Supplementary information to: Assessment of functional alternatives to fluorinated foam blowing agents in insulation materials

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Summary

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SI 1: Background information on MCDA methods

Multi-criteria decision analysis (MCDA) methods were developed to guide and help decision makers to achieve multiple, and usually conflicting, objectives. These methods can be classified in two main categories[1]:

- Full aggregation approaches
- Outranking approaches

Full aggregation approaches

In the full aggregation approaches aim to rank different options to solve a problem based on a predefined set of criteria. The options are ranked based on a single score calculated according to the performance of the option in each criterion being considered. In those approaches, compensation between the criteria being evaluated is made possible. The multi attribute utility theory (MAUT) method is one of the most common full aggregation approaches. This method assumes that the decision maker is trying to optimize a function which aggregates all their preferences. These preferences are represented by a utility function which measures the desirability of each option (or alternative) for each criterion being considered[1].

In short, the utility function is used to transform the data used to evaluate the different alternatives according to the set of criteria into a dimensionless scale from 0 to 1 (Figure S1.1). 0 represents the least favored outcome of the criterion, while 1 represents the best possible outcome. An aggregation function is then used to calculate a final score for each alternative being evaluated. The aggregation function can translate the preferences of the decision makers for certain criteria compared to the other, for example by increasing their weight in the calculation. This final score is used to rank the alternatives and to identify the best option[1–3].

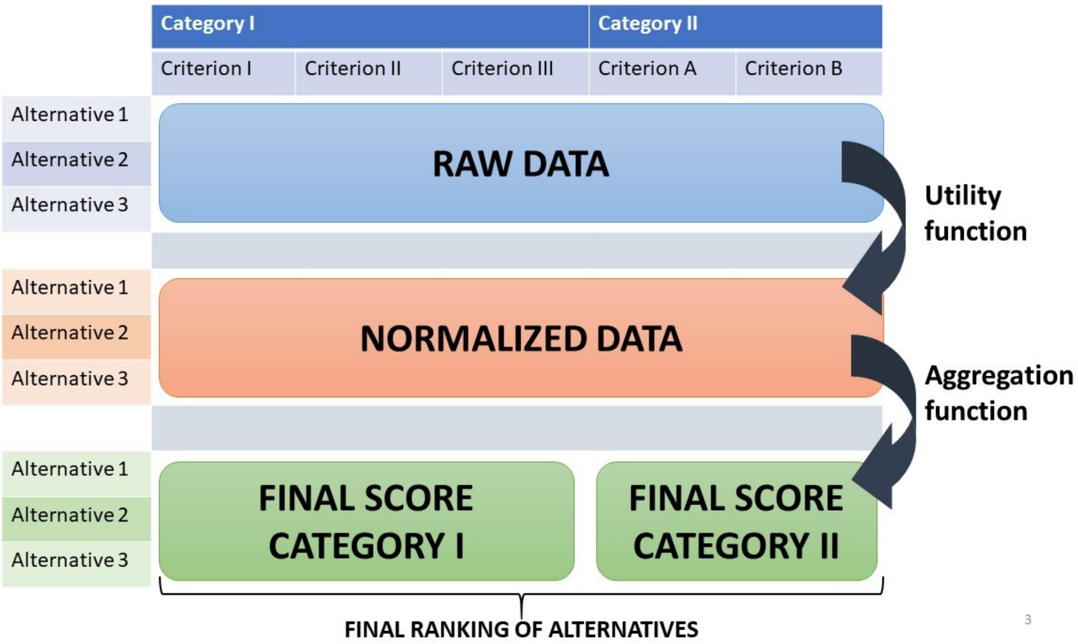

Figure SI 1.1. Overview of the MAUT method

Analytical hierarchy and analytical network processes are other full aggregation approaches commonly used. In short, those processes are similar to the MAUT method except that the decision maker does not need to determine a utility function beforehand[1].

