Towards a more sustainable surface transport infrastructure: A Case study of applying multi criteria analysis techniques to assess transport noise reducing devices

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Abstract

The surface transport infrastructure (i.e. road and rail) has seen increasing pressure in recent years to achieve better sustainability performance. Transport Noise Reducing Devices (NRDs) form a major part of the surface transport infrastructure system in mitigating undesirable surface noise pollution to impacted communities. Their sustainability is a growing interest for practitioners in this area as NRDs projects now have to balance integrating and assessing social, environmental, and economic objectives besides meeting key technical requirements. This paper presents an account of the first study carried out to assess the absolute sustainability of NRDs via the application of multi criteria analysis (MCA) techniques. The general procedure, selection of criteria, data gathering, and the use of three MCA techniques, SAW, PROMETHEE, and ELECTRE III, to assess the absolute sustainability of two built and operating European NRDs projects (one in Spain, and one in Italy) is presented. The novel notion of defining an Optimal Hypothetic Ideal Solution (OHIS) to assess the sustainability of NRDs in absolute terms to achieve this end is also introduced and discussed. The presented case studies will thus provide a useful model for practitioners to adopt or amend to conduct their own assessments of NRDs' sustainability. The paper further concludes that the generation of index values by the three MCA techniques to denote the overall absolute sustainability of solutions is a useful feature for communicating the sustainability of NRDs across a broad range of stakeholders, and for conducting "what-if" analyses. The presented research could also support broader aims of developing harmonized sustainability standards for the NRDs industry to adopt and so forward the sustainability transport agenda.

Keywords*:* Criteria; framework; indicators; multi-criteria analysis; practicality; sustainability; stakeholders; noise barriers, transport, case study, road, rail, noise reducing devices.

1. Introduction: the Importance of Considering Transport Noise Reducing Devices' (NRDs) Sustainability as a Component Towards Advancing the Overall Sustainability of Surface Transport Infrastructure Systems

The surface transport infrastructure (i.e. road and rail) and the systems that support it have seen increasing pressure in recent years to achieve better sustainability performance (Commission of the European Communities', 2001; European Commission, 2011). Transport Noise Reducing Devices (NRDs) form a major part of the surface transport infrastructure system as a means of mitigating undesirable surface noise to impacted communities. The consideration of their sustainability is a growing interestfor practitioners in this area as typical NRDs projects need to balance addressing environmental and social needs, involve the utilization of raw materials comparable to other large built structures, and have a high economic impact that needs to be justified. The problem is further heightened as considerations of the above and the need for transport NRDs are unlikely to decrease in the near future as surface transport noise is projected to get increasingly worse over the next two decades as a consequence of traffic growth (e.g. Transport and Environmental, 2010; Boer and Schroten, 2007; Organisation for Economic Co-operation and Development-OECD, 2008; Ying, 2000). Figure 1 illustrates the complexity of such a task and the typical scope of considering NRDs' sustainability. It shows the NRDs Sustainability Life Cycle Analysis (SLCA) system boundary developed by the authors of this paper for the purposes of conducting a whole life sustainability assessment of NRDs projects.

The aim here is to succinctly show visually and describe the key stages, processes, and activities to consider and therefore aid criteria selection pertinent to the project and priorities of the decision maker. By definition, a sustainability analysis in principle implies assessing the whole life of buildings, projects and construction products.

