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Life cycle assessment-based decision making under methodological uncertainty: A framework proposal

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ABSTRACT

The inherent multi-criteria nature of Life Cycle Assessment (LCA), tailored to unearth trade-offs amidst environmental aspects, presents a challenge in directly aiding decision-makers when comparings products. These difficulties are due to both the multi-criteria nature of the instrument and the multiple forms of uncertainty that affect the results. This article aims to present a new framework, integrated with the ISO 14040 and ISO 14044 standards, designed to support LCA-based decision-making under methodological uncertainties. The framework encompasses three innovative phases within the LCA structure: a systematic mapping of sector-specific methodological choices, an in-depth analysis delving into the spectrum of conclusion variability, and the adoption of a weighting system for methodological combinations capable of managing divergent outcomes. This innovative framework was successfully applied in a real-world case study in the packaging sector.

1. Introduction

The intensifying global environmental crisis underscores the necessity for companies to incorporate data concerning the environmental performance of products and processes into their decision-making processes (Hellweg et al., 2023; Luglietti et al., 2016; Molin et al., 2023). This integration can be achieved through the adoption of environmental sustainability metrics and tools; among these Life Cycle Assessment (LCA) currently occupies a central role across institutional, academic and industrial sectors (Moutik et al., 2023; Sala et al., 2021; Sonnemann et al., 2018). Attributes such as a life-cycle perspective and a comprehensive, quantitatively rigorous, science-based approach (Bjørn et al., 2018) have contributed to its prominence. Nevertheless, certain methodological challenges persist that may threaten its reliability as decision support tool. Indeed, numerous authors have pointed out that the use of LCA as a decision support tool faces, among other critical issues, two main challenges: dealing with multiple indicators and uncertainty (Laurent et al., 2020; Laurin et al., 2016; Mendoza Beltran et al., 2016, 2018b; Zanghelini et al., 2018).

The first challenge arises from the tool's inherent multi-criteria nature, aiming to provide a broad and comprehensive view of key environmental aspects. This thorough assessment, along with its complexity of interpretation, requires the use of weighting procedures to draw conclusions and assist decision-makers (Laurin et al., 2016; Pizzol et al., 2017). However, it's important to note that these approaches don't ensure definitive outcomes. During the interpretation phase, it's crucial to consider the assumptions, hypotheses, and causes of uncertainty that might introduce variability in the conclusions.

Indeed, the second challenge stems from the uncertainty that affects all the phases of LCA (Mendoza Beltran et al., 2018b). Uncertainty can arise from the inventory data used, due to its unrepresentativeness or inherent errors, from the impact assessment models, but also from the methodological choices (Lloyd and Ries, 2008; Mattila et al., 2012; Mendoza Beltran et al., 2016, 2018a, 2018b). The methodological choices made in the scope definition can have a dramatic impact on its conclusions. Taking the plastics sector as an example, several reviews have shown a great deal of methodological heterogeneity in LCA studies and that the impact of different choices on conclusions is often not evaluated (Bishop et al., 2021; Marson et al., 2023; Tonini et al., 2021). Currently, the management of this variability is delegated, at best, to panels of experts tasked with defining sectoral rules, or directly to the LCA practitioner. Furthermore, for many methodological aspects, the crucial issue is not identifying the sole correct approach among a set of choices, but rather choosing among equally valid approaches that may result in significantly different conclusions. This leads to confusion and uncertainty among decision-makers and can potentially trigger greenwashing phenomena (*is it wrong for a company to communicate its*

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Abbreviation and symbols

Abbreviation

CFF	Circular footprint formula
EoL	End of life
EPD	Environmental product declaration
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MCDA	sMulti criteria decision analysis
nsd	not significantly different
PCR	Product category rules
PEF	Product environmental footprint
PEFCR	PEF category rules
r-CB	Partially recycled carton board tray
r-XPS	Partially recycled extruded polystyrene tray

Symbols

$\mathbf{w}$	weighting vector
W	weighted index
P_j	j-th Product system
P_k	k-th Product system
C_i	i-th LCA relevant methodological combination
M	number of LCA relevant methodological combinations
γ_0	Minimum threshold value
Θ	Heaviside step function
CI	Comparison index
$K_{4,j,k,i}$	superiority of P_j over P_k under the i-th methodological combination
As_b	b-th methodological aspect
B	number of the methodological aspects
α_c^b	c-th methodological choice for the methodological aspect As_b
Ω_i	weight of i-th methodological combination C_i
ω_c^b	weights of α_c^b
Ψ_l	weight assigned to the l-th source considered
$\psi_{c,l}^b$	weight assigned to the c-th methodological choice for As_b in the l-th source

product's footprint using a combination of methodological choices that minimizes its impact compared to a competitor's one?).

Previous studies have partially addressed this issue. An illustrative approach was proposed by Myllyviita et al. (2012) that involved a panel of experts to define the impact categories and indicators to be considered (in addition to assigning weights). Zanghellini and co-authors (2018) in their review identified this study as the only case of multi criteria decision analysis (MCDA) application in scope definition. A different approach, consisting in treating the methodological choices in the context of the uncertainty of the LCI in order to obtain a simultaneous view of the variability of the results, has been proposed by several authors (Blanco et al., 2020; Jung et al., 2014; Kätelhön et al., 2016; Mendoza Beltran et al., 2016, 2018a). Again, the application is limited to only one methodological aspect (e.g., allocation among co-products, treatment of emerging technology), and the proposed framework is not supplemented with an approach to support decision-making in case of conflicting results.

The identified gap can be formalized as follows. Let P_j and P_k two product systems capable of providing the same functions. Let M be the number of methodological combinations (C_i) considered relevant and necessary to be tested (note that a methodological combination is defined as a set of methodological choices in the different aspects to be covered in the scope definition). Thus, at the different levels of analysis, not individual results, but sets of results $\{W_j^1, W_j^2, \ldots, W_j^M\}$ for P_j and $\{W_k^1, W_k^2, \ldots, W_k^M\}$ for P_k are obtained.

