Propagating Uncertainty in Life Cycle Sustainability Assessment into Decision-Making Problems: A Multiple Criteria Decision Aid Approach

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Abstract Life cycle sustainability assessments (LCSA) are a comprehensive source of information on product performance to support decision-making processes toward sustainable production and consumption. Multiple criteria decision aid (MCDA) approach provides a structured decision modelling that considers the value judgments of the decision-makers and it has been proved to be useful to support decision-making based on LCSA results. We proposed an approach able to take into account LCSA performances when making decisions. We applied our approach through a case study of tire life extension scenarios selection. The scenario with retreading is the solution that offer the best compromise between the three sustainable dimensions with more than 63% probability to rank first for Weighted sum, Topsis and Prométhée II MCDA methods.

1 Introduction

Supporting sustainable decision-making problems involves taking into account environmental, social and economic performance assessments into mathematical decision models, in order to communicate results to decision-makers. However,

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Martín-Gamboa et al. [1] highlights the need to develop frameworks able to integrate sustainability indicators and decision-makers preferences.

One of the challenges in assessing these potential impacts is the dispersion of them throughout product life cycle, making complex the assessment process. Life cycle approach is able to deal with it. As such, Life Cycle Sustainability Assessment (LCSA) analysis takes into account all stages of a product's lifecycle, when assessing performances, being considered a holistic tool used to measure product sustainability. Therefore, LCSA refers to environmental, social and economic assessments of product systems from a life-cycle perspective in order to promote product sustainability [2, 3].

However, the use of this type of result in organizational decision-making is not obvious. Halog and Manik [4] highlight three characteristics that increase the complexity of decision-making through LCSA results: (i) the indicators are multidimensional (each one is expressed in different units), (ii) the objectives are contradictory for the majority of decision-making problems (it is impossible to maximize the performance of a product system in all indicators) and (iii) performance evaluation is uncertain.

In this type of decision-making problem, decision makers must choose according to different criteria (LCSA indicators), leading to multiple criteria decision problem. Multiple criteria decision analysis (MCDA) approach aims to recommend an ideal solution, which is not necessarily optimal in all criteria, but a compromise solution according to the value judgment of decision-makers. The main advantage of this approach is its ability to consider a relatively large number of criteria when making a decision [5]. Laurin et al. [6] remark this approach when comparing product systems through the analysis of compromise recommendations.

LCSA results could be too disaggregated and, as such, too difficult to understand and interpret by decision-makers [7]. The use of these indicators in combination to support sustainable decision-making can be done through MCDA methods, as proposed by several authors [8–11].

We found few scientific researches discussing the use of the multiple criteria decision analysis approach into decision-making comprising LCSA results for sustainable decision-making ([9, 12–15, 7]).

The researches carried out by Vynies et al. [9] and Keller et al. [12] rely on arbitrary and unjustified aggregation procedures and neglect uncertainty when selecting a product system between a set of alternatives based on LCSA performances. Myllyvitta et al. [13] used MCDA approach to identify and weight relevant impact categories when assessing the environmental impacts of biomass production. Traverso et al. [7] provide a tool for comparing LCSA performance-based product systems. However, it is not clear how they defined the procedure for establishing the weighting factors and they do not take into account the uncertainty associated to LCSA performances. Finally, Hanandeh and El-Zein [14] adapted Electre III method to account for the uncertainty associated with preference data as weighting factors when choosing between alternatives based on LCA performance.

As such, we did not find many studies carrying out analyses including LCSA uncertainties, or the implications of choosing among the various MCDA methods

existing in the scientific literature. This paper aims to propose an approach able to support sustainable decision-making where the considered indicators are defined as LCSA performances.

2 Methodology

The assessment of the performance of products in each pillar of sustainability is uncertain and can vary widely due to the parameters of the impact assessment model and input data. Different sources of uncertainty are present in environmental, social and economic studies, considering life cycle analysis. It is therefore necessary to take these uncertainties into account when deciding.

