only the weighting of the "normalized" values ($NF_{C,\alpha}$ vis-à-vis EI_{α}) is equal but also the weighting of the "improved" values ($PP'_{C,\alpha}$ vis-à-vis $PP'_{E,\alpha}$) is equal. This would suggest that if we take the data in "normalized" units and add up the two variables, a consistent EE ranking would emerge. Indeed, if we compute $NF_{C,\alpha} + EI_{\alpha}$ for the example data, we find exactly the same values for products 1 and 2, affirming their equal scores in "improved" coordinates. We prove this point more formally in Appendix 3 in the Supporting Information. It is therefore a big question why the whole exercise is undertaken at all: calculating "preliminary" positions, next calculating "improved" positions, and finally calculating distances from the diagonal line, if we can base exactly the same decision on just a simple addition of the "normalized" numbers.

Likewise, it remains a mystery that Kicherer et al.[31] emphasize the "environment to cost relation" $R_{E,C}$, but that this variable plays no role in the ranking or products. It influences the "preliminary" positions, but it drops out of the final metric,

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which is based on the distance of the "improved" points to the diagonal line.

RECENT DEVELOPMENTS

Our analysis of the portfolio analysis was mainly based on Kicherer et al.,[31] with supporting information.[15,40] These sources are 15−20 years old, and it is therefore of interest to study to what extent more information or updates have become available. We analyzed the following sources:

- two articles in peer-reviewed journals,[39,46]
- a book[38] and a book chapter[47],
- two documents on the Internet[49,50], and
- two websites.[51,52]

These sources give a mixed impression. Grosse-Sommer et al.[39] mention that the method "was fundamentally overhauled in 2014", adding a reference to a hyperlink that does not work, but which is perhaps similar to a document by BASF.[49] [It cannot be the same document. The hyperlink given by Grosse-Sommer et al.[39] was "accessed 21 March 2015", whereas the document[49] is dated January 2016.] This report contains several new elements:

- "the eco-efficiency is inversely proportional to the distance from the alternative to the origin (0, 0)";
- "the eco-efficiency plot always includes the point (0, 0)";
- the mentioning of an "eco-efficiency index [which] shows these distances for all alternatives";
- "alternatives...located closer to the lower left corner" are not "an indication of low eco-efficiency";
- the presence of eco-efficiency portfolio plots with axes expressed in "person years".

These new elements are not explained or referenced; instead, only references to the older articles[15,40] are provided. Particularly interesting to us is the "eco-efficiency index" that is even visualized in Figure 6 of the BASF reports,[49,50] but is not defined in an operational sense. We can only speculate that this eco-efficiency index is equal to d'.

CONCLUSION

The eco-efficiency analysis and portfolio plot, proposed by a team of authors from BASF,[15,31,40] have been analyzed in detail, and a number of unexpected conclusions could be drawn: (1) Although the authors explicitly define EE as the ratio between an economic and environmental variable (or the other way around), they effectively use a weighted sum of the economic and environmental variables to operationalize EE. (2) The weighting factor in this weighted sum is not defined by experts or other external information like policy targets, but it is 1. (3) No EE values for individual products are calculated or reported. (4) The actual determination of the ranking of products, in a complicated multistep procedure (from "normalized" to "preliminary", from "preliminary" to "improved", and from "improved" to distance) can entirely be replaced by an unweighted sum of the "normalized" variable cost and environmental impact. (5) The "environment to cost relation" ($R_{E,C}$), although calculated for the project and receiving emphasis in their discussion, plays no role in the analysis nor in its results.

These conclusions raise serious concerns on the validity of the approach. These concerns are strengthened by the lack of scientific justification. The "preliminary" coordinates are "corrected" into "improved" coordinates, but what actually needs to be "corrected" or "improved" is not explained. An appeal is made to two mathematical theorems (the Pythagorean Theorem and the cathetus theorem), but why and how these theorems are used is not described. Altogether, the scientific validity of the approach is doubtful.

