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Analysis

Critical Analysis of Methods for Integrating Economic and Environmental Indicators

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ABSTRACT

The application of environmental strategies requires scoring and evaluation methods that provide an integrated vision of the economic and environmental performance of systems. The vector optimisation, ratio and weighted addition of indicators are the three most prevalent techniques for addressing this need.

The vector optimisation evaluates the original indicators independently in a dominance check. No real integration is performed, as the method seeks the optimisation of both indicators at once. This technique reveals win-win situations and can also identify, but not solve, the trade-off situations involved in economy versus ecology.

The ratio method establishes a relation among the original indicators. This concept is suitable when one dimension has to be optimised against the other. A number of conceptual problems in the definition of the sense of direction of the ratio method make its interpretation ambiguous.

The weighted-addition provides a fair evaluation of the integrated performance of a system, with regard to the decision-maker's preference for ecology and economy. This is crucial to reconcile trade-offs between conflicting criteria. Special attention must be paid to the selection and definition of weighting factors, being a source of potential inconsistencies.

1. Introduction

Throughout the last half century, global population and economic growth have contributed to the progression and expansion of environmental problems. In response, environmental management became a topic of concern for individuals, businesses and governments. Management strategies evolved to embrace an integrated vision that advocates for merging economic growth with social and environmental problems through institutional change (Colby, 1991). In this context, the link between economic and environmental gain is seen as necessary in order to facilitate the ecological advantage (Boons, 2009).

Eco-development strategies and, among them, eco-efficiency (Colby, 1991) adopted this perspective, which applies tools and methods to practice. A number of scoring and evaluation methods allow for an integrated assessment of systems, which enables decision-making processes and supports production and consumption choices. The integrated vision requires the methods to face and solve the trade-offs that are present between economic and environmental costs and gains, which certainly complicate the decision-making processes.

In the scientific and business domains, there is poor alignment and not much consensus when it comes to integrating economic and environmental indicators. Large variability in integration methods is found due to three main differences:

- Firstly, there is no agreement about the selection of the indicators to represent ecology and economy. For instance, with respect to the environmental dimension, some authors focus on climate change impacts, while others calculate a loss of species diversity.
- Secondly, the indicators are differently prepared for integration. Different authors use different references within the measurement scale, defining absolute or relative indicators (e.g., Dyer, 2005); and some methods require normalisation whereas some others don't (e.g., Figueira et al., 2013).
- Finally, the combination rule that is used to achieve the actual integration of the indicators differs. Some authors (e.g., Lippiatt, 2007) use a weighted aggregation, others divide the two separate indicators (e.g., Huppes and Ishikawa, 2005b), and there exist even

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more complicated aggregation formulas (e.g., Böhringer and Jochem, 2007).

This article reviews and analyses the methods that combine indicators of economic and environmental performances of systems. The scope of the study strictly focuses on the integration techniques, rather than on the selection and preparation of indicators. The main purpose is to explore from a theoretical perspective the attempts that have been made to combine economic and environmental indicators, and to draw conclusions about the strong and weak points of such approaches in relation to the realm of applicability.

The research builds on existing literature in the identification and selection of methods for review and the relevant criteria to assess them. A theoretical study of the selected methods, which analyses their basic characteristics and the common operations that influence them, is performed. This is supported with reflections and observations found in academic literature. A qualitative assessment draws together the descriptions of the techniques, the relevant criteria for assessing their performance and the theoretical analysis. Conclusions and recommendations are subsequently derived for the appropriate use of the methods.

The article is structured as follows. Section 2 provides an overview of current methods that integrate environmental and economic indicators and Section 3 explores the consequences of common operations applied to the indicators. The results of the review are discussed in Section 4, therefore presenting a complete assessment of the techniques regarding the different criteria that define their performance. Finally, Section 5 offers conclusions and recommendations for the successful implementation of the analysed methods.

2. Description of the Three Methods

This section introduces the most widely-used methods that integrate economic and environmental indicators, as present in the literature. We have organized the approaches into three groups (references are postponed to the sections in which we discuss the three approaches in detail):

- Methods that do not calculate a composite indicator value from the economic and environmental indicators, but that nevertheless integrate the two aspects. This is primarily a graphic-based method, but it also includes methods that are based on Pareto efficiency. These methods will hereafter be referred to as vector optimisation.
- Methods that calculate a composite indicator value by dividing the value of the economic indicator by that of the environmental indicator, or the other way around. Many eco-efficiency indicators are based on this approach. In this article, we refer to them as ratio methods.
- Methods that calculate a composite indicator value by adding the values of the economic and the environmental indicators, possibly after a weighting step. Some multi-criteria methods (MCDM) are based on such a weighted-addition method.

In addition to the three groups mentioned, one sometimes sees methods that take a different approach, although most-often in a slightly different context (e.g., within the environmental domain). For instance, the Life Planet Index consists of a geometric mean of biodiversity indexes for terrestric, freshwater and seawater ecosystems (Böhringer and Jochem, 2007). Within the multi-criteria decision-making field, many methods are available that can also be used to integrate the economic and environmental dimensions (Cinelli et al., 2014 and Diaz-Balteiro et al., 2016). Among them, the TOPSIS method uses weighted Euclidean distances to rank alternatives (Lu et al., 2007). The review of the literature shows a limited use of these and other methods to integrate economic and environmental indicators and therefore, they are excluded from the scope of this study.

2.1. Original Indicators

In presenting our findings, we must first harmonize terminology and notation. In order to keep a consistent criterion throughout this article, a negative sense of direction is defined for the original indicators, standing for economic cost and environmental impact. A high indicator means a high cost or environmental impact, and therefore the optimal alternative has the lowest score. We refer to this as a *lower is better* criterion. The analysis, results and conclusions are trivially rephrased for other conventions.

Mathematical notation is as follows. The economic indicator is written as M and the environmental indicator as E. For a specific system (e.g., product, country, company), an index i is added; thus M_i refers to the economic impact of system i. In a practical situation, a decision-maker is confronted with a set of alternatives ($i = 1, \ldots, n$) where each alternative can be indicated by coordinates (M_i, E_i). Our analysis below will focus on trying to rank the alternatives in order of preference. Thus, binary operators ($\succ$, $\prec$, $\succcurlyeq$, $\preccurlyeq$ and $\sim$; see Binmore, 1992 and Mas-Colell et al., 1995) will indicate the relation between two alternatives. For example $(M_1, E_1) \succ (M_2, E_2)$ (or alternatively: $1 \succ 2$) indicates that alternative 1 is preferred to alternative 2, and $1 \sim 2$ that there is an indifference relation between the two. Observe that $1 \succ 2$ does not necessarily mean that $M_1 < M_2$ and that $E_1 < E_2$, but rather that $\pi(M_1, E_1) > \pi(M_2, E_2)$ (or alternatively: $\pi_1 > \pi_2$), where π represents a preference function or variable. Notice that the negative sense of direction discussed above implies that preference (so $\succ$) corresponds to smaller than (so $<$).

As stated in Section 1, the preparation of indicators prior to integration is outside the scope of this research. Nevertheless, it is necessary to briefly discuss the different forms that an indicator can present, because this may have a relevant influence on the performance of the integration method.