As such, our methodology includes three phases: (i) assessing uncertain LCSA performances for the three pillars of sustainability (ii) extending LCSA performances uncertainty to MCDA methods and (iii) interpreting stochastic rankings provided by the MCDA methods implemented, followed by conclusions.

The achievement of uncertain performance followed the ReCiPe method [16] for the environmental component and Social Hotspot database results for the social pillar. For the economic pillar, life cycle cost was considered. We applied "environmental life cycle costing (LCC)" according to Hunkeler et al. [17] to calculate the sum of private costs supported by all stakeholders involved throughout entire product life cycle, i.e. beyond the costs of the producer. Please note that in environmental LCC, no externalities are monetized (e.g. health care costs due to air pollution from trucks). Because of the strong inflation in Brazil in recent years, costs from year 2012 were have been adjusted with national inflation rates. No discounting was considered because of the relatively short duration of the tire life cycle.

The sources of uncertainty for environmental, social and economic dimensions are related to reference flows (number of tires required—considering the lifetime and the fuel consumption during use). For environmental dimension, we also considered the uncertainty related to ecoinvent, the end-of-life benefits, tire wear, transport distances, land use change and yield for hevea and soybean agriculture and emission factors. On the other hand, we did not consider the uncertainty associated to prices for social and economic dimensions and the ones associated to environmental and social characterization factors.

To represent these sources of uncertainty in LCSA performances, we performed a Monte Carlo simulation for all indicators comprised in the three pillars of sustainability.

In order to propagate the uncertainty on LCSA performance scores to decision-making problem, we applied three MCDA models (Weighted sum, Topsis and Prométhée II). These models were chosen according to the type of results provided (multiple criteria methods able to provide full rankings), the ease of being implemented without specific software package (ease of use in generic software, for example Microsoft Excel) and the type of parameters requested from decision
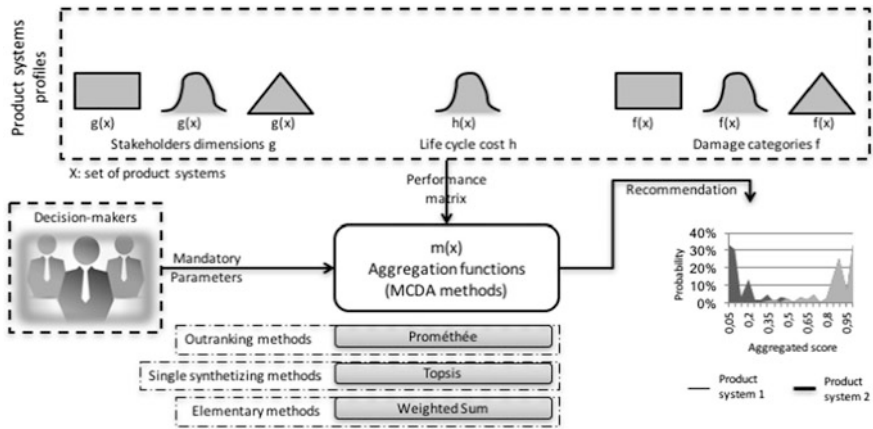
Fig. 1 Methodology proposed for support sustainable decision-making through LCSA uncertain performances

makers (parameters needed must be easy to be understood by decision makers through direct elicitation process).

Each method requires different parameters, for example the weights of each criterion (all methods) and the equivalence, weak preference and strict preference zones (for the Prométhée II method), as remarked by Carmo et al. [18]. These parameters were defined from an interview (elicitation process) with decision makers (three company's truck tire development experts). We run each model 1000 times, equivalent to the amount of Monte Carlo simulations we have carried out to generate the overall environmental, social and economic performances. As such, we got 1000 comparisons between product systems, each of which gives an order of preference.

In the last step, we analysed the probabilities for a product system to rank in a given position. This generates the level of confidence of the general ranking. Figure 1 illustrates the proposed method.

Our approach can be applied to all decision problems where uncertain social, environmental and economic life cycle performances are used as decision criteria when ranking products according to LCSA performances.