A pairwise comparison of the weighted results in the different methodological combinations can lead to three situations (considering also the uncertainty resulting from the background and foreground data used:

- Situation 1 if there is a product system that has a lower or not significantly different weighted index in all relevant methodological combinations, and there is at least one methodological combination for which it has a lower weighted index,
- Situation 2 if in all comparisons the product systems are equivalent or not significantly different,
- Situation 3 in all the other cases.

Only Situation 1 appears to produce a conclusive result, while further investigation or aggregation procedures are necessary in the other two cases. Similarly, one can move from Situation 1 to 3. To the best of the author's knowledge, and consistent with literature (Zanghelini et al., 2018), the use of MCDA to deal with decision making under Situation 3 have not been previously investigated. Based on this problem description, the following challenges emerge: (1) How to determine which methodological aspects require further investigation by testing alternative approaches? (2) How to effectively manage and summarize results under different methodological combinations? (3) How to address the non-conclusiveness of Situation 3?

The objective of this research is to develop and test a framework for the assessment of the environmental performance of products and to support decision-makers under Situation 3. The case study was conducted by applying the proposed framework to support decision making among two packaging alternatives (trays for meat), one made by partially recycled XPS (r-XPS) and one made by recycled carton board (r-CB). The case study was selected because its sector is particularly exposed to methodological variability in the application of LCA (Bishop et al., 2021; Marson et al., 2023; Tonini et al., 2021).

The article is structured in this way: the proposed framework is described in section 2; the illustrative case study is described in section 3 and integrated by Supporting Information; the results have been discussed in section 4; and finally, conclusions are reported in section 5.

2. Methodology

2.1. Overview of the proposed framework

The proposed framework integrates the LCA methodology structure as described by the ISO 14040 and ISO 14044 standards (ISO, 2020a, 2020b). The first integration takes place in the Goal and Scope definition phase. To identify the methodological choices potentially applicable to the case study, the main relevant sources such as scientific literature and sectoral guidelines or rules are analyzed. A detailed description of this phase is reported in 2.2. The relevant methodological choices are then processed in the subsequent LCI, LCIA, and interpretation phases, thereby obtaining numerous sets of results in terms of weighted impact values (2.3). By integrating the uncertainty analysis, the recognition of the situation in which the comparison falls is then carried out (2.4). If the comparison falls under Situation 1, it is conclusive and does not require further steps (other than validation), while if the comparison falls under Situation 2, the entire application must be repeated, and the inventory refined to reduce uncertainty. If the comparison falls under Situation 3, a system for weighting different methodological combinations must be defined and applied (2.5). A graphic representation of the proposed methodological framework is shown in Fig. 1.

2.2. Definition of the relevant methodological combinations

In this first phase, according to the goal of the study and the intended stakeholders, all sources that could contribute to selecting the methodological choices of the LCA study should be identified. As relevant sources, literature certainly plays a key role. Other relevant sources are Product Category Rules (PCRs) from the Environmental Product Declarations (EPD) context (ISO, 2010), that are developed by a panel that shall meets requirements of both expertise in LCA methodology and knowledge of the product category. Finally, the third considered source is Product Environmental Footprint (PEF) methodology and (where existing) the sector-specific rules (PEFCR) (Zampori and Pant, 2019). As reported by Sala et al. (2021), the PEF has steadily increased its presence in European policies. Contrary to ISO standards, the PEF methodology sets certain methodological choices, removing degrees of freedom at the practitioner but increasing the comparability of results.

For these reasons, at least in the European context, these three sources are expected to be considered when applying the framework. Based on specific peculiarities of the study or the sector under investigation, other sources may also be implemented alongside or in substitution of those listed above.

The next step is to analyze relevant sources to see how they handle methodological aspects of scope definition, mainly: functional unit, system boundary, multifunctionality management, LCIA methods, normalization, and weighting. For each methodological aspect, practitioners must decide among several alternatives, known as methodological choices. For instance, for multifunctionality management, one may choose between system expansion and economic allocation. The results of this analysis are summarized in tabular form in the so-called *'Map of methodological choices'*. This synthetic form simplifies the discussion phase aimed at identifying the methodological aspects for which there is no consensus. At this stage, the methodological choices, although widespread in the literature, shall be compared with the specific objectives of the study to eliminate those that are not compatible. Assuming that for each methodological aspect there are two choiches that are considered relevant, the number of result sets to be handled grows exponentially. There are methodological aspects that can be easily handled by using parametric models, while others prove to be time-consuming bottlenecks, especially for uncertainty analyses. For this reason, in the mapping phase, it is necessary to carry out a first screening by focusing on the methodological aspects that may have the greatest impact on the results and/or on the most common