Before integration, the indicators may be subject to a normalisation process, aiming at contextualising and better understanding the magnitude of the result and/or removing the influence of an arbitrary choice of measurement units (Pollesch and Dale, 2016). Several normalisation procedures are applied. Within this article, we refer to the quotient of the indicator value by a normalisation reference, as in Eqs. (1) and (2).

$$M_i' = \frac{M_i}{M_{ref}} \tag{1}$$

$$E_i' = \frac{E_i}{E_{ref}} \tag{2}$$

where M_{ref} and E_{ref} can be external references such as the total value of the indicator for a given geographic area and time period. Alternatively, internal normalisation is used when the decision-maker is confronted with a set of alternatives, and uses the values of (part of) it to derive a baseline scenario, which is used as normalisation factor. Examples of internal normalisation factors are the value of the indicator for one of the alternatives (e.g. best or worst performing) or the average value of the alternative in the set, as in Eq. (3).

$$M_{ref} = \max_{i=1}^{n} M_i \tag{3}$$

The original indicators are sometimes contextualised by making them relative to a baseline (e.g. one of the alternatives in the alternative set). Accordingly, we distinguish between absolute (original) and relative indicators.

A graphic representation is usually adopted and is generally regarded as a useful means to visualise the integration of economic and environmental indicators. In this article, we will concentrate on using a two-dimensional graph, where the axes denote the environmental and economic indicator. We consistently present the economic indicator on the abscissa and the environmental one on the ordinate. In the sections below, a common data set is used to illustrate the graphic

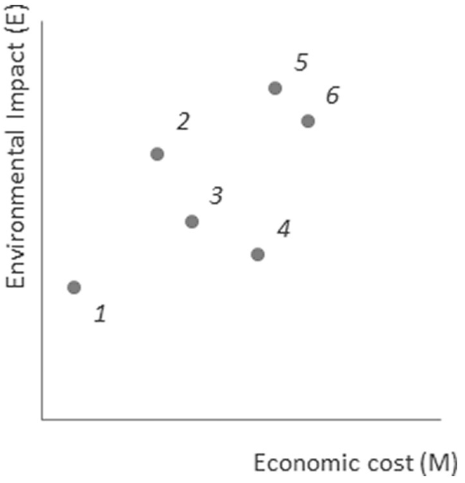

Fig. 1. Graphic representation of the example data set in a two dimensional diagram. The coordinates of the alternatives ($i = 1,2,\ldots,6$) are defined by the values of the economic ($M_1, M_2, \ldots, M_6$) and environmental indicator ($E_1, E_2, \ldots, E_6$).Alternative i is therefore plotted as a point with coordinates (M_i, E_i).

representation of all methods. The alternatives of the data set are represented by points, having their environmental and economic performance as coordinates. According to these conventions, the example data set is presented in Fig. 1.

2.2. Method I: Vector Optimisation

The vector optimisation is a multi-objective optimisation approach that implies the independent treatment of the different objectives (Marler and Arora, 2004). Within this article, it refers to the independent optimisation of an environmental and economic indicator to identify Pareto-optimal solutions. Although there is no genuine aggregation of indicators, the method still allows for the integrated analysis of systems.

The term vector optimisation refers to a wider range of techniques, but it is here limited to a dominance check of a set of alternatives. A dominant solution is one that improves one objective, either the environmental or economic, without worsening the other (Allacker, 2010). Thus we say that alternative 1 dominates alternative 2 if and only if either $M_1 < M_2$ and $E_1 \le E_2$ or $M_1 \le M_2$ and $E_1 < E_2$. When no solution dominating all others can be identified the method fails to appoint a clear winner, or to provide a clear ranking of alternatives without addressing the economy versus ecology trade-off (Suh et al., 2005; Seip and Wenstøp, 2006). We will write that $1 \sim 2 > 3$ when alternatives 1 and 2 dominate alternative 3, but alternatives 1 and 2 do not dominate each other. The final choice between the non-dominated alternatives has to be made with a method that can support value choices, such as the ratio method (Section 2.3) or the weighted-addition method (Section 2.4). A practical application of such approach (combination of methods) is the design strategy of Mestre and Vogtlander (2013), or the DEA eco-efficiency measure of Kuosmanen and Kortelainen (2005), who use data envelopment analysis combining the ratio method and the weighted-addition.

The vector optimisation is a mainly comparative method, and, as such, is not suitable as a scoring technique. The method evaluates alternatives for their independent performance in relation to both dimensions, allowing for the identification of win-win solutions and trade-off situations (Simões et al., 2013).

When integrating economic and environmental indicators, the graphic representation of the method (see Section 2.1) is commonly used to analyse and illustrate the results. Developed by Vogtländer et al. (2001), this approach is used to evaluate “products, processes and overall systems over the entire life cycle” (Saling et al., 2002). Suh et al. (2005) use this method to assess pollution prevention strategies of small and medium enterprises, while Ostermeyer et al. (2013) use it for the analysis of site-specific building refurbishment solutions.

Both academic and business domains recognise the utility of graphic representations for facilitating communication about the economic and environmental performances of systems (Janssen, 1991; Saling et al., 2002; Shonnard et al., 2003; Suh et al., 2005). The dominance check of a graphic representation is clear, therefore enabling stakeholders to understand and interpret the outcome of a complex situation “at a glance” (Saling et al., 2002). Consequently, and because this method does not require contested choices on weighting economy versus environment, this method has been widely adopted across the business and scientific fields.

In a graphic representation, the relative position of the alternatives, regarding both axes, determines their performance. The dominant alternatives perform better in both dimensions, and they are placed in the bottom-left part of the diagram. This sense of direction is absolute and it is consistently respected in the four quadrants of the space (observing that economic cost may be benefits and environmental impacts may be repairs). Fig. 2a illustrates that alternative 1, at the lowest and most left position, dominates the rest of the alternatives of the example data set.

When there is no dominant solution, as in Fig. 2b (alternative 1 has now been excluded from the set), the Pareto front or optimal curve can be drawn. Alternatives 2, 3 and 4 are superior, because they represent those alternatives for which no alternative is available that is better on both aspects. Alternative 5 and 6 have a higher environmental impact

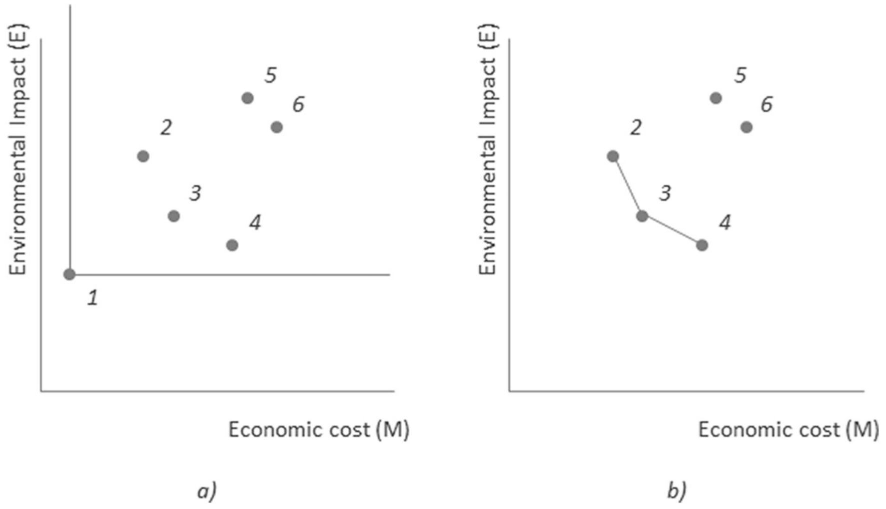

Fig. 2. (a) Dominance in vector optimisation. The dominant alternative (Alternative 1) is at the lowest and most left position of the diagram. (b) Pareto front in vector optimisation. The alternatives in the Pareto front (Alternatives 2, 3 and 4) are not dominated by other alternatives in the set.