3   Results

3.1   Case Study Description

The focus of this case study is the life cycle of truck tires in Brazil. More specifically, this study compares, from a life cycle perspective, the potential
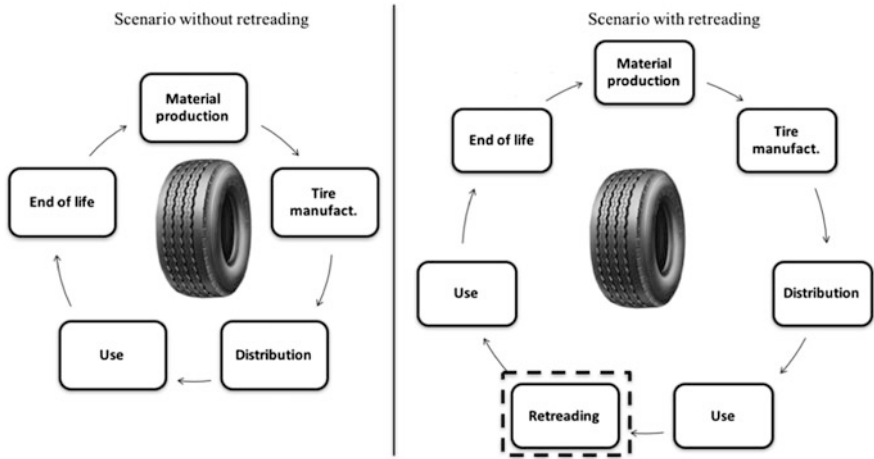
Fig. 2 Life cycle phases included into life cycle sustainability assessment

environmental and social impacts; together with life cycle costs of used tire management scenarios associated with different life extension options.

As such, this case study aims to analyse environmental, social and cost performances obtained through life cycle assessment approach in order to support the choice between two scenarios:

Scenario 1, without retreading—the tire reaches its final end-of-life once its original tread reaches maximum wear.

Scenario 2, with retreading—when the tread reaches maximum wear, the tire is retreaded and reused for the same freight transport.

The functional unit is the same for the three sustainability dimensions: "providing tires for truck transport with a payload of 32 metric tons over 600,000 km in Brazil in 2012 and managing used tires". It offers an impact evaluation based on the kilometres travelled rather than the number of units sold. Figure 2 illustrates the product system considered in our analysis.

3.2 Case Study Results

For the first phase of our methodology, assessing uncertain LCSA performances for the three pillars of sustainability, the performances were obtained from 2 successive studies conducted in 2015 and 2016 [19, 20]. Both studies are not publicly disclosed and include confidential information. The indicators considered in our Case study are illustrated in Fig. 3.

Figure 4 presents the performances for each indicator considered for the three pillars of sustainability.
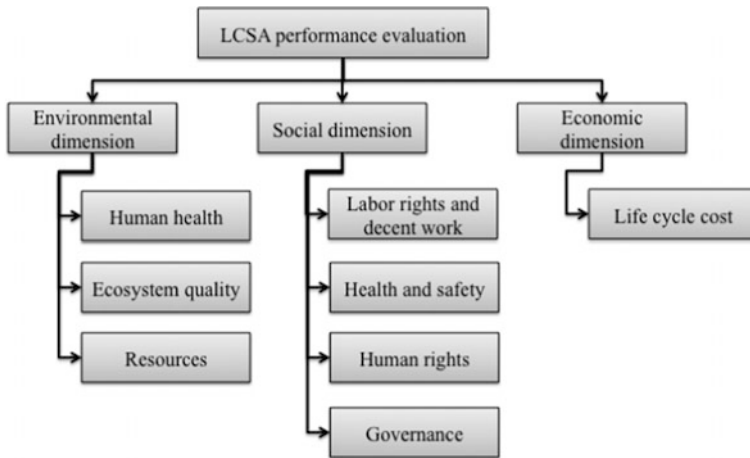
Fig. 3 Indicators adopted for life cycle sustainability assessment

Considering the second phase of our methodology, extending LCSA performances uncertainty to MCDA methods, we applied the three MCDA methods through two sets of weighting factors, as presented in Table 1.