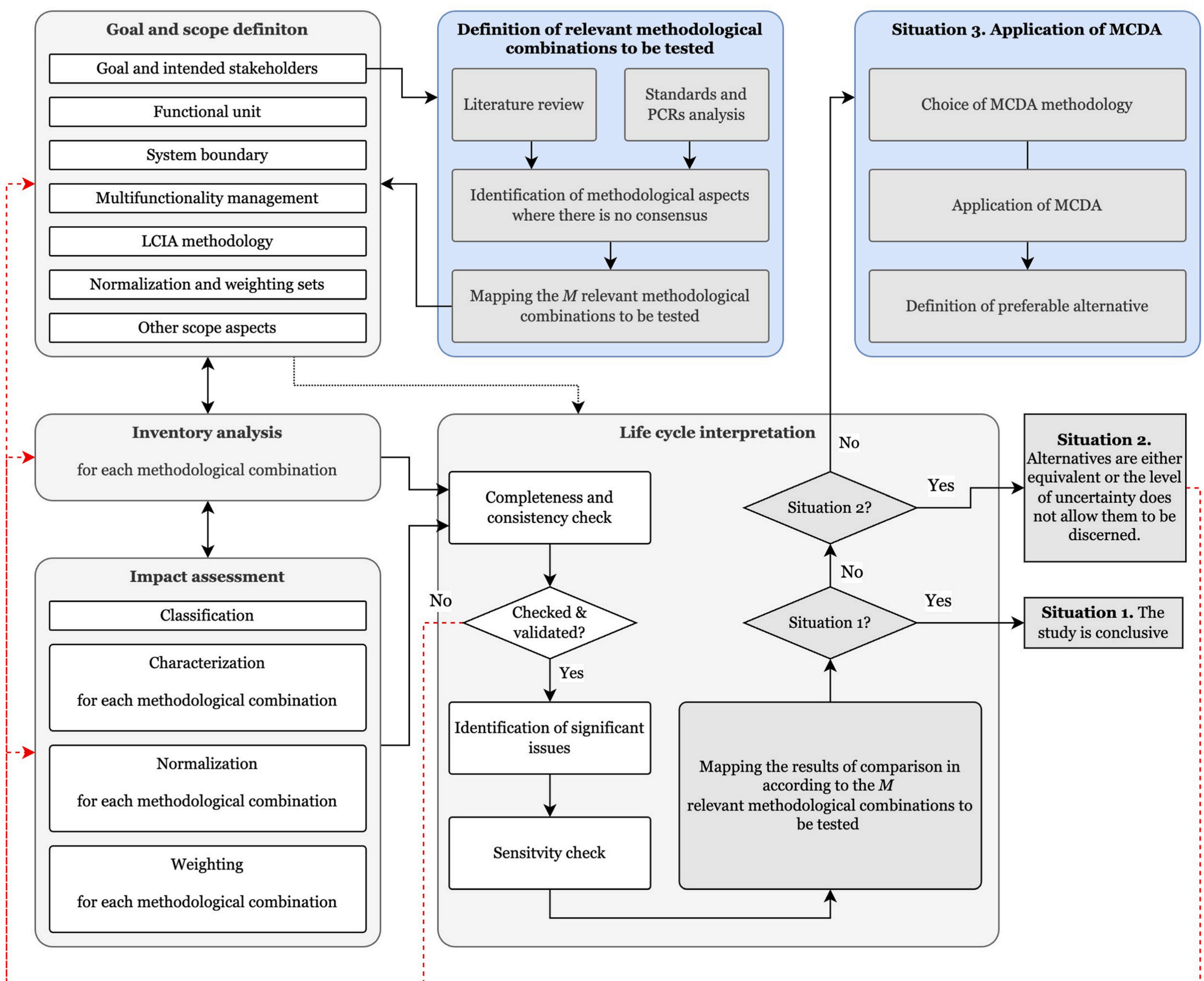

Fig. 1. Scheme of the proposed framework. Additions to ISO 14044 steps are highlighted by grey colour

methodological choices. In both cases, screening assessments based on contribution and sensitivity analyses can be carried out.

Once the methodological choices have been identified for each aspect, the *M* relevant methodological combinations are defined.

2.3. LCI, LCIA and interpretation of characterized results

The Life Cycle Inventory and LCIA phases are then carried out. Based on these results, the interpretation steps required by the standards can be performed. At this point, it is necessary to focus on the characterized results to identify trade-offs in terms of environmental aspects between the alternatives considered and to evaluate the variability of the rankings according to the methodological choices made. Uncertainty analysis of the characterized impacts can be omitted because it's evaluated after weighting in later stages.

2.4. Situation analysis

It is uncommon for a comparison of numerous product systems to clearly determine the optimal choice across all impact categories and methodologies (Marson et al., 2023). Therefore, applying weighting procedures becomes necessary to determine the most favorable alternative based on chosen criteria. Subsequently, only weighted results are taken into consideration in the analysis.

The objective of this phase is to assess which Situation the case study falls into (1, 2, or 3) by ranking the alternatives (in terms of weighted index) for all methodological combinations. Two cases arise: (a) one of the alternatives has a lower weighted index in all the methodological combinations. In this case, data uncertainty analysis is used to determine whether the comparison falls into Situation 1 or 2; (b) two or more alternatives rank first in different methodological combinations. An uncertainty analysis is necessary to determine if the comparison falls under Situation 2 or 3.

In both cases, is necessary to proceed with data uncertainty analysis to identify for which pairwise comparisons the differences are significant (for each methodological combination). In the first case (a), the analysis must be conducted to assess whether there is at least one methodological combination for which the alternative with the lower (mean) weighted index is significantly different from the others. If at least one of these methodological combinations exists, the comparison falls under Situation 1, otherwise it falls under Situation 2. In the second case (b), the uncertainty analysis must be conducted among all alternatives whose the (mean) weighted index was the lowest in at least one methodological combination. From the results of the analysis, it can be verified whether the comparison falls under Situation 2 or 3.

In this framework the '*modified comparison index*' as described by Heijungs (2021) has been be applied. Two comparison indexes are then defined:

$$CI_{j,k,i,r} = W^i_{k,r} \Big/ W^i_{j,r} \quad CI_{k,j,i,r} = W^i_{j,r} \Big/ W^i_{k,r} \tag{Eq. 1}$$

where $r = 1, \dots, n$ indicates the run of the model in the Monte Carlo simulation sampling from probability distributions for data uncertainty for the *i*-th methodological combination. Next, a minimum threshold value γ_0 shall be defined. This is used for assessing the superiority of P_j under the *i*-th methodological combination:

$$K_{4,j,k,i} = \frac{1}{n}\sum_{r=1}^{n}\Theta\left(\mathrm{CI}_{j,k,i,r} - \gamma_0\right) \tag{Eq. 2}$$

And the superiority of P_k under the *i*-th methodological combination:

$$K_{4,k,j,i} = \frac{1}{n}\sum_{r=1}^{n}\Theta\left(\mathrm{CI}_{k,j,i,r} - \gamma_0\right) \tag{Eq. 3}$$

where Θ represent the Heaviside step function $\Theta(\mathrm{y})$ which return 1 if $\mathrm{y} > 0$ and 0 otherwise. To reach a decision, three arbitrary, goal and scope related, numbers must be defined (Heijungs, 2021):

- The threshold value for the comparison index γ_0. A γ_0 value of 1,10 is arbitrarily assumed (so differences of more than 10% are considered significant), but both 1,01 and 1,20 have been considered to assess the stability of the conclusions.
- The minimum probability of beating an inferior product alternative (assumed 50%).
- The maximum probability of being beaten by an inferior product alternative (assumed 30%).