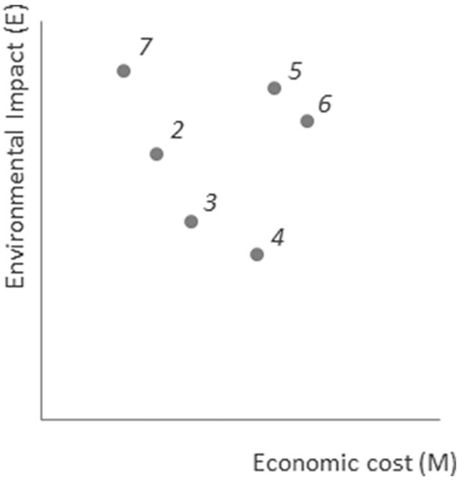

Fig. 3. When a new alternative is added ($M_7 < M_2$ and $E_7 > E_5$), the originally dominating solutions 2, 3 and 4 continue to dominate 5 and 6, even though 7 does not dominate 5 and 6.

and economic cost than 2, 3 and 4. They are therefore dominated. Altogether, alternatives 2, 3 and 4 form the Pareto front, and are preferred over the rest. Their relative rankings, however, cannot be determined without addressing the economy versus ecology trade-off.

To derive a ranking of alternatives that is partial but as complete as possible, the vector optimisation method should be subsequently applied in a step-wise process. The dominant alternatives found in each step have to be excluded from the original set, allowing for the dominance analysis at a lower level. This is done for the example dataset in Fig. 2b, where the dominant alternative for the entire set has been excluded. Accordingly, a partial ranking of alternatives is derived using the vector optimisation method: $1 \succ 2 \sim 3 \sim 4 \succ 5 \sim 6$ because $(M_1, E_1) \succ (M_2, E_2) \sim (M_3, E_3) \sim (M_4, E_4) \succ (M_5, E_5) \sim (M_6, E_6)$.

The addition of a new alternative will not change the dominance relations in an existing set. In the example set, when we add a new alternative, 7, with $M_7 < M_2$ and $E_7 > E_5$, the new Pareto front is defined by the original Pareto front (alternatives 2, 3 and 4) plus alternative 7 (Fig. 3). We can still write $2 \sim 3 \sim 4 \succ 5 \sim 6$, and we can now add $2 \sim 3 \sim 4 \sim 7$ to that. But it is no longer possible to concatenate the two statements into $2 \sim 3 \sim 4 \sim 7 \succ 5 \sim 6$, because $7 \nsucc 5 \sim 6$.

2.3. Method II: The Ratio Method

The generally-accepted definition of eco-efficiency is the ratio between an economic and an environmental indicator, or vice versa (Verfaillie and Bidwell, 2000; UN, 2004; Huppes and Ishikawa, 2005b). Environmental costs-effectiveness or, simply, cost-effectiveness, are alternative terms naming the same approach (Wit et al., 1993; Huppes et al., 2007). Zanou et al. (2003) employ the ratio method to analyse measures for the improvement of watershed quality, and Huppes et al. (2007) use it to prioritise environmental measures in oil and gas exploration activities. Figge and Hahn (2005) compare the value added of a company to the environmental burden to evaluate the sustainability performance of companies, and Wever and Vogtländer (2012) apply it at a product level to assess packaging solutions in the food industry.

Additional examples of the application of the ratio technique in different situations are presented in Koskela and Vehmas (2012). Hur et al. (2004) define green productivity as a singular variation of the ratio method, where the economic dimension is replaced by a productivity ratio. Similarly, Park and Tahara (2008) propose an alternative that substitutes the economic dimension for a ratio showing the quality of a product as per consumer and producer perspectives.

Within this article, we choose to have the environmental indicator in the numerator and the economic indicator in the denominator. Thus we calculate the ratio indicator (R), as in Eq. (4).

$$R_i = E_i / M_i \tag{4}$$

The ratio method is essentially measuring the relationship between criteria to evaluate the productivity, or the optimisation of one dimension against the other. Along these lines, Rüdenauer et al. (2005) recognise the capacity of eco-efficiency for evaluation, priority setting, and optimization purposes. As a scoring method, the ratio technique eliminates all magnitude information, even if absolute figures are used. Thus, the result only shows the relative relationship of both indicators for the different alternatives, while it fails to express the overall performance of the alternatives under study (Kicherer et al., 2007). Indeed, Zanou et al. (2003) propose to use a ratio method when specific targets, either environmental or economic budgets, are set. Moreover, the ratio method by itself does not accommodate trade-off information on how important the environment is vis-à-vis the economy. Using monetised environmental indicators addresses this issue and makes the ratio method a direct indicator of the trade-off.

In literature on eco-efficiency (e.g. Kicherer et al., 2007), the smallest ratio is often supposed to be the most preferable, as the decision-maker aims at minimising the environmental impact per monetary unit spent. However, this interpretation is not obvious and riddled with paradoxes. We discuss two cases of such problems.

The results of a ratio method may not be consistent with the results of the vector optimisation. An alternative presenting the best performances in both dimensions may not be the most preferable choice when the ratio is considered. See, for instance the case of alternative 3 compared to 5 and 6:

$$(M_3, E_3) = (4.5, 6);\ R_3 = 1.33$$

$$(M_5, E_5) = (6, 10);\ R_5 = 1.66$$

$$(M_6, E_6) = (7, 8);\ R_6 = 1.14$$

Although alternative 3 performs better in both environmental and economic indicators, its ratio is not the highest nor the lowest, but it is just the one in between.

Another problem is that the sense of direction of the indicator might not change when the ratio reverses. If we consider the conventions of Section 1, the inverse ratio ($R_i' = M_i / E_i$) represents the monetary costs per unit of environmental impact. In this case, the decision-maker would aim at minimising the costs per unit of environmental impact, leading to a negative sense of direction and a *lower is better* criterion. The sense of direction is therefore the same for the original ratio (R) and its inverse (R'). This proves that the sense of direction does not follow mathematical reasoning, and that it cannot be directly derived from the sense of direction of the original indicators.

These arguments reinforce the idea that the ratio method does not integrate the original indicators, but that it establishes a relation between them. The definition of the sense of direction requires an analysis of the specific decision-making situation to arbitrarily set the performance criterion.

Within the scope of this study, the negative sense of direction and the *lower is better* criterion are valid for any alternative showing positive values (> 0) for both indicators. Nevertheless, if the sign of one of the indicators reverses, the sign and the sense of direction of the ratio changes as well. This situation is more plausible when relative indicators are used. Depending on the chosen reference, the four situations illustrated in Table 1 can arise. This variability is another major barrier for the clear interpretation of the results. Previous studies have observed this problem as well; they proposed to treat them “in a practical way on a case-by-case basis” (Huppes and Ishikawa, 2005b).