Outranking approaches[1]

Outranking approaches are based on a pair-wise comparison of the alternatives for each criterion. In other words, the alternatives are compared two-by-two for each criterion. In those methods, the decision makers must set indifference, preference and veto thresholds which are meant to reflect how much an option is preferred than another in a given criterion. In those approaches, no compensation between the criteria being evaluated is possible. As a consequence, the comparison between two alternatives might become too difficult as they have profile too different: one alternative might be preferred based on one set of criteria, while the other is preferred on a second set of criteria. As a consequence, a complete ranking of the different alternatives might not be always possible. The Preference Ranking Organization METHod for Enriched Evaluation (PROMETHEE), and the *ELiminiation Et Choix Traduisant la RÉalité* (ELECTRE) (translated into elimination and choice exoressing reality) are two outranking methods commonly used[1,3–6].

Approach of this study

In this study, alternatives were compared by following the MAUT approach based on their technical performance and environmental impacts attributes. Given the high number of criteria identified for evaluation in each attribute (i.e., performance, and environmental impacts), they were gathered in different criteria categories, as illustrated below (Figure SI 1.2).

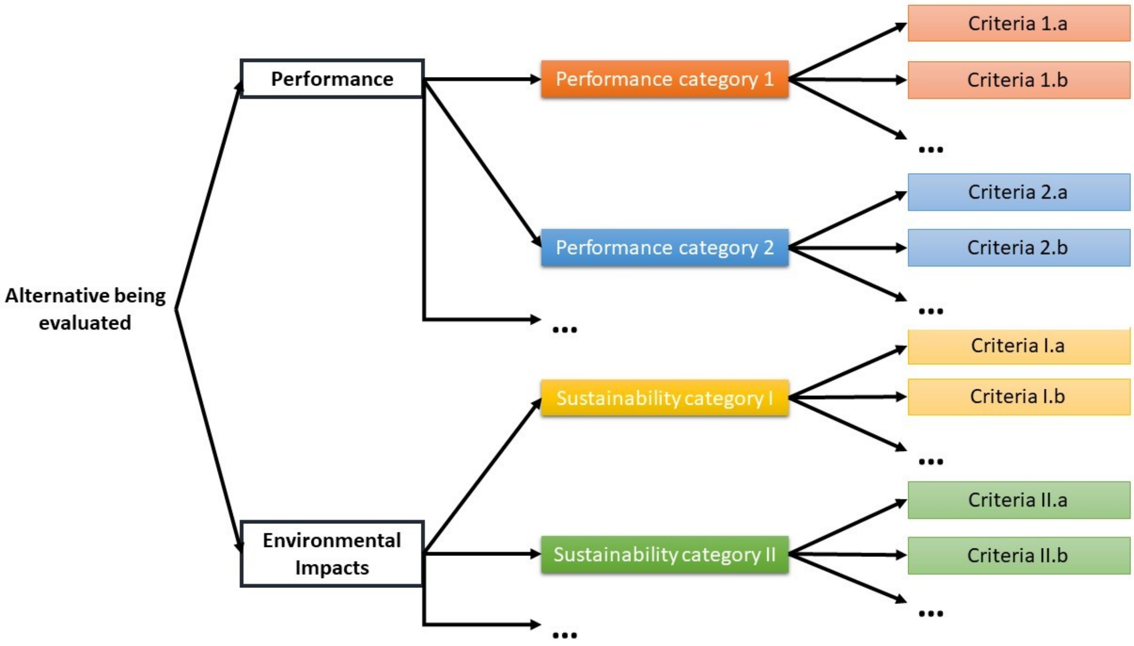

Figure SI 1 2 Categorization of the criteria for evaluation of the identified alternatives

SI 2: Identification of the substances to be substituted and potential functional alternatives

The Table SI 2 presents the information collected from the ZeroPM database to identify the substances of concern and the potential functional alternatives[7]. The list of potential functional alternatives was completed with the information collected from a previous literature review on insulation materials[8].