On the one hand, there is ample evidence of a mainstream acceptance: (1) The method has been described in peer-reviewed journals.[15,31,40] (2) These descriptions have been cited several hundreds of times by other peer-reviewed articles, with only very few critical notes.[27,45] (3) Hundreds of articles have appeared in peer-reviewed journals in which independent authors have applied the approach. (4) The method was "validated"[51] and "approved"[47] by authoritative bodies, such as the Rhineland Technical Surveillance Association (TÜV Rheinland) and the U.S. National Sanitation Foundation (NSF, Protocol P352). (5) The method has been used by BASF as well as other companies to assess hundreds of products.[39] (6) The method is based[51] on the ISO 14045 standard.[17]

On the other hand, our analysis leaves little room for another conclusion. Unless, of course, there is a gross misunderstanding. We have identified quite a few unclear, unjustified, and inconsistent parts in the text by Kicherer et al.,[31] and it may still be the case that the method is valid, but only partially reported, with a number of typos and/or ambiguous phrasings. We would obviously welcome a more complete and more coherent description of the approach. [In an attempt to better understand the procedure, we followed Saling's (ref 38) suggestion to check the "Eco-Efficiency Analysis Manager Online" website.[52] This website is password-protected, and there is no option to create an account. The author has contacted the email address on this website (on 19 January 2022), but no answer was received.]

Eco-efficiency and the portfolio analysis have been extended to the social domain. Proposals have been made[53,54] to introduce a socio-efficiency portfolio for cost and social impact, next to the eco-efficiency portfolio for cost and environmental impact. No details or formulas are given, so it is not possible to assess the degree to which the socio-efficiency analysis suffers from similar problems as the eco-efficiency analysis. But the socio-efficiency portfolio in Figure 15 of Kölsch et al.[54] bears a large similarity to the eco-efficiency portfolio, so we expect that the details work out in the same way. The merging of the two portfolio plots in a SEEbalance through a three-dimensional SEEcube is, however, more open to speculation. The distance to a line in a square is to be replaced by the "distance from the central plane"; now points with an equal distance "have the same socio-eco-efficiency". This suggests, once more, a sum-based indicator, for instance,

$$\text{SEE} = \text{cost} + \text{environmental impact} + \text{social impact} \tag{15}$$

This suggestion seems to be confirmed by the statement that "the results of the ecological and societal fingerprint are multiplied with their weighting factors to obtain a total impact",[54] even though there is no explicit mentioning of a sum. A single ratio-based indicator would not be possible in three-dimensional space. Equation 15 is clearly in need of a more detailed analysis, especially because the social indicator is not presented in a detailed mathematical form in any of the papers of which we are aware.

As a final note, it is worthwhile to come back to the question of whether a ratio-based indicator or a sum-based indicator is the most appropriate. As argued in the Introduction, this depends

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on the perspective: For whom is the analysis done? A manufacturer wants valuable products and little impact, and as such a ratio-based indicator seems useful. A customer, by contrast, wants to minimize cost and impact and that requires a sum-based indicator. The fact that a manufacturer (BASF) would put "customer benefit...at the heart of the analysis" is an interesting reversal of roles in that respect. As stated in the Introduction, a ratio-based indicator can do without weighting, whereas a sum-based indicator needs one. We refer to Huguet Ferran et al.[27] for a comparative discussion, including the option of keeping the two variables separate in a Pareto style.

Our critical analysis of the BASF eco-efficiency method may in follow-up work be used in a more constructive way to design an improved method that is in agreement with *a priori* stated principles and that is also robust for the introduction or deletion of irrelevant alternatives. In the end, the sum-based approach by Kicherer et al.[31] may be, to some extent, appropriate, in the end, for the customer. The big caveat is the weighting, which should be explicit and made by relevant parties. Right now, it is based on the portfolio composition.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.2c01073.

Appendix 1 presents the transformation of the NF_C values into PP'_Cvalues and the similar procedure for transforming EI into PP'_E; Appendix 2 discusses the concept of the distance to the diagonal lines; Appendix 3 contains the derivation of the implicit weight between the "normalized" variables NF_C and EI (PDF)

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Notes

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