Finally, for the third phase of our method, Fig. 5 presents the probability that the scenario with retreading scores better than the scenario without retreading, considering the three MCDA methods, two sets of weighting factors provided by decision makers (Table 1) and the probabilistic environmental, social and economic performances obtained by LCSA approach (Fig. 3). The confidence level is obtained by the counts of simulations where a scenario ranks higher than the other and normalized the count by total number of simulations.

Scenario with retreading is the preferred solution compared to scenario without retreading with more than 80% probability for the weighted sum and Topsis methods. The preference of the retreading scenario is reduced down up to 60% with the Prométhée II method, because this type of approach (outranking) takes into account the indifference and preference thresholds, creating the zones of equivalence and weak preference. As such, scenario with retreading seems to be a strong compromise solution for our case study for all combinations of MCDA methods and sets of weighting factors.

3.3   Discussion

This research highlights that it is feasible to account for the uncertainty associated with LCSA indicators in a decision-making process when applying MCDA methods. We were able to generate ranking about the preference of an option compared to the other whilst informing the decision-maker on the level of
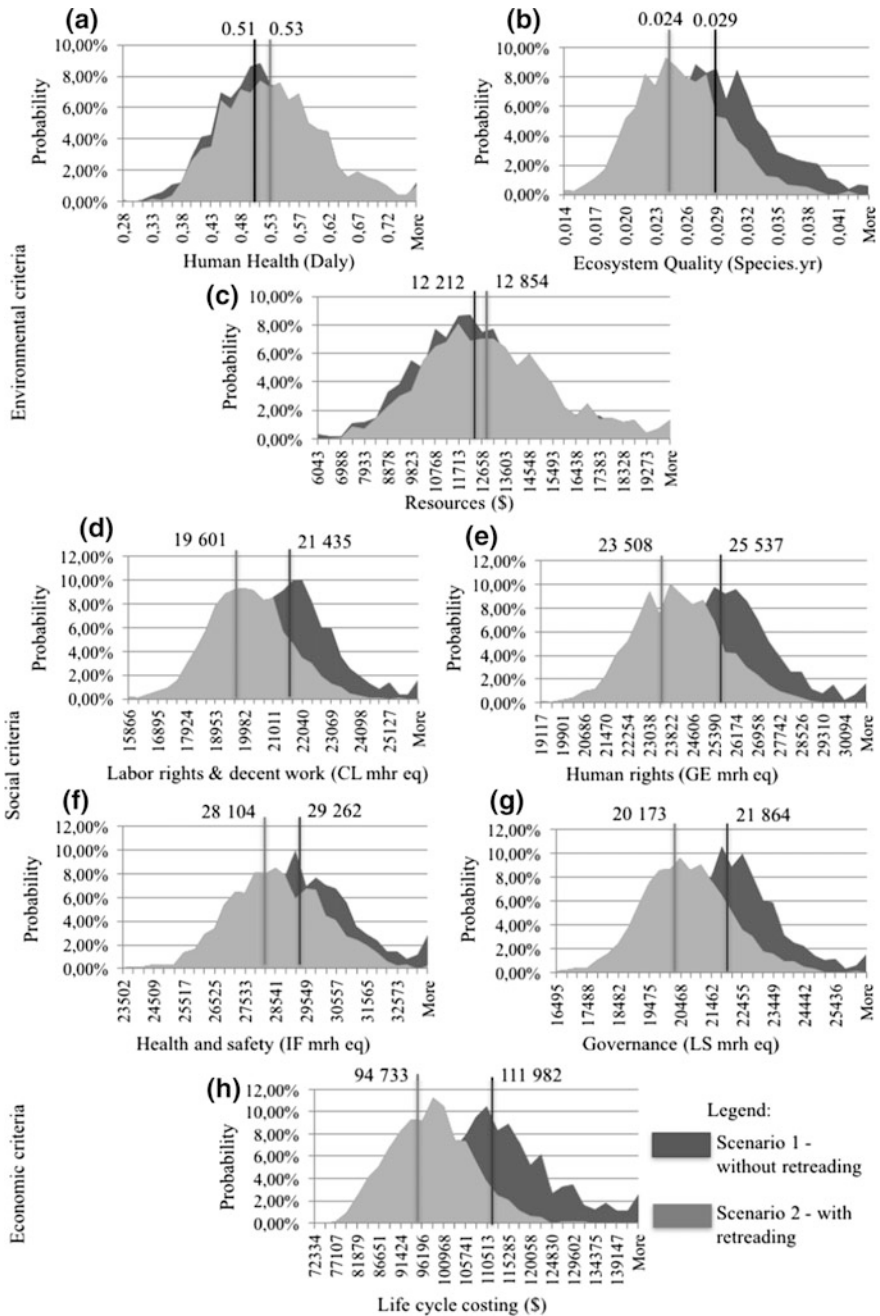
Fig. 4 LCSA performances for scenarios with retreading and without retreading