Table SI 2. Description of substances to be substituted and identified potential functional alternatives

SI 3: Background information on the collection of the life cycle impact assessment (LCIA) data

Thermal insulation materials offer environmental benefits by reducing energy consumption for heating and cooling, thus cutting down energy demand during the use phase of a building (Bhandari et al., 2016; Biswas et al., 2016; Braulio-Gonzalo & Bovea, 2017; Petrosyan, 2019). However, these materials can also present environmental and health concerns, particularly through resource extraction, production processes, and end-of-life disposal along with indoor air emissions (Balo & Sua, 2023; Biswas et al., 2016; Foti et al., 2023; Gadallah & Aboulnaga, 2020; Naldzhiev et al., 2020; Velichko et al., 2017; Wi et al., 2021). This study included the environmental impacts of different insulation materials, focusing not on their energy-saving benefits in use phase but on comparing alternative materials in production phase to identify the option with the lowest potential environmental impact. Life Cycle Assessment (LCA) is an established methodology for assessing the environmental footprint of products and processes (Baumann & Tillman, 2004; Hauschild, 2018; ISO, 2006a, 2006b). This approach considers a product's life cycle encompassing all associated inputs and outputs. LCA is increasingly utilized to quantify the potential environmental impacts of products, including thermal insulation materials, to inform sustainable material choices. There is a substantial body of literature on LCA applications for insulation materials, reflecting the field's focus on both improving energy efficiency and reducing environmental impacts. This study contributes to that body of knowledge by examining thermal insulation options to determine the most environmentally favorable choice, supporting decision-making.

This study covers a variety of thermal insulation materials, each with distinct environmental profiles, including fibreglass, expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane, cellulose, hemp, cork, wood fibre, and sheep wool. Several comprehensive literature reviews have explored the environmental impacts of these materials. Notably, Füchsl et al. (2022) provide an in-depth review of the environmental profiles of traditional and bio-based insulation materials, while Schiavoni et al. (2016) investigate the different insulation options, focusing on their environmental impact and technical performance offering valuable insights into the advantages and drawbacks of each material.

Fibreglass is a widely studied insulating material for its high insulation efficiency. It is discussed in the context of environmental impacts in studies such as Ardente et al. (2008); Arellano-Vazquez et al. (2020); Asdrubali et al. (2015); Carabaño et al. (2017); Casas-Ledón et al. (2020); Colli et al. (2020); Cozzarini et al. (2020); Dickson and Pavía (2021); Kadziński et al. (2018); Mattoni et al. (2019); Ricciardi et al. (2014); Sierra-Pérez et al. (2016); Zhao et al. (2018). These studies evaluate the lifecycle impact of fibreglass, particularly its energy consumption during production, emissions, and disposal challenges. Known for its durability and fire resistance, rock wool is another popular insulation material. Research by Ardente et al. (2008); Arellano-Vazquez et al. (2020); Asdrubali et al. (2016); Casas-Ledón et al. (2020); Čekon et al. (2017); Cozzarini et al. (2020); de la Hera et al. (2017); Densley Tingley et al. (2015); Dickson and Pavía (2021); Ingrao et al. (2014); Intini and Kühtz (2011); Kadziński et al. (2018); Ma et al. (2014); Mattoni et al. (2019); Papadopoulos and Giama (2007); Ricciardi et al. (2014); Sierra-Pérez et al. (2016); Struhala et al. (2016); Zabalza Bribián et al. (2011); Zampori et al. (2013) focuses on rock wool's environmental impacts. Studies by Arellano-Vazquez et al. (2020); Asdrubali et al. (2016); Biswas et al. (2016); Casas-Ledón et al. (2020); Čekon et al. (2017); Colli et al. (2020); Cozzarini et al. (2020); Densley Tingley et al. (2015); Gomes et al. (2020); Ingrao et al. (2014); Intini and Kühtz (2011); Kadziński et al. (2018); Mattoni et al. (2019); Pargana et al. (2014); Ricciardi et al. (2014); Struhala et al. (2016); Usubharatana and Phungrassami (2019); Zabalza Bribián et al. (2011) discuss Expanded Polystyrene (EPS) environmental concerns. Extruded Polystyrene (XPS) is frequently studied for its high insulation performance and environmental challenges during production. Research by Antoniadou et al. (2015); Arellano-Vazquez et al. (2020); Asdrubali et al. (2016); Biswas et al. (2016); Carabaño et al. (2017); Casas-Ledón et al. (2020); Colli et al. (2020); Ma et al. (2014); Papadopoulos and Giama (2007); Pargana et al. (2014); Ricciardi et al. (2014); Sierra-Pérez et al.