Another important interpretation problem arises when the indicator in the denominator (here, the economic indicator) equals zero. For this situation, the ratio cannot be calculated. Again, this is especially relevant when relative indicators are used. However, it might be argued that a ratio of two indicators requires that both indicators are defined

Table 1
Sign and sense of direction of the integrated ratio indicator. The sign and sense of direction of the integrated indicator depends on the sign and sense of direction of the original ones.

	Benefit or cost reduction ($M < 0$)	Cost or cost increase ($M > 0$)
Impact or impact increase ($E > 0$)	Negative values ($R < 0$) *Higher is better*	Positive values ($R > 0$) *Lower is better*
Impact reduction ($E < 0$)	Positive values ($R > 0$) *Higher is better*	Negative values ($R < 0$) *Lower is better*

on a ratio scale (Krantz et al., 1971), thus possessing a “true” zero, which would preclude the use of relative indicators (see Section 3.2).

Summarising, although the ratio method is the practical, non-standardised, common definition for eco-efficiency, and is generally regarded as a good communication means when it comes to expressing the productivity of a system (Verfaillie and Bidwell, 2000), its interpretation is complicated, especially when relative indicators are employed.

The ratio indicator can also be presented in a two-dimensional graph. As illustrated by Park et al. (2006), the graphic representation of the ratio indicator is “proportional to the gradient from the x-axis”. In other words, the ratio determines the slope of the line that connects the reference point, the origin of coordinates, and the evaluated alternatives, as expressed by the tangent of the angle θ_i ($\tan\theta_i = E_i/M_i = R_i$, see Fig. 4). Following the usual assumption in the literature that *lower is better*, the preferred alternatives are those with lower slopes, or angles. Thus, in the diagram, the increasing slope determines the ranking of alternatives for the example data set: $4 \succ 6 \succ 3 \succ 5 \succ 2 \succ 1$ because $R_4 < R_6 < R_3 < R_5 < R_2 < R_1$.

It is critical to recognise that, as focus is placed on the relation between the indicators, the goal is not to have the best performance in both indicators, but rather, to optimise their quotient. Thus, the lowest impact and cost do not define the best alternative and, on the graph, the absolute position (bottom-left) does not indicate the preferred option. In Fig. 2, alterative 1 was the dominant solution; using the ratio method, in contrast, it is the worst alternative because its performance across dimensions, the integrated ratio or the slope of the lines, is the lowest.

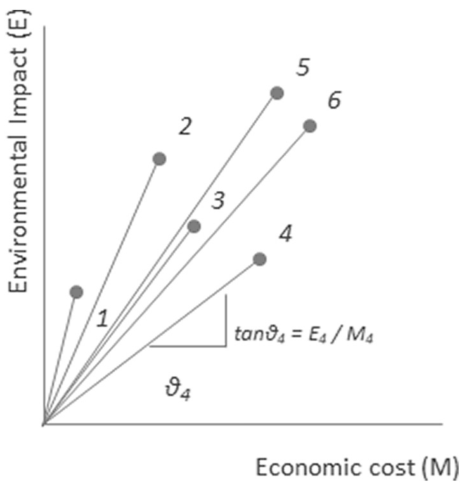

Fig. 4. Graphic representation of the ratio method. The integrated indicator is expressed by the tangent of the angle θ_i ($\tan\theta_i = E_i/M_i = R_i$). The increasing slope of the lines determines the ranking of alternatives.

2.4. Method III: The Weighted-Addition Method

In order to solve the trade-off of economy versus ecology, Lippiatt (2007) integrates the indicators in a weighted addition. This method is applied to select “environmentally-preferred, cost-effective building products”, based on their overall performance and according to the relative importance of both dimensions. Lamond and Gent (1973 cited in Talaq et al., 1994) had already described a weighted-sum method to explore the consequences of a sulphur tax in fuels. More generally, the weighted-addition is recognised as a suitable technique for green public procurement (EC, 2004).

The application of weighting to the environmental dimension allows for the monetisation of the integrated indicator, provided the economic indicator is in money terms. This process can be integrated in the definition of the - monetised - environmental indicator (Vogtländer et al., 2001; Itsubo et al., 2004; Oka et al., 2005) or be implemented later, in an independent weighting stage. For instance, Delson (1974) calculates the implied costs of NOx emissions using a conversion factor or price penalty to translate the emissions into monetary units.

Monetised environmental indicators can be analysed on their own, for instance, as a measure of social expenditures (Itsubo et al., 2004), or be integrated with economic indicators. In Cost Benefit Analysis (CBA), the monetised indicator is directly added or subtracted from the economic one (Delson, 1974; Huo and Saito, 2009). This is, all evaluation criteria are marketed in monetary units to select the most profitable option, from an economic perspective (Allacker, 2010).

In a weighted addition in a linear, fully compensating framework with infinite substitution elasticity, the weighting factors (A and B) express the decision-making preferences of ecology versus economy, as in Eq. (5).

$$S_i = A\cdot E_i + B\cdot M_i \tag{5}$$

S is the composite indicator, which can alternatively, be written as in Eq. (6). Some systems further normalise the weighing factors, for instance, their sum should be 1 (the weighted addition then becomes the arithmetic sum), or they divide by the sum of squares of the weighting factors (Hong et al., 2012). Further, the factor A/B can be interpreted as the monetisation factor for the environmental impact.

$$S'_i = (A/B)\cdot E_i + M_i \tag{6}$$

The value of the integrated indicator depends on the trade-offs between economic and environmental performance of the systems from a normative point of view (Huppes and Ishikawa, 2005a). McAllister (1982) recognises the need to make judgements of relative importance to address trade-offs and assumes that these might be converted into quantitative expressions. More explicitly, Seppälä et al. (2002) identify weighting as the mechanism to reflect these trade-offs. The weighted-addition method aligns with these perspectives, and solves the trade-offs between conflicting criteria by considering the preferences of the decision-makers, expressed by giving weighting factors. This is only valid for cases where the trade-offs are identical in all circumstances – i.e. where the decision-maker has always the same preference. In other cases, the utility function is not linear and cannot be defined with a simple weighted addition. The extension to non-linear utility functions is outside the scope of the present paper, but a good entry is Rowley et al. (2012).

The weighted-addition method is thus a scoring and evaluation technique that analyses the integrated performance of a system according to the preferences of the person(s) or administrative body setting the weights. The resulting score provides information about the magnitude of the indicator and, as an evaluation method, the weighted-addition technique defines an unequivocal and complete ranking of alternatives (it allows to discriminate infinitely more cases than vector optimisation).

In the weighted-addition method, incommensurable units are aggregated. In order to make them comparable and to be added, they must be transformed into common units (or to a common dimensionless scale) (Janssen, 1991; Janssen and Munda, 1999; Seppälä et al., 2002). Likewise, all indicators must have the same sense of direction, which might require them to be reversed (i.e., multiplying with -1) (Dodgson et al., 2000). Normalisation is seen by several authors as the optimal means for solving the incommensurability of units (Norris, 2001; Nardo et al., 2005; Lippiatt, 2007; Lu et al., 2007). Nevertheless we should acknowledge that it does not solve the weighting problem and that there is a seductive danger of considering equal units as a signal to aggregate with equal weights (Prado-Lopez et al., 2014).