Table 1 Sets of weighting factors considered for MCDA methods

Decision variables		Weighting factors	
Sustainability dimensions	Decision criteria	Set 1 (%)	Set 2 (%)
Social	Labour rights and decent work	8	8
	Health and security	8	8
	Human rights	8	8
	Governance	8	3
Environmental	Human health	11	8
	Ecosystem quality	11	5
	Resources	11	13
Economic	Life cycle cost	34	50
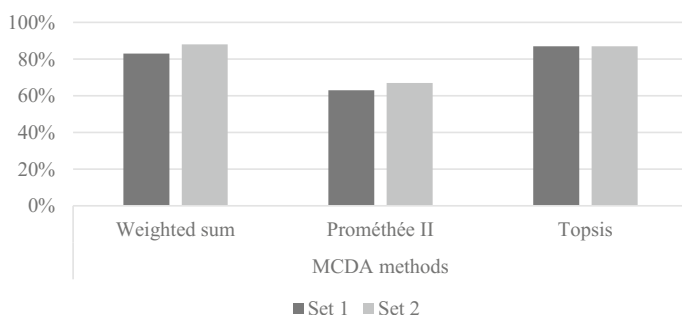
Fig. 5 Probability that Scenario with retreading scores better than Scenario without retreading for the two sets of weighting factors

confidence in such final ranking. Stochastic results provide a measure of the robustness of the ranking and conclusions. Scenario with retreading show a higher probability to reflect the best compromise solution according the value judgments of the decision-makers.

Our approach is very useful when ranking products considering their uncertain LCSA performances. It be also applied in cases where many scenarios are compared.

4   Conclusions

As all sustainable decision-making problems based on LCSA approach, choosing a scenario to supply tires for road transportation involves trade-offs when including the three pillars of sustainability into decision-making process. We used the MCDA approach to rank the potential scenarios and recommended a solution offering the better compromise in the view of decision-makers value judgments.

The implementation of three MCDA methods through two sets of weighting factors and uncertain LCSA performances allowed analysing the robustness of the recommendation. From the results, we conclude that scenario with retreading is preferred than the one without retreading. The stochastic results revealed this scenario as a strong compromise solution.

This case study presented the importance of taking into account the following three elements when supporting decision-making process through the MCDA approach applied to LCSA performances: (i) implement different MCDA methods with different aggregation characteristics; (ii) vary the MCDA mandatory parameters and (iii) take into account the uncertainty of the LCSA performances.

The first element allowed analysing the similarity among the compromise recommendations from each method. Secondly, using different sets of mandatory parameters allowed incorporating the imprecision associated to the preference elicitation process, improving the representativeness of the decision-maker's value judgment. Finally, taking into account the uncertainty of the performances increased the robustness of the compromise ranking provided by each method.