(2016); Usubharatana and Phungrassami (2019); Židoniene and Kruopiene (2015) evaluates the lifecycle impacts of XPS, including greenhouse gas emissions and energy consumption. Studies by Ardente et al. (2008); Colli et al. (2020); Cozzarini et al. (2020); Intini and Kühtz (2011); Kadziński et al. (2018); Ma et al. (2014); Marconi et al. (2020); Pargana et al. (2014); Sierra-Pérez et al. (2016); Usubharatana and Phungrassami (2019); Zabalza Bribián et al. (2011) highlight polyurethane's environmental impacts. Cellulose is considered a sustainable option due to its use of recycled materials. Studies by Ardente et al. (2008); Asdrubali et al. (2016); Buratti et al. (2018); Casas-Ledón et al. (2020); Colli et al. (2020); Dickson and Pavía (2021); Mattoni et al. (2019); Ricciardi et al. (2014); Zabalza Bribián et al. (2011) reviewed cellulose's potential as an environmentally friendly insulation material. A bio-based insulation material, hemp is reviewed in studies by Arrigoni et al. (2016); Arrigoni et al. (2017); Colli et al. (2020); Dickson and Pavía (2021); Kadziński et al. (2018); Sinka et al. (2018); Zampori et al. (2013). These studies discuss hemp's renewable properties, environmental impact, and potential as a sustainable alternative in construction, particularly due to its lower embodied energy and carbon sequestration benefits. Cork insulation is praised for its renewable and biodegradable properties. Asdrubali et al. (2016); Buratti et al. (2018); Carabaño et al. (2017); Demertzi et al. (2017); Dickson and Pavía (2021); Ingrao et al. (2014); Kadziński et al. (2018); Pargana et al. (2014); Ricciardi et al. (2014); Sierra-Pérez et al. (2016); Silvestre et al. (2016); Zabalza Bribián et al. (2011) discuss cork's life cycle environmental impact. Wood fibre insulation is reviewed for its sustainability, biodegradability, and carbon sequestration potential. Studies by Nakano et al. (2018); Rocchi et al. (2018); Yildrim (2018) discuss wood fibre's environmental impacts. Dickson and Pavía (2021) examine the use of sheep wool as an insulation material, noting its energy performance and environmental impact.

Each of these insulation materials presents different environmental considerations and benefits, and the cited literature provides comprehensive assessments of their life cycles impacts. By analyzing these materials, this study aims to identify insulation options that minimize environmental impacts.

In this study, the LCA impacts are calculated based on the functional unit of providing a thermal resistance of 1 R over a 1 square meter area. The material's thermal conductivity and density are used to determine the reference flow, which is the amount of insulation material necessary (in kilograms) to meet this functional requirement. This LCA follows a cradle-to-gate approach, focusing only on the potential environmental impacts of producing the insulating material, including all production-related emissions and waste. However, waste generated during the material's use phase is not included, representing one of the study's limitations, as different materials might produce varying amounts of waste in real-life applications.

The geographical scope of the impact assessment is both global and European, utilizing data from Ecoinvent 3.9 with a cutoff methodology (Ecoinvent, 2024). This data set includes market data, which also accounts for transportation impacts. One of the key assumptions in this study is that the insulation materials under evaluation are equivalent in fulfilling the thermal resistance requirement over their design life without needing replacement. While different materials may have different lifespans, this study does not consider scenarios where a material might need replacement if it fails before the end of the application design life.