Alternatively, the weighting process can also serve to the purpose of equalizing units. For instance, Suh et al. (2005) identify the possibility of making weighted decisions without involving a normalisation step, allowing incommensurate units and conflicting senses of direction to be directly addressed through the process of weighting. Practically, this means that the weighting factors A and B have units that give AE_i and BM_i the same unit. Note that the sense of direction and units of the addition are consistent with those of the original indicators and the weighting factors. The sense of direction is clear and uniform, which facilitates interpretation of the results. Within this article, assuming both weighting factors as positive, the weighted sum stands for the integrated impact of the system. This defines a *lower is better* approach.

Multi-criteria decision analysis is a well-known and established field for decision-making, and is applied in various disciplines in order to solve problems between conflicting criteria. From all methods within the field, the weighted-sum technique is among the simplest and the most commonly used (Park et al., 2006; Diaz-Balteiro et al., 2016). Although it is not the most prevalent option for combining economic and environmental indicators, the method is accepted and applied as the standard technique in life cycle sustainability assessment (LCSA) (Finkbeiner et al., 2010). The technique and its interpretation have no intrinsic difficulty; however, setting the weighting factors is recognised as a difficult process (Janssen, 1991). Several differently complex methods serve this purpose, and determine the acceptability of results.

In a two-dimensional diagram, all the alternatives that have the same weighted and aggregated value form lines with a slope that equals the relative weighting among criteria ($-B/A$), as represented in Fig. 5. The weighted addition of the abscissa and ordinate values is the same for all the points in each line. Since these are the values for the economic and environmental indicators, all the alternatives on the line have the same integrated performance. The lines are called iso-utility lines, since the utility is the function defined by the weighted addition of the indicators.

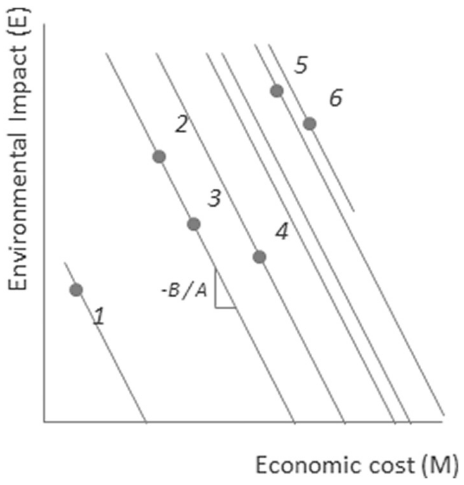

Fig. 5. Graphic representation of the weighted-addition method. Alternatives with the same integrated performance fall in the same iso-utility line. The position of the lines is a measure for the value of the integrated indicator. From left to right it determines the ranking of alternatives.

The position of a line in the graph is an indicator for the aggregated value of all the points that fall on it, and it is therefore used to graphically rank alternatives. The weighted sum of the abscissa and ordinate increases while lines move from left to right, leading to a higher environmental impact according to the defined conventions (Suh et al., 2005). For the example data set and given weighting factors ($A = 1$ and $B = 2$), the full ranking of alternatives is defined: $1 \succ 2 \sim 3 \succ 4 \succ 5 \succ 6$ because $S_1 < S_2 = S_3 < S_4 < S_5 < S_6$.

The dominant alternative that was identified as preferred option according to the vector optimisation method is also the best choice for the weighted-addition method. For any set of weighting factors (as long as they maintain the sense of direction, being both positive), the dominant solutions will have preferable integrated values over the dominated ones. For instance, alternative 3 dominates alternatives 5 and 6, and its integrated impact is therefore always lower than the others (as long as $A > 0$ and $B > 0$). Conversely, for every non-dominated alternative one can always come up with a set of weighting factors ($A > 0$ and $B > 0$) that makes its integrated impact lower and, therefore, the solution preferred over others (cf. Dyckhoff and Allen, 2001).

These relationships make explicit the connection between the independent and the integrated evaluation of indicators. The weighted-addition method expands the boundary of the vector optimisation; as recognised by Suh et al. (2005) and Seip and Wenstøp (2006), considering the trade-offs allows to derive full rankings of alternatives, and therefore, to overcome the limitations of the vector optimisation method.

3. Linear Transformations of Indicators

As mentioned above, there is no common agreement in the selection and preparation of the original indicators for their integration. Although they are explicitly left out of the scope of this research, it is crucial to realise that the integration methods are often sensitive to these processes. This section explores the consequences of linear operations commonly applied to the original indicators (translation and scaling) in order to evaluate the appropriateness of the integration methods.

Translation adds or subtracts a constant to the original indicator. Graphically, translation consists of moving the origin of coordinates to a new baseline. The absolute position of the alternatives in the graph varies, but their relative position remains the same. This is illustrated in Fig. 6b, where the origin of coordinates is translated to alternative 1.

We introduce the following notation: Translation changes E into E' and M into M' according to Eqs. (7) and (8), where E_1 and M_1 are the original indicators for the new reference (alternative 1).

$$E'_i = E_i - E_1 \tag{7}$$

$$M'_i = M_i - M_1 \tag{8}$$

Translation of the original indicators is applied when relative indicators are used, and there is a variation in the reference point. For example, when a systems performance is compared to a baseline situation, and this reference changes.

In other circumstances, translation can be the consequence of a change in units, not only involving a scaling factor but also a change in the origin of the scale. For example, consider the economic costs with or without a subsidy to illustrate this point.

Scaling is modelled as the product of the original indicator and a scaling factor. In its graphical representation, the axis of the diagrams are scaled up or down with a certain factor, changing the absolute position of the alternatives in the plot. In this case, the distances between the alternatives are adjusted according to the scaling factors. Fig. 6c illustrates the scaling operation, using a scaling factor $m = 0, 5$ for the economic dimension and $e = 1$ for the environmental one.

Scaling changes E into E'' and M into M'', proceeding according to

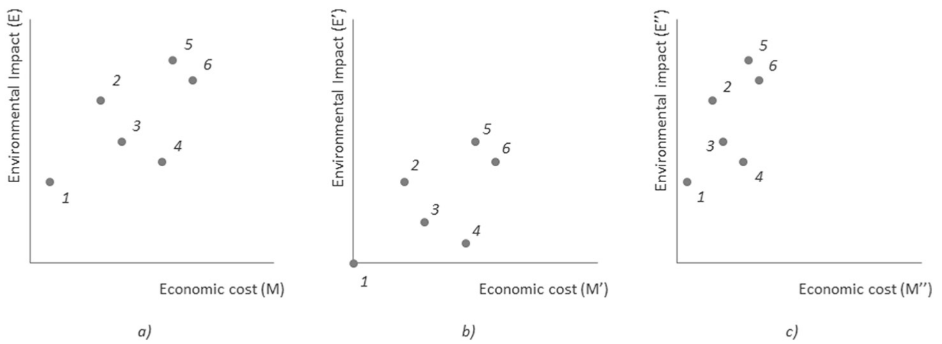

Fig. 6. Graphic representation of translation and scaling operations. (a) Graphic representation of the alternatives. (b) Graphic representation of the alternatives after translation. The position of the alternatives shifts to the new reference point. (c) Graphic representation of the alternatives after scaling. The axes of the diagrams are adjusted to the respective scaling factors.

Eqs. (9) and (10), where *e* and *m* are the linear scaling factors.

$$E''_i = e \cdot E_i \tag{9}$$

$$M''_i = m \cdot M_i \tag{10}$$

Scaling is applied in linear multiplicative changes to the units of the original indicators, as variations from dollar to euro. Scaling is also implemented when the original indicators are normalised before integrating.