In other words, $K_{4,j,k,i}$ represents the fraction of Monte Carlo runs where P_j is preferable to P_k under the *i*-th methodological combination (only cases where the difference is greater than the threshold γ_0 are counted). Similarly, $K_{4,k,j,i}$ represents the fraction of Monte Carlo runs where P_k is preferable. Given the values defined in the previous points, P_j is preferred if $K_{4,j,k,i} > 50\%$ and $K_{4,k,j,i} < 30\%$. Note that $K_{4,j,k,i} + K_{4,k,j,i} \leq 1$ because all runs where the CI is lower than γ_0 are not counted.

The output of this analysis consists of a table in which the specific methodological combination is associated with the preferred option (so-called '*map of the comparisons results*'), or it is indicated that the results are not significantly different (*nsd*). It then becomes immediate to recognize in which situation the comparison falls.

2.5. Decision making under situation 3

To handle conflicting results under different methodological combinations, a second weighting system is needed. For the sake of clarity, the general structure of the novel method is presented below, and then the weights computation is explained (in addition, a numerical example is reported in Section 3.5).

Let As_b, with $b \in \{1, \dots, B\}$, be the methodological aspect that encompasses multiple relevant methodological choices α^b_c. The weight Ω_i for each methodological combination C_i is derived through the multiplication of the weights ω^b_c corresponding to each choice α^b_c across all B methodological aspects within the *i*-th combination:

$$\Omega_i = \omega^1_i \cdot \omega^2_i \cdot \ldots \cdot \omega^B_i \tag{Eq. 4}$$

For the methodological choice α^b_c the associated weight ω^b_c is determined by its prevalence in the considered sources, using an additive method:

$$\omega^b_c = \sum_{l=1}^{L}\Psi_l \cdot \psi^b_{c,l} \tag{Eq. 5}$$

where Ψ_l is the weight assigned to the *l*-th source considered (with $l \in \{1, \dots, L\}$) and $\psi^b_{c,l}$ is the weight assigned to the *c*-th methodological choice for the *b*-th methodological aspect in the *l*-th source.

The Ψ_l and ψ^b_c are calculated by creating a pairwise comparison matrix and assessing qualitatively the relative importance according to the typical procedures of the Analytical Hierarchy Process (AHP) (Saaty, 1987) and the criteria given in Table 1. The selection of AHP is based not

Table 1
Table of relative scores (Saaty, 1987).

Value	Interpretation
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments
Reciprocals	If criteria/option *i* has one of the above numbers assigned to it when compared with criteria/option *j*, then *j* has the reciprocal value when compared with *i*

solely on its widespread acceptance (Lin et al., 2020) but also due to its efficacy in structuring complex decision-making scenarios into a hierarchical model. This hierarchization allows for a clear decomposition of the problem and facilitates a systematic analysis of the components and their respective influences. Once the pairwise comparison matrix has been defined the principal eigenvector corresponds to the vector of weights (Saaty, 1977).

Finally, each alternative is assigned the weight Ω_j of the methodological combinations in which it is the preferred option. Unassigned weights correspond to all combinations in which the results are not significantly different.

3. Case study

3.1. Case study description

The aim of the case study is to support the choice between two alternatives for protein packaging in supermarkets, considering a European geographic scope. The first alternative is a tray made of r-XPS with a PS/EVOH/PE barrier film. The tray has an internal volume of 950 ml, a weight of 9.60 g, and a recycled content of 36%. The second tray, on the other hand, is made of r-CB and a PE/EVOH/PE barrier film (internal volume 1050 ml, 21.35 g weight, and 89% recycled content). The LCA model was developed in SimaPro (PRé Sustainability, 2022) environment, while results processing, statistical analyses, and data visualization were carried out using OriginPro software (OriginLab, 2023).

3.2. Definition of the relevant methodological combinations to be tested

To create the *map of methodological combinations*, the spread of methodological choices in the main aspects of scope definition in the literature (limited to comparative studies for the packaging industry), Packaging PCR (2019:13 v1.1) by The International EPD System (EPD International, 2020), and PEF guidelines (Zampori and Pant, 2019) were analyzed. The literature information is extrapolated from the review presented in Marson et al. (2023).

The detailed analysis of the methodological choices found in Table 2 and the map of the relevant methodological combinations (C_i) is provided in Table 3.