The study also does not factor in end-of-life impacts. The disposal processes for insulation materials such as landfilling, recycling, incineration, and incineration with energy recovery could vary in their environmental impacts. Materials requiring disposal in hazardous waste landfills or incineration facilities due to the presence of toxic substances, like flame retardants, would likely have a higher end-of-life impact than those disposed of through conventional means. However, these aspects are beyond the scope of this study. Based on the functional unit, the total reference flow for each material is calculated, and from this, the cradle-to-gate LCA impacts are determined for comparative analysis.

The impacts are calculated using the Product Environmental Footprint (PEF) recommended life cycle impact assessment method EFv3.1 EN15804 along with IPCC 2021 to evaluate the potential environmental impacts, as shown in Table SI 3 (European Commission, 2023; IPCC, 2023). In total, different impact indicators were selected to compare the materials. Among these indicators, special emphasis was placed on climate change impacts, given that toxicity impacts are assessed in other criteria of the comparison. These sustainability impact categories are pivotal in the overall analysis, highlighting the importance of environmental criteria alongside other criteria.

Table SI 3. Selected life cycle impact categories

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SI 4: Shortlisting of potential alternatives and collection of data for evaluation

Table SI 4.1 is listing the alternatives shortlisted for further evaluation. Tables SI 4.2 presents the collected data related to the technical performance the shortlisted alternatives, and Table SI 4.3 presents the characterization factors calculated for 1 kg of each shortlisted alternative, respectively.

Table SI 4.1. Potential functional alternatives shortlisted for further evaluation

Table SI 4.2. Data related to the technical performance of insulation materials

Table SI 4.3. Characterization factors for 1 kg of the insulation materials

The life cycle impacts of each shortlisted alternative were calculated by multiplying the characterization factors by the amount of materials (in kilograms) required to fulfil the defined functional unit, i.e. the insulation of an area of 1 m^2 with a thermal transmittance of 1 W/m^2K. The amount of materials required could be calculated using the relationship between the thermal transmittance, the thickness and the thermal conductivity of the material (Equation 1), and the density of the material (Equation 2).

$$Thermal\ Transmittance\left(\frac{W}{m^2K}\right) = \frac{Thermal\ conductivity\ (\frac{W}{mK})}{Thickness\ (m)}$$

Equation 1: Relationship between thermal transmittance, thermal conductivity and thickness.

$$Mass\ of\ materials\ (kg) = Density\ of\ materials\left(\frac{kg}{m^3}\right) * Area\ (m^2) * Thickness\ (m)$$

Equation 2: Calculation of the mass of materials based on the density of the material, the area, and the thickness

As the values for the thermal conductivity and the density of the shortlisted alternatives varied according to the approach taken, the life cycle impacts used as input in the MAUT models changed. Tables SI 4.4.A, SI 4.4.B, and SI 4.4.C present the mass of materials required to fulfil the functional unit, and the resulting life cycle impacts for each shortlisted alternative following the neutral approach, optimistic approach, and pessimistic approach, respectively.

Table SI 4.4.A. Life cycle impacts of the shortlisted alternatives - Neutral approach

Table SI 4.4.B Life cycle impacts of the shortlisted alternative - Optimistic approach

Table SI 4.4.C Life cycle impacts of the shortlisted alternative - Pessimistic approach

SI 5: Performance matrices for the baseline scenario

Tables SI 5.1, SI 5.2, and SI 5.3 present the input data used for the baseline scenario following the neutral approach, optimistic approach, and pessimistic approach, respectively.

Table SI 5.1 Performance matrix for the baseline scenario - Neutral approach

Table SI 5.2. Performance matrix for the baseline scenario - Optimistic approach

Table SI 5.3. Performance matrix for the baseline scenario - Pessimistic approach

SI 6: MAUT models for the baseline scenarios

Tables SI 6.1.A, SI 6.1.B, and SI 6.1.C present the MAUT models which based on raw input data for the baseline scenario following the neutral approach, optimistic approach, and pessimistic approach, respectively.