Scaling and translation of original indicators cause changes in the integrated results, which might lead to changes in the ranking of alternatives. Nevertheless, the ranking of alternatives should be preserved because the situations mentioned above do not involve real variations in the set of alternatives. For instance, changing the measurement units does not modify the real performance of alternatives, and therefore the preferences should remain the same. The inability to maintain the ranking of alternatives is considered a malfunction of the method, which must be identified and prevented.

The sensitivity to these operations is determined by the nature of the integration method. The sections below explore the potential consequences of scaling and translation of the original indicators.

3.1. Vector Optimisation

For both scaling and translation, the relative position of the alternatives in the graph is maintained. The order in which the alternatives are found, from left to right and from bottom to top remains the same, as it is illustrated in Fig. 7. Therefore, the ranking of alternatives for the vector optimisation is always preserved: $1 \succ 2 \sim 3 \sim 4 \succ 5 \sim 6$.

3.2. Ratio Method

Assuming a *lower is better* interpretation of the ratio indicator, the ranking of alternatives for the original situation in Section 3.2 was found to be $4 \succ 6 \succ 3 \succ 5 \succ 2 \succ 1$ because $R_4 < R_6 < R_3 < R_5 < R_2 < R_1$. Fig. 8b illustrates that translation can cause a variation of the ranking of alternatives in combination with the ratio method. The slope of the lines changes differently per alternative, and the ranking is not preserved: $4 \succ 3 \succ 6 \succ 5 \succ 2$ because $R'_4 < R'_3 < R'_6 < R'_5 < R'_2$. Note that we previously mentioned the possibility of excluding such translations due to the fact that the ratio method requires indicators that are defined on a ratio scale. Scaling, in contrast, causes a proportional variation in all slopes, and the ranking of alternatives remains the same: $4 \succ 6 \succ 3 \succ 5 \succ 2 \succ 1$ because $R''_4 < R''_6 < R''_3 < R''_5 < R''_2 < R''_1$; see Fig. 8c.

3.3. Weighted-Addition Method

For the weighted sum, the original ranking of alternatives in Section 2.4 was found to be $1 \succ 2 \sim 3 \succ 4 \succ 5 \succ 6$ because $S_1 < S_2 = S_3 < S_4 < S_5 < S_6$. In contrast to the ratio method, the weighted-addition preserves the ranking of alternatives against translation. The relative position of the iso-utility lines remains the same, from left to right $1 \succ 2 \sim 3 \succ 4 \succ 5 \succ 6$ because $S_1 < S_2 = S_3 < S_4 < S_5 < S_6$ (Fig. 9b). But scaling units may change the order of the lines, not preserving the ranking of alternatives against scaling: $1 \succ 3 \succ 2 \sim 4 \succ 5 \sim 6$ because $S''_1 < S''_3 < S''_2 = S''_4 < S''_5 = S''_6$ (Fig. 9c). Note that this analysis assumes that the weights remain constant in the translation of scaling process.

4. Discussion

In the previous sections, the three main methods that integrate environmental and economic indicators have been introduced and analysed for their capacity to deal with linear transformations. From these analyses, an overall evaluation of the techniques regarding the most relevant criteria that define their performance is derived. In the following paragraphs, the criteria and the performance of the methods are presented and discussed.

The three methods are fundamentally different. It has been shown that the object of analysis and the results that they provide are not identical. The vector optimisation method aims at the independent evaluation of both indicators, separately, by selecting dominant solutions to identify win-win and trade-off situations. The ratio method

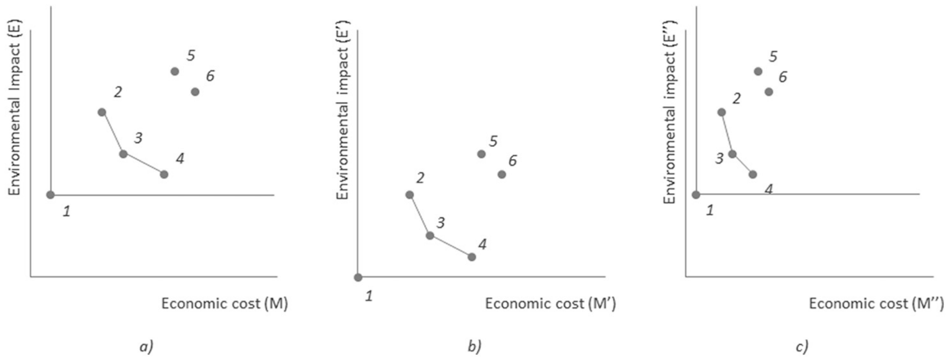

Fig. 7. Evaluation of the vector optimisation when operations are applied to the original indicators. (a) Original ranking of alternatives. (b) The ranking of alternatives is preserved after translation, as the relative position remains the same. (c) The ranking of alternatives is preserved after scaling, as the relative position of alternatives remains the same.

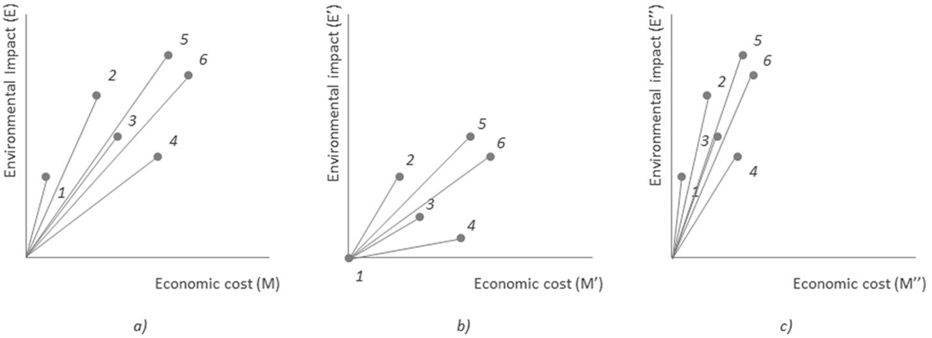

Fig. 8. Evaluation of the ratio method when operations are applied to the original indicators. (a) Original ranking of alternatives. (b) The ranking of alternatives is not preserved after translation, as the slope of the lines changes differently per alternative. (c) The ranking of alternatives is preserved after scaling, as the slope of the lines changes proportionally for all alternatives.

shows the relationship between the two dimensions, economy and ecology. Finally, the weighted-addition method aims to evaluate the genuine integrated performance of a system, according to the preferences of the decision-maker.

Typically, the graphic interpretations of vector optimisation and ratio methodologies are commonly used in the field of eco-efficiency and in integrated analysis of environmental and economic indicators. Nevertheless, the weighted-addition is a trusted method within the field of multi-criteria decision-making, and it is accepted and recommended as an evaluation technique for green public procurement and sustainability analysis in the form of LCSA.

The vector optimisation and the weighted-addition methods are simple and clear to the practitioner, and allow for ease of communication to the stakeholders involved in decision-making. Only the setting of weighting factors can be regarded as a barrier for the understanding and acceptance of the results, as it has proven a difficult issue in several fields (Janssen, 1991). In contrast, the interpretation of the ratio method is not obvious, despite the suggestive texts in the field of eco-efficiency. The definition of the sense of direction cannot be trivially derived from the original indicators, but it requires a detailed analysis of the decision-making situation to arbitrarily set the performance criterion.