The three sources considered are consistent in three methodological aspects (As_b). In fact, all sources converge on the use of cradle-to-grave system boundaries (excluding the use phase) and the use of co-product allocation according to the Ecoinvent approach for background data. See Supplementary Information (section SI-1.1) for a more detailed description of the system boundary. There was no need to use co-product allocation for foreground processes. Instead, only the EF Method 3.0 was considered as the LCIA method, as it is proposed by both PEF and PCR, even though it is not the most widely used method in the literature reviewed (although it has been increasingly used in recent years) (Marson et al., 2023). See Supplementary Information (sections SI-1.2 and SI-1.3) for a description of impact categories, indicators, and methods. However, other aspects led to the identification of more than one relevant option. The choice of functional unit (As_1) can fall into two options: 1 L of internal volume (α_1^1) or one tray (if the alternatives have similar geometry, with small differences in capacity) (α_2^1). In fact, for the intended application, it is rare for the tray to be completely filled, so volume is not always strictly related to function. For EoL allocation (As_2), the two approaches recommended by PCR and PEF, cut-off (α_1^2) and Circular Footprint Formula (CFF) (α_2^2), respectively, were considered relevant. The latter is considered representative of the substitution approach, which is the most widely used in literature. See section SI-1.4 for an explanation of the two approaches. Finally, for the weighting sets (As_3), both those proposed (at different periods) by PEF methodology were considered ($\boldsymbol{w_{tox}}$ (α_1^3) and $\boldsymbol{w_{no-tox}}$ (α_2^3), differ in whether they include toxicity-related impact categories, see section SI-1.3). In accordance with these considerations, eight relevant methodological

Table 3
Map of the relevant methodological combinations for the case study.

C_i	Functional unit (As_1)	EoL allocation (As_2)	Weighting set (As_3)	Weighted indexes
C_1	1 tray	Cut-Off	$\boldsymbol{w_{tox}}$	W^1_{r-XPS}, W^1_{r-CB}
C_2	1 tray	CFF	$\boldsymbol{w_{tox}}$	W^2_{r-XPS}, W^2_{r-CB}
C_3	1 L	Cut-Off	$\boldsymbol{w_{tox}}$	W^3_{r-XPS}, W^3_{r-CB}
C_4	1 L	CFF	$\boldsymbol{w_{tox}}$	W^4_{r-XPS}, W^4_{r-CB}
C_5	1 tray	Cut-Off	$\boldsymbol{w_{no-tox}}$	W^5_{r-XPS}, W^5_{r-CB}
C_6	1 tray	CFF	$\boldsymbol{w_{no-tox}}$	W^6_{r-XPS}, W^6_{r-CB}
C_7	1 L	Cut-Off	$\boldsymbol{w_{no-tox}}$	W^7_{r-XPS}, W^7_{r-CB}
C_8	1 L	CFF	$\boldsymbol{w_{no-tox}}$	W^8_{r-XPS}, W^8_{r-CB}

Table 2
Map of the methodological choices and identification of relevant methodological choiches to be tested and justification.

Aspect	Literature review	PCR Packaging	PEF Guideline	Relevant methodological choices	Comment
Functional unit	20% Number of items 60% Number of items with the same carrying capacity 20% Amount of contained products	1 tray	–	1 trays 1 L	Both literature and applicable standards, as well as comparisons with Italian manufacturers, have shown that both of these functional units can be representative (considering trays with similar geometries).
System boundary	90% Cradle to grave	Cradle to Grave			Cradle to grave
Co-product allocation	For background processes the Ecoinvent approach is the most used	There are no specific indications other than avoiding substitution.			Ecoinvent approach for background data. Not necessary for foreground processes.
EoL allocation	51% Substitution (several approahes) 9% Cut-off 40% Not defined	Cut-off	Circular Footprint Formula (CFF)	CFF Cut-off	In addition to the cut-off approach, the CFF was also considered to be representative of the substitution approach.
LCIA method	33% ReCiPe 18% CML 7% IMPACT 2002+ 5% EF method	EF method 3.0 (CML until 2022)	EF method 3.0	EF method 3.0	The EF method was chosen as it is the reference for the PCRs and PEF guidelines. It is emphasised that the EF method uses the same methods as those implemented by ReCiPe for many impact categories.
Weighting set	50% ReCiPe 25% IMPACT 2002+ 12,5% EF method 12,5% CML-IA	–	EF method 3.0	$\boldsymbol{w_{tox}}$ – EF method 3.0 (including toxicity categories) $\boldsymbol{w_{no-tox}}$ – EF method 3.0 (excluding toxicity categories)	The weighting vectors ($\boldsymbol{w}$) s developed within the PEF methodology were taken as references as they are more in line with the study's stakeholders (European consumers) than ReCiPe weighting system.

combinations C_i were defined ($M = 8$).

3.3. LCI, LCIA and interpretation of characterized results

To keep the focus of the main text on the application of the framework, a detailed description of the LCI is provided in the Supporting Information (section SI-2), as well as the characterized results of the LCIA and their interpretation (section SI-3). The highlights of the analysis carried out are therefore presented below.

Tray characteristics are primary data obtained in collaboration with manufacturers and analysis of trays actually on the market. To characterize the production and sourcing of raw materials, datasets from Ecoinvent v3.8 (Wernet et al., 2016) and Eurostat import data (Eurostat, 2021) were used to define the origin of materials. The tray production process was described using datasets from Ecoinvent, modifying the energy mixes to be representative of the actual production in Europe (Eurostat, 2021). To characterize the EoL, average European statistics were considered (Eurostat, 2022): 64.18% energy recovery and 35.82% landfilling for r-XPS (the recycling supply chain for XPS trays is being developed with pilot projects, but is not considered relevant to date); 81.71% recycling, 9.14% energy recovery, and 9.15% landfill for r-CB. Inventory and characterized LCIA results were calculated for all relevant combinations of functional unit and EoL allocation approach.

The characterized results revealed numerous trade-offs between environmental aspects as identified by previous studies in the field (Maga et al., 2019). For 11 impact categories, r-XPS appears to have the lowest impact (in terms of average) across all method combinations. In contrast, for two impact categories, Climate change and Photochemical ozone formation, r-CB is the alternative with the lowest impact across all method combinations. Finally, for four categories the rankings vary as the methodological choice changes. For Acidification and Abiotic Depletion Potential-fossil, r-XPS is the preferred alternative in all methodological combinations except C_3 and C_7. Conversely, for Water Use, r-CB is always preferred except in C_2 and C_6. Finally, for Eutrophication Potential-freshwater, r-XPS has a minor impact only when the allocation approach is CFF.