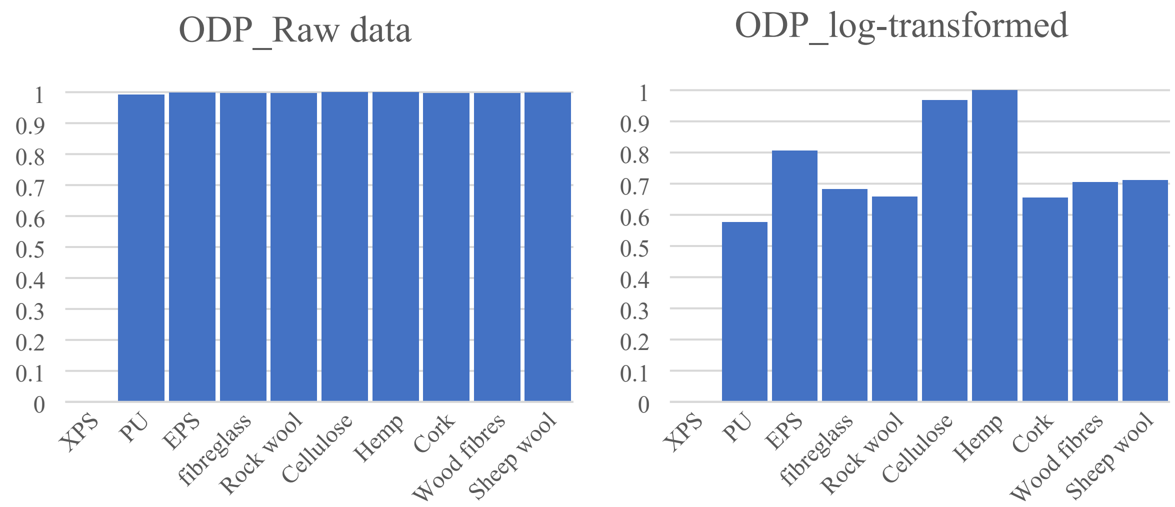
Table SI 6.1.A. MAUT model with raw data for the baseline scenario - Neutral approach

Table SI 6.1.B. MAUT model with raw data for the baseline scenario - Optimistic approach

Table SI 6.1.C. MAUT model with raw data for the baseline scenario - Pessimistic approach

For some criteria, the data for the different alternatives are distributed on a range of several order of magnitude (especially for environmental impacts criteria). When normalising the data, this results in alternatives being grouped with very little differences in normalised data. To ensure that the normalised data of the different alternatives are better distributed between 0 and 1, the input data was log-transformed before running the normalisation step. Figures SI 6.1.A and B illustrate the effect of the log-transformation of the raw data on the distribution of the normalised data for criteria on ozone layer depletion potential (ODP) and on ecotoxicity (Ecotox.), respectively.

A)



B)