References

1. Martín-Gamboa M, Iribarren D, García-Gusano D, Dufour J, A review of life-cycle approaches coupled with data envelopment analysis within multi-criteria decision analysis for sustainability assessment of energy systems, *Journal of Cleaner Production*, vol. 150, 2017, pp 164–174.
2. Zamagni A, Pesonen H-L, Swarr T, From LCA to life cycle sustainability assessment: concept, practice and future directions, *The international journal of life cycle assessment,* Vol. 18, 2013, pp 1637–1641.
3. Heijungs R, Huppes G, Guinée J.B, Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis, Polymer Degradation and Stability, Vol. 95, 2010, pp 422–428.
4. Halog A, Manik Y, Advancing integrated systems modeling framework for life cycle sustainability assessment, Sustainability, Vol. 3, 2011, pp. 469–499.
5. Shärlig A, Décider sur plusieurs critères: panorama de l'aide à la décision multicritère, Presses polytechniques et universitaires romandes, 1985.
6. Laurin L, Amor B, Bachmann T.M, Bare J, Koffler C, Genest S, Preiss P, Pierce J, Satterfield B, Vigon B, Life cycle assessment capacity roadmap (section 1): decision-making support using LCA, *The international journal of life cycle assessment,* Vol. 21, 2016, pp 443–447.
7. Traverso M, Finkbeiner M, Jorgensen A, Schneider L, Life cycle sustainability dashboard, Journal of industrial ecology, Vol. 16, No. 5, 2012, pp 680–688.
8. Finkbeiner M, Schau E M, Lehmann A, Traverso M, Towards life cycle sustainability assessment, Sustainability, Vol. 2, 2010, 3309–3322.
9. Vinyes E, Oliver-Solà J, Ugaya C, Rieradevall J, Gasol C.M, Application of LCSA to used cooking oil waste management. *The international journal of life cycle assessment,* Vol. 18, 2013, 445–455.
10. Lora E.E.S, Palacio J.C.E, Rocha M.H, Reno M.L.G, Venturini O.J, Olmo O.A, Issues to consider, existing tools and constraints in biofuels sustainability assessments, Energy, Vol. 36, 2011, pp 2097–2110.

11. Bachmann T.M, Towards life cycle sustainability assessment: drawing on NEEDS project's total cost and multi-criteria decision analysis ranking methods, *The international journal of life cycle assessment*, Vol. 18, 2013, pp 1698–1709.

12. Keller H, Rettenmaier N, Reinhardt G.A, Integrated life cycle sustainability assessment—a practical approach, Applied Energy, Vol. 154, 2015, pp 1072–1081.

13. Myllyviita T, Holma A, Antikainen R, Lähtinen K, Leskinen P, Assessing environmental impacts of biomass production chains—application of life cycle assessment (LCA) and multi-criteria decision analysis (MCDA), Journal of Cleaner Production, Vol. 29, 2012, pp 238–245.

14. Hanandeh A.E, El-Zein, The development and application of multi-criteria decision-making tool with consideration of uncertainty: The selection of a management strategy for the bio-degradable fraction in the municipal solid waste, Bio resources Technology, Vol. 101, 2010, pp 555–561.

15. Benetto E, Dujet C, Rousseaux P, Fuzzy multicriteria approach with uncertainty analysis for Life Cycle Assessment. Environmental Software and Modelling, Vol. 23, Issue 12, 2008, pp 1461–1467.

16. Goedkoop M.J, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R, ReCiPe—A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterisation; 6 January 2009, http://www.lcia-recipe.net.

17. Hunkeler D, Lichtenvort K, Rebitzer G (eds.) Environmental life cycle costing. SETAC, Pensacola, FL (US) in collaboration with CRC Press, Boca Raton, FL, USA, 2008.

18. Carmo B.B.T, Margni M, Baptiste P, Ranking product systems based on uncertain life cycle sustainability assessment: A stochastic multiple criteria decision analysis approach, Journal of Cleaner Production, submitted.

19. Imbeault-Tétreault H, Carmo B.B.T, Life cycle sustainability assessment of tires retreading. Montréal, 51 p, 2017.

20. Imbeault-Tétreault H, Beaulieu L, Fallaha S, Russo Garrido S, Samson R., Revéret J-P, ACV environnementale et sociale d'options de prolongation de la vie utile de pneus de poids lourds au Brésil. Montreal, 294 p, 2015.