For both systems analyzed, the contribution analysis showed that the main source of impact is the raw materials production, followed by EoL (for r-XPS also the extrusion and thermoforming process is relevant). Finally, the model assumed a distribution distance of 500 km (from trays production plant and filling plant). A sensitivity analysis showed that changing this distance does not affect the ranking in all the impact categories.

3.4. Situation analysis

Weighted indexes are reported in Table 4. To determine which situation the comparison falls under, an uncertainty analysis was conducted. Fig. 2 displays a box plot illustrating the distribution of results from the Monte Carlo analysis for r-XPS and r-CB across eight different methodological combinations. In both product systems, approximately 71% of the values contain uncertainty data, defined through pedigree approach (Weidema et al., 2013). The modified comparison index (Heijungs, 2021) has been applied for each methodological combination. Three levels of γ_0 have been considered (1,01; 1,10; 1,20). In Table 5 the trays having a lower weighted index than the alternative (considering γ_0) in at least 50% of the Monte Carlo runs and not having a higher weighted index in more than 30% of the runs are reported. The results proved to be stable as the threshold γ_0 changed. In fact, in three methodological combinations (C_2, C_4, C_6) r-XPS is the preferable solution regardless the threshold, while in two combinations (C_3, C_5) no superior alternative is ever detected. Moving instead to a significance threshold of 20%, the results for two combinations become non-significantly different. Contrasting results therefore emerged in the different methodological combinations. For this reason, this case study falls in Situation 3.

Table 4
Weighted results and ranking of the trays under different methodological combinations.

C_k	W_{r-XPS} [Pt]	Ranking	W_{r-CB} [Pt]	Ranking
C_1	3,589E-06	1	3,862E-06	2
C_2	3,227E-06	1	4,263E-06	2
C_3	3,778E-06	2	3,678E-06	1
C_4	3,397E-06	1	4,060E-06	2
C_5	3,628E-06	2	3,527E-06	1
C_6	3,287E-06	1	3,964E-06	2
C_7	3,819E-06	2	3,359E-06	1
C_8	3,460E-06	1	3,775E-06	2

3.5. Decision making under situation 3

According to the procedure described in 2.5, the first step in dealing with Situation 3 is the definition of the weight Ψ_l assigned to the sources considered (literature, PCR, and PEF in this case study). To calculate the weights Ψ_l, a pairwise comparison matrix was built using the scores described in Table 1. The highest value is attributed to the literature, as the review identified 49 comparative studies in the field of packaging relating to plastics and alternatives (Marson et al., 2023). According to the selected PCRs, 28 published EPDs are currently available (as of early 2023) (EPD International, 2023). Finally, for the PEF methodology, uses are sporadic, although a pilot application focusing precisely on plastic trays is worth mentioning (Nessi et al., 2021). The pairwise comparison matrix is reported in Eq. (6).

$$\begin{vmatrix} & L & PCR & PEF \\ L & 1 & 3 & 5 \\ PCR & 1/3 & 1 & 3 \\ PEF & 1/5 & 1/3 & 1 \end{vmatrix} \quad \text{(Eq. 6)}$$

The weights were defined by calculating the principal eigenvector:

$$\Psi = (\Psi_L; \Psi_{PCR}; \Psi_{PEF}) = (0,637;\ 0,258;\ 0,105) \quad \text{(Eq. 7)}$$

with consistency ratio CR = 4% and principal eigen value $\lambda = 3039$.

Next, the weights $\psi^b_{c,l}$ were defined. All pairwise comparison matrices are shown in Table 6. Values were assigned considering the prevalence of the choice (for the literature), and the PCR/PEF recommendations. For the values in the source Literature, the results of the review presented in 3.2 were considered. For the assignment of the scores in the PCR source, it was considered that the suggested functional unit is the unit of product, but it is also possible to express the values with respect to the contained volume. For this reason, a strong (but not absolute) importance was recognized for the functional unit '*1 tray*'. For the EoL allocation approach, reference was made to the results of the literature review, while for the two guidelines, the highest score was given to the recommended option. Finally, for the weighting system in the literature source, the set without toxicity categories was given a slightly higher score because it was used in a reviewed case study. For the PEF methodology, a high value (but not the highest) was given to the set with the toxicity categories because the one currently in force, but for some years the reference was the other.

The obtained weights $\psi^b_{c,l}$ are reported in Supplementary Information (section SI-4). By combining the values given in Eq. (7) and $\psi^b_{c,l}$, applying Eq. (5), it was possible to calculate the weights ω_c associated with each individual methodological choice (Table 7). By applying Eq. (4), it was then possible to calculate the weights Ω_i associated with each methodological combination (Table 8). The scores associated with the different alternatives as a function of the three γ_0 considered values are therefore shown in Table 9.

The results show that r-XPS is the preferred solution with an absolute majority for the 1% and 10% thresholds, while it falls below the score of '*nsd*' for the 20% threshold. In the latter case, it is also observed that