As a scoring indicator, the vector optimisation method fails to provide a full picture of a system's performance, not adding any value to the mere listing of original indicators. By contrast, the weighted-sum technique provides an integrated score that shows the total performance of the system. Finally, the ratio method loses the magnitude information, but provides a clear and self-explanatory understanding about the productivity of the analysed system.

The limitations of the dominance analysis restrict the capacity of the vector optimisation method to derive full rankings of alternatives, as only dominant and non-inferior solutions can be identified and ranked as superior, relative to other alternatives. Inconsistencies in the sense of direction when relative indicators are used limit the capacity of unequivocally ranking alternatives in the ratio method. With regard to the weighted-addition method, the ranking of alternatives is always complete and unequivocal, and reflects the overall performance of the system under study.

It is not relevant whether the sense of direction is positive or negative (*higher is better* or *lower is better*) (Huppes and Ishikawa, 2005b), but it must be clear to all stakeholders, and it must be maintained within each approach. Thus, changes in the sense of direction should be avoided. Only the ratio method presents consistency problems to preserve the sense of direction if relative indicators are used (Section 2.3).

As stated in Section 2.4, stakeholders are confronted with multiple and conflicting criteria for measuring and evaluating systems under analysis (Lu et al., 2007). Some scholars argue that good performance relative to either economy or ecology can compensate for poor performance relative to the other (Saling et al., 2002). By contrast, others state that some environmental issues cannot be compensated for economic trade-offs (Janssen, 1991; Lippiatt, 2007). The vector optimisation is a non-compensatory method. Dominance requires better performance in both dimensions, and cannot address compensatory situations, where one dimension performs better, but the other does not. By contrast, the ratio and the weighted-addition methods are compensatory; that is, they assume that the dimensions can compensate for one another. In order to deal with non-compensatory problems, several multi-criteria methods are available, see, e.g. Seppälä et al. (2002), Cinelli et al. (2014) and Domingues et al. (2015). Such methods can also help to establish unique dominance within the Pareto front when we use vector optimisation. These methods are not further discussed in this paper that focuses on the currently prevalent methods.

If the compensatory nature of economic and environmental problems is assumed, then trade-offs between conflicting dimensions arise and have to be addressed by the integration methods. In order to express the trade-offs, relative weights can be estimated and incorporated into the available methods (Dodgson et al., 2000). This feature is already embedded into the weighted-sum method, which explicitly incorporates the weighting factors in order to capture the decision-making preferences. The ratio method and the vector optimisation can accommodate trade-off information only if the environmental indicators are monetised. Nevertheless, they are not sensitive to the scaling of the original indicators, so they are not able to take into account the decision-making preferences by means of weighting factors. The capacity to incorporate weighting factors depends on the sensitivity to scaling operations, making vector optimisation and the ratio method

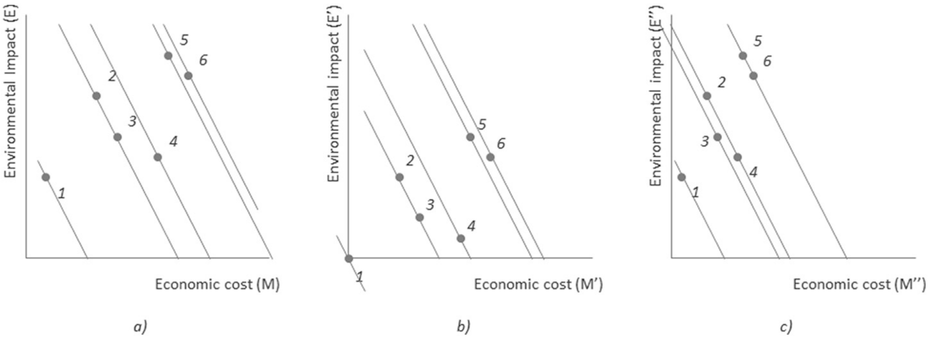

Fig. 9. Evaluation of the weighted-addition method when operations are applied to the original indicators. (a) Original ranking of alternatives. (b) The ranking of alternatives is preserved after translation, as the relative position of the iso-utility lines remains the same. (c) The ranking of alternatives is not preserved after scaling, as the order of the iso-utility lines changes after scaling.

not fitted for this purpose.

In order to be consistent, the evaluation methods should preserve the ranking of alternatives against changes in the alternative set, such as the removal, addition or variation of an alternative (Triantaphyllou, 2000). Many scholars recognise that the independence on irrelevant alternatives is not fulfilled when internal normalisation is performed (Norris, 2001; Nardo et al., 2005; Suh et al., 2005; Dias and Domingues, 2014). After internal normalisation, the values of the original indicators depend on the values of the full set of alternatives. Nevertheless, depending on the integration method, the ranking of alternatives might be still preserved. Normalisation is a scaling process, and therefore the ranking of alternatives is preserved for both vector optimisation and ratio methods. Regarding the weighted-addition method, the normalisation and weighting factors must be congruent, as they are not independent of one another (Norris, 2001). If a weighted sum is performed and internally normalised, the dependency on irrelevant alternatives must be addressed by co-transforming the weighting factors by "taking the case-specific performance of alternatives explicitly into account" (Norris, 2001) (Eisenführ et al., 2010 in Dyckhoff et al., 2015).

As mentioned in Section 3.2, the ratio method fails to preserve the ranking of alternatives when there are changes to the reference point, which is important regarding the use of relative indicators. A change to the baseline reference might cause the ranking of alternatives to be modified, which should be prevented because the real performance of the system remains unaltered. The vector optimisation and the weighted-addition methods, on the other hand, prove consistent and perform adequately when shifts in the reference point are made.

Similarly, the ranking of alternatives should be preserved against changes in units of the original indicators, as the real performance of the system does not change. Changing the units is a scaling process that can also incorporate a translation operation. This is the case of, for instance, the conversion from degrees Celsius to Fahrenheit. The results of the vector optimisation are not sensitive to changes in units, as the ranking of alternatives is preserved against both scaling and translation. The ratio technique is not sensitive, as long as the change of units is limited to linear scaling. When a shift in the origin is added, the method cannot preserve the ranking of alternatives and, thus, inconsistencies may arise. Regarding the weighted-sum method, the weighting factors that express the preferences must co-transform, adjusting to the new units, as they are dependent on them. If this is properly addressed, the method is robust against inconsistencies caused by variation in units and, thus, performs successfully.

The integrated analysis of systems is often not limited to the evaluation and ranking of alternatives, but also includes interpretation of the results. The capacity for decomposition or aggregation is a crucial feature in order to enable further analyses. For instance, integrated scores of products can be directly aggregated to obtain the integrated value of the full portfolio of a company, companies' results can be aggregated to sectors, or sectors to society results. Similarly, the different stages within a product life cycle can be added to obtain a complete picture of it. The other way around, the integrated result can be decomposed in a contribution analysis, which allows for the study of the contribution by sub-systems to the overall performance. The decomposition of the indicator also allows for the analysis of the contribution of the conflicting criteria, economy and ecology, to the integrated result. The weighted-sum method is the only integration method that allows for the direct sum and decomposition of the results, expanding the potential scope of the analysis. The aggregated ratio can be calculated as the weighted average of the ratio steps in the sub-systems (Vogtländer et al., 2001). The contribution of the sub-systems to the total can be decomposed based on the weighted average, but the ratio does not allow for the contribution analysis on the integrated criteria - how economy and ecology contribute to the total score.

New approaches on sustainability assessment go beyond the pure environmental LCA vision and the eco-efficiency frameworks. Along these lines, LCSA consists of an integrated assessment of the three pillars of sustainability (ecological, economic and social dimensions) (Finkbeiner et al., 2010). Another good example of this extended approach is the SEEbalance method, developed by BASF, which adds the social dimension to the already developed eco-efficiency concept (Schmidt et al., 2004; BASF, 2013). In our analysis above, we have studied the integration of two dimensions. In the broadened framework, three dimensions are integrated. Finkbeiner et al. (2010) argue that the three-dimensional problem has to be solved with multi-criteria decision-making. Accordingly, they suggest the weighted-sum method, which allows for the addition of any amount of conflicting criteria to be analysed. If a new criteria, in this case, social performance, is added, new weighting factors must be defined, but the integration method remains essentially the same. The vector optimisation also allows for the integration of a third component. Nevertheless, its direct graphic interpretation is non-trivial and the method is considered to be non-satisfactory. To keep it visual, Schmidt et al. (2004) use the two-dimensional projections of a three-dimensional cube to analyse socio-efficiency and eco-efficiency separately, reducing again the problem of integration to a two-dimensional analysis. Finally, a ratio method only allows for the integration of two criteria into a single indicator. If a third component is to be analysed, new approaches must be developed. Schmidt et al. (2004) use two different ratios to integrate social and environmental aspects with costs, separately.

As a discussion summary, Table 2 presents the overall assessment of the three analysed methods regarding all relevant criteria found in literature.

5. Conclusions and Recommendations

The need to evaluate systems according to their environmental and economic integrated performance is implemented through a number of methods that combine these indicators into a single index or achieve an integration otherwise. Depending on the field of the system being evaluated, different established practices exist. Nonetheless, there is, in the field of sustainability analysis, little analysis about the method to be used and little discussion regarding the most suitable technique for each specific purpose. This article sought to make a significant contribution based on the assessment of the prevalent methods to this immature discussion.

Three main methods are identified as the most widespread techniques to integrate economic and environmental performances of systems: the vector optimisation (mainly using its graphical interpretation), the ratio method, and the weighted addition of the original indicators. These methods aim at different objectives and, therefore, one single technique is insufficient to fit all purposes. In selecting the best technique to perform an integrated analysis, the specific objective of each method is the main criteria to take into consideration.

The vector optimisation method evaluates the original indicators independently in a dominance check. Thus, it aims at the maximisation or minimisation of both indicators separately, depending on their original definition. No real integration of the two dimensions is performed, and the method aims at finding an optimal solution for both criteria at the same time. The vector optimisation can also identify, but not solve, the trade-off situations involved in economy versus ecology.

The ratio method establishes a relationship between ecology and economy, which is a measure of the productivity of the particular system under study. The ratio focuses on the optimisation of one dimension against the other. When the maximisation or minimisation of one dimension is desired, the ratio allows for selecting the best option according to the optimal use of the other. In other circumstances, if the decision-making situation is limited by budget constraints or aims at specific economic or environmental targets (e.g., an emission cap situation), the ratio method can indicate the best way of achieving the previously defined goals.

A number of conceptual problems in the definition of the sense of

Table 2
Comparison of the three most prevalent methods regarding the criteria that define their performance.

	Vector optimisation	Ratio	Weighted addition
Object of analysis	Dominance	Relationship or productivity	Integrated performance
Acceptance	Accepted and used in graphic form	Accepted as common definition of eco-efficiency	Accepted in the field of multi-criteria decision-making and LCSA
Simplicity	Trivial	Difficult to determine the sense of direction	Difficult to set weighting factors
Capacity to rank alternatives (evaluation method)	Limited to dominant and non-inferior solutions	Unequivocally	Unequivocally
Information included (scoring method)	Magnitude of original indicators	Productivity. No magnitude information	Magnitude information. No relative information
Capacity to address incommensurable units	Irrelevant (no integration is performed)	Possible (aggregated in a ratio)	Incommensurability solved with weighting factors
Compensatory method	Non-compensatory	Compensatory	Compensatory
Capacity to accept a third component	Possible, but difficult to visualise	Not possible	Possible
Consistency in sense of direction.	Consistent	Inconsistent	Consistent
Independence of ranking from irrelevant alternatives	Independent	Independent	Independent when weighting factors co-transform
Consistency through changes in units	Consistent	Consistent when limited to linear scaling	Consistent when weighting factors co-transform
Consistency through changes in reference point	Consistent	Not consistent	Consistent
Capacity to be aggregated and decomposed	Not possible	Based on weighted average	Based on direct sum
Capacity to capture decision-making preferences	Not possible	Not possible	Embedded in the method as weighting factors for identical trade-offs in the entire domain

Table 3
Criteria for the selection of the best available method according to the object of study.

Vector optimisation

- Separated evaluation of both dimensions at the same time
- Identification of win-win and trade-off situations (supported with graphic representation)

Ratio method

- Optimisation of one dimension against the other

Weighted addition

- Fair evaluation of the performance of systems according to the decision-makers' preferences
- Reconciliation of trade-offs between economic and environmental dimensions

direction of the ratio method make its interpretation ambiguous or even doubtful. The decision-maker should evaluate the specific decision-making situation to be able to set the performance criterion (sense of direction), and determine the ranking of alternatives. Shortcuts in the definition of the sense of direction based on the original indicators can lead to misinterpretation and to the wrong evaluation of the preferences.

It has been also proved that the ratio method presents a number of drawbacks when it comes to use relative indicators. Firstly, the ranking of alternatives might not be preserved against changes in the reference point. Secondly, inconsistencies in the sense of direction can cause interpretation problems. A thorough analysis of the signs of the results and of the original indicators, altogether, can identify the specific circumstances of each case, and facilitate the correct interpretation of the results. Finally, changing units has also been determined to be a cause of inconsistencies. Thus, a careful selection of the original indicators and their units is required to align the results with the purpose and the goal of the study.

The weighted-addition technique consists of a measurement of the integrated performance of systems according to the decision-making preferences. The method is consistent with the vector optimisation, and expands its scope by reconciling trade-offs between conflicting criteria. A fair evaluation of the system is the essence of this technique which certainly aligns with LCA and LCSA frameworks, and with the multi-criteria decision-making field. Setting weighting factors is regarded as the main barrier for the communication and acceptance of the results. Moreover, it is also a potential source of inconsistencies, if normalisation or changes of units are involved. In such cases, an adequate adjustment (co-transformation) of the weights to the exact characteristics of the study is required.

The graphic representation of indicators is commonly used to perform vector optimisation analyses, although it is also a good complementary support for ratio and weighted-addition techniques.

This paper shows that the combined analysis of economic and environmental aspects is indispensable to describe complex systems, however, simple ratios, weighted additions and vector optimisation fall short in terms of simple tools for decision-making. All evaluated methods are considered satisfactory when used in the appropriate context, but there is no method to fit all purposes. In addition to this, there is a role for composite protocols that combine elements of different methods.

Table 3 provides a guideline to select the best available method according to the exact object of study. For integrated economic and environmental assessments, a thorough goal and scope study is regarded as necessary prior to the selection of the method in order to make required adjustments to the analysis and provide decision-makers and stakeholders with the necessary information to achieve their objectives.

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