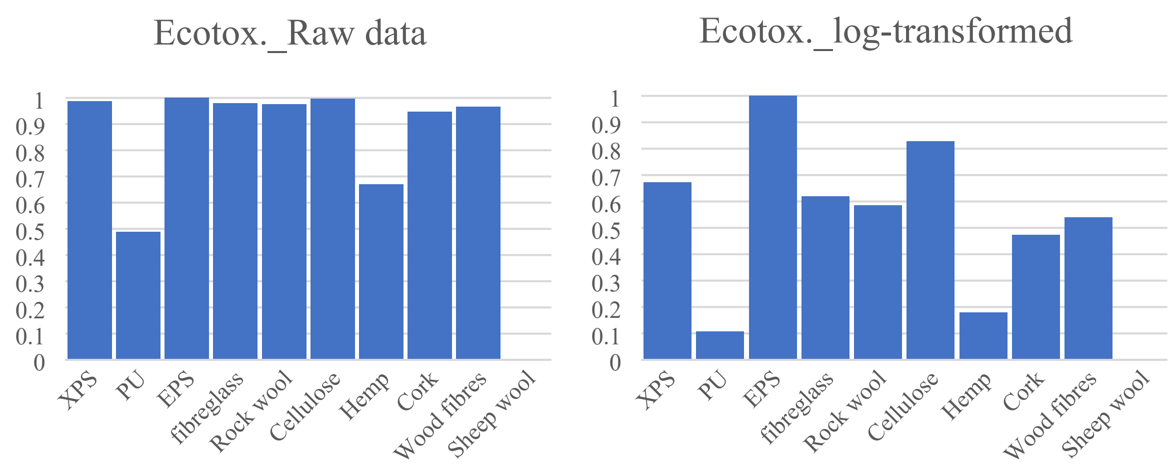


Figure SI 6 1 Effect of log-transformation of the raw data on the distribution of the normalised data for the ozone layer depletion potential (A) and the ecotoxicity (B) criteria

Tables SI 6.2.A, SI 6.2.B, and SI 6.2.C present the MAUT models based on log-transformed input data for the baseline scenario following the neutral approach, optimistic approach, and pessimistic approach, respectively.

Table SI 6.2.A. MAUT model with transformed data for the baseline scenario - Neutral approach

Table SI 6.2.B. MAUT model with transformed data for the baseline scenario - Optimistic approach

Table SI 6.2.C. MAUT model with transformed data for the baseline scenario - Pessimistic approach

SI 7: MAUT models for the no compensation scenarios

Tables SI 7.1, SI 7.2, and SI 7.3 present the MAUT models based on log-transformed input data for the scenario which does not allow for compensation between the criteria following the neutral approach, optimistic approach, and pessimistic approach, respectively.

Table SI 7.1. MAUT model for the no compensation scenario - Neutral approach

Table SI 7.2. MAUT model for the no compensation scenario - Optimistic approach

Table SI 7.3. MAUT model for the no compensation scenario - Pessimistic approach

SI 8: MAUT models for the sequential decision-making scenario, by considering technical performance attributes first

Tables SI 8.1, SI 8.2, and SI 8.3 present the results from the MAUT models based on log-transformed input data by considering criteria related to the technical performance only, following the neutral approach, optimistic approach, and pessimistic approach, respectively.

Table SI 8.1. MAUT model for the sequential scenario - Performance ranking for the neutral approach

Table SI 8.2. MAUT model for the sequential scenario - Performance ranking for the optimistic approach

Table SI 8.3. MAUT model for the sequential scenario - Performance ranking for the pessimistic approach

Tables SI 8.4, SI 8.5, and SI 8.6 present the results from the MAUT models based on sustainability criteria only for the five best alternatives regarding technical performance attributes according to the previous step, following the neutral approach, optimistic approach, and pessimistic approach, respectively.

Table SI 8.4. MAUT model for the sequential scenario - Final ranking for the neutral approach

Table SI 8.5. MAUT model for the sequential scenario - Final ranking for the optimistic Scenario

Table SI 8.6. MAUT model for the sequential scenario - Final ranking for the pessimistic Scenario

SI 9: MAUT models for the sequential decision-making scenario, by considering sustainability attributes first

Tables SI 9.1, SI 9.2, and SI 9.3 present the results from the MAUT models based on log-transformed input data by considering criteria related to sustainability only, following the neutral approach, optimistic approach, and pessimistic approach, respectively.

Table SI 9.1. MAUT model for the sequential scenario - Sustainability ranking for the neutral approach

Table SI 9.2. MAUT model for the sequential scenario - Sustainability ranking for the optimistic approach

Table SI 9.3. MAUT model for the sequential scenario - Sustainability ranking for the pessimistic approach

Tables SI 9.4, SI 9.5, and SI 9.6 present the results from the MAUT models based on technical performance criteria only for the five best alternatives regarding sustainability attributes according to the previous step, following the neutral approach, optimistic approach, and pessimistic approach, respectively.

Table SI 9.4. MAUT model for the sequential scenario - Final ranking for the neutral approach

Table SI 9.5. MAUT model for the sequential scenario - Final ranking for the optimistic approach

Table SI 9.6. MAUT model for the sequential scenario - Final ranking for the pessimistic approach

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