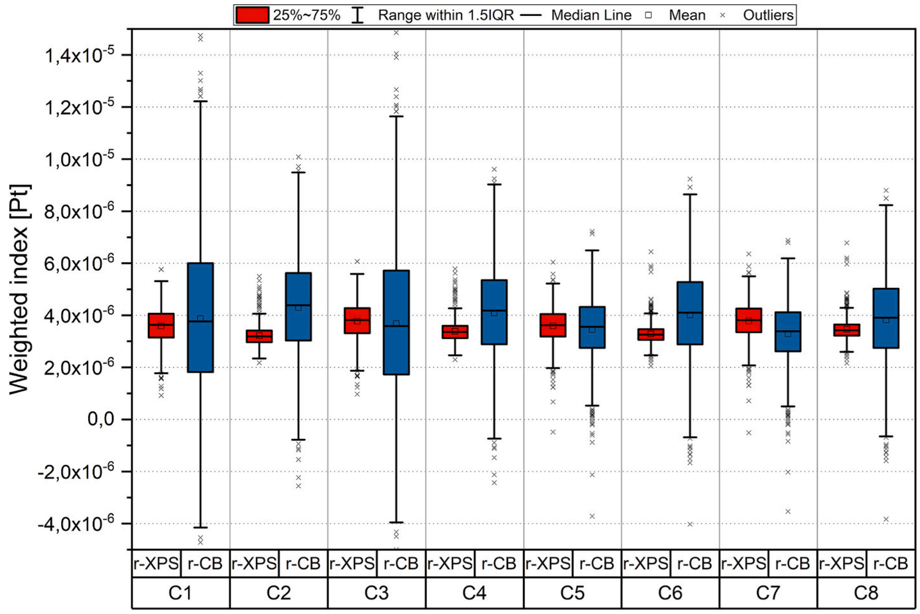

Fig. 2. Box plot of the weighted index for r-XPS and r-CB for all the methodological combinations.

Table 5
Results of the modified comparison index test for three levels of threshold value γ_0.

γ_0.	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
1,01	r-XPS	r-XPS	nsd	r-XPS	nsd	r-XPS	r-CB	nsd
1,10	nsd	r-XPS	nsd	r-XPS	nsd	r-XPS	r-CB	r-XPS
1,20	nsd	r-XPS	nsd	r-XPS	nsd	r-XPS	nsd	nsd

alternative r-CB receives a score of 0, since it never turns out to have a lower overall impact than r-XPS as the difference threshold increases. Therefore, it can be concluded that alternative r-XPS is the preferred choice for all significance thresholds considered.

4. Discussion

4.1. Application of alternative approach to case study

To validate the conclusions obtained with the modified comparison index the weighted indexes of r-XPS and r-CB were tested each other using the nonparametric Wilcoxon signed rank test (with $\alpha = 0{,}05$). In this way, was possible to assess the statistical difference between the results of the Monte Carlo analysis without taking the significance threshold into account. The test was chosen because it does not impose any requirements on the distribution of the two samples (unlike *t*-test).

From the test application and the post hoc analysis, the conclusions obtained are consistent. In fact, the results of the two tests are not contradictory. The modified comparison index shows more combinations with results that are not significantly different due to the presence of the threshold γ_0. The results of Wilcoxon signed rank test are reported in Supplementary Information (section SI-4.2), while the preferable

Table 7
Overall weights of the methodological choices.

Methodological aspect As_b	Methodological choice α_c^b	ω_c^b
Functional unit	1 tray	0,421
	1 L	0,579
EoL allocation	Cut-Off	0,349
	CFF	0,651
Weighting	w_{tox}	0,433
	w_{no-tox}	0,567

Table 8
Overall weights of the methodological combinations.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
Ω_i	0,064	0,119	0,088	0,163	0,083	0,155	0,115	0,214

Table 9
Sum of the weights in which the alternatives are the preferred choice.

Ω	$\gamma_0 = 1{,}01$	$\gamma_0 = 1{,}10$	$\gamma_0 = 1{,}20$
Ω_{r-XPS}	0,501	0,651	0,437
Ω_{r-CB}	0,115	0,115	0,000
Ω_{nsd}	0,385	0,234	0,563

Table 6
Pairwise comparison matrix among the methodological choices in the considered sources.

	Literature	PCR	PEF
Functional unit	1 *tray* 1 *liter* / 1 *tray* 1 1/ 41 *liter*41	1 *tray* 1 *liter* / 1 *tray* 1 5 51 / 1 *liter* 1/	1 *tray* 1 *liter* / 1 *tray* 1 3 31 / 1 *liter* 1/
EoL allocation	*Cut − off* *CFF* / *Cut − off* 1 1/ 5*CFF*51	*Cut − off* *CFF* / *Cut − Off* 1 9 91 / *CFF* 1/	*Cut − off* *CFF* / *Cut − off* 1 1/ 9*CFF*91
Weighting	w_{tox} w_{no-tox} / w_{tox} 1 1/ 2w_{no-tox}21	w_{tox} w_{no-tox} / w_{tox} 1 1 / w_{no-tox} 1 1	w_{tox} w_{no-tox} / w_{tox} 1 7 71 / w_{no-tox} 1/

alternatives identified through post hoc analysis are summarized in Table 10.

To assess the extent to which the assignment of scores in the pairwise comparison matrices influence the final conclusions, an algorithm was created for the random weighting in the two levels of analysis (assignment of weight at the sources and at the methodological choices). 10,000 iterations were performed (this value was chosen as stability of results was observed), measuring in how many of these combinations the different alternatives were preferred. The analysis was conducted both considering the results of the Wilcoxon Signed Rank test and on the results of the modified comparison index at the three γ_0 threshold levels. The results are shown in Table 11.

This validation analysis showed that the random assigning weights to different sources and different methodological choices (and thus introducing subjectivity) hasn't affected the final choice, since the conclusions are the same even with random assignment.

In this case, the results are consistent, although it is possible that the validation method may produce divergent results in general. It is important to note that the Wilcoxon signed rank test does not consider significance thresholds and minimum superiority values, leading to fewer nsd comparisons. Therefore, it offers an understanding of the results' robustness regarding the parameter choices used for the modified comparison index. Likewise, utilizing a randomized weighting system allows for the assessment of subjectivity impact on assigning relative scores. The proposed validation approach serves to provide feedback on the stability of the results in relation to the methodological choices of uncertainty assessment and weighting and is not intended to replace the methodologies outlined in the framework, but rather working as a sensitivity check in a LCA analysis.

4.2. Feasibility and limitations of the proposed framework

The literature highlighted that LCA is, by far, the most used environmental sustainability tool for comparative purpose, although its use is accompanied by inherent limitations (as any model attempting to represent natural mechanisms) and significant variability in its application. Even when the scope of application is limited, such as in this research, by approach (comparative ex-post attributional LCA) and area of analysis (packaging), the founded variability is vast.

It is evident that the proposed framework should not only guide decision-makers in their choices but also ensure transparency in terms of trade-offs between environmental aspects and the sensitivity of conclusions to various methodological choices. In theory, these two principles are already covered by the ISO 14044 standard in the interpretation phase, albeit with no comprehensive systematic treatment and no indication of how to handle conflicting results under varying methodological conditions.

All these requirements were considered in defining the proposed framework. In particular, the first and most important stage is the definition of the *map of methodological combinations*. Its definition is one of the most critical points, as it influences all subsequent steps. Two crucial issues arise at this stage. Firstly, the choice of sources from which to derive methodological choices is essential. The analysis of literature on similar products or within the same sector is indispensable in understanding the range of methodological choices and identifying institutional or industry guidelines such as PCRs.

The second critical issue concerns the number of methodological combinations considered in the analysis and the relative calculation efforts. As discussed in Section 2.2, the use of pre-assessment strategies can reduce the number of methodological combinations, allowing for a focus on the most influential methodological aspects/choices. For instance, sensitivity analyses or preliminary assessment of methodological combination weights can be applied to reduce the number of combinations to be tested. If cut-offed combinations could potentially affect the conclusions, the initial decision can be iteratively reevaluated.

Table 10
Preferable alternatives in the different methodological combinations according to post hoc analysis (validation).

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
Preferable alternative	r-XPS	r-XPS	nsd	r-XPS	r-CB	r-XPS	r-CB	r-XPS

Table 11
Percentage of cases in which the alternative is preferrable out of the total number of random runs performed.

Alternative	Wilcoxon Signed Rank test	Modified comparison index		
		$\gamma_0 = 1{,}01$	$\gamma_0 = 1{,}10$	$\gamma_0 = 1{,}20$
r-XPS	88,1%	65,5%	63,5%	22,4%
r-CB	10,5%	0,8%	1,4%	0,0%
Nsd	1,4%	33,7%	35,1%	77,6%

Once the methodological combinations to be considered have been determined, the process for generating characterized and weighted results is established. While it is possible to calculate and utilize only weighted results, this approach would not fulfill the transparency requirements that are considered essential in the framework design.

The situation analysis phase involves choosing a method for evaluating the data uncertainty and discernibility among the result sets obtained by Monte Carlo analysis. The modified comparison index was selected because of its many advantages, specifically the ability to set relevance thresholds. This on the other hand introduces a level of subjectivity that cannot be overlooked. Therefore, several significance thresholds are evaluated at this stage as a validation tool, including the use of another nonparametric statistical test.

For comparisons under Situation 3, a qualitative/quantitative weighting and ranking system has been proposed based on the spread of specific methodological choices and the relevance of different sources. Indeed, many MCDA tools could be applied at this stage, e.g., systems based on panels of experts could be considered. In all cases, a degree of subjectivity is introduced at this stage. As a validation tool, a completely random weighting system is provided to assess whether the assignment of weights leads to bias in the results and to evaluate the degree of stability of the conclusions.

The framework was successfully implemented in the case study. However, limitations were also identified. The most notable challenge is the large amount of time and computational resources required to handle multiple methodological combinations in parallel. To reduce the number of combinations, it is necessary to introduce levels of subjectivity, which must be approached with caution. Finally, it is necessary to underline the basic assumption of the framework. The proposed approach starts from the assumption that the more a methodological choice is widespread, the more value it assumes. In general, all the sources considered have undergone a peer review process (for literature) or a debate among stakeholders and experts (for PCRs/PEF/PEFCRs), thus providing a level of assurance of their adequacy.

5. Conclusion

This study developed a framework for LCA-based decision making under methodological uncertainty. Undoubtedly, the foremost advantage of this framework is the increased transparency it provides in evaluating the effects of different methodological choices. While ISO 14044 also requires such assessments, the literature review highlights that they are not adequately explored. Additionally, the standard does not provide guidance on managing conflicting results, aside from acknowledging the limitations that emerge. The proposed framework adds value by guiding practitioners through the entire process, from identifying relevant methodological combinations to analyzing results considering uncertainty. If needed, the weighting system for different methodological combinations can be developed based on their diffusion in relevant sources. This leads to the introduction of limitations that were encountered. Firstly, the proliferation of methodological combinations to be tested results in an exponential increase in computational time. Furthermore, as with all decision-making processes, some subjectivity remains in this framework. In fact, the weighting system of individual methodological choices, which forms the basis for the weights assigned to methodological combinations, relies on qualitative and quantitative assessments that can be subject to different interpretations. This risk can be reduced, for example, by applying more sophisticated MCDA approaches, such as involving panels of experts to provide as many different perspectives as possible. In this direction, the random-based validation approach proposed within the framework is particularly relevant.

The framework in this research has been applied to the area of packaging, but no limitations have been found that would preclude its applicability in other areas. In fact, once the most critical methodological aspects have been identified for the specific sector, the framework becomes independent of the area of application. More critical, however, is the application where the available literature is scarce, making it difficult to identify a priori the methodological aspects to be addressed and the alternatives available. In such cases, it is necessary to carry out a thorough analysis of the product's lifecycle and to interpret and deduce possible sources of variability. Finally, the framework was tested only in the context of ex-post LCA evaluations using an attributional approach.

Results of this research work open to new perspectives: testing the framework to other sectors to demonstrate its applicability, especially where supporting literature is scarce, and testing the framework for ex-ante LCA, where it needs to be adapted, for example, to handle more scenarios in parallel and deal with data gaps.

Declaration of generative AI and AI- assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Alessandro Marson: Writing – original draft, Methodology, Data curation, Conceptualization. **Filippo Zuliani:** Writing – review & editing, Validation, Supervision, Resources. **Andrea Fedele:** Writing – review & editing, Data curation. **Alessandro Manzardo:** Writing – review & editing, Supervision, Resources, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141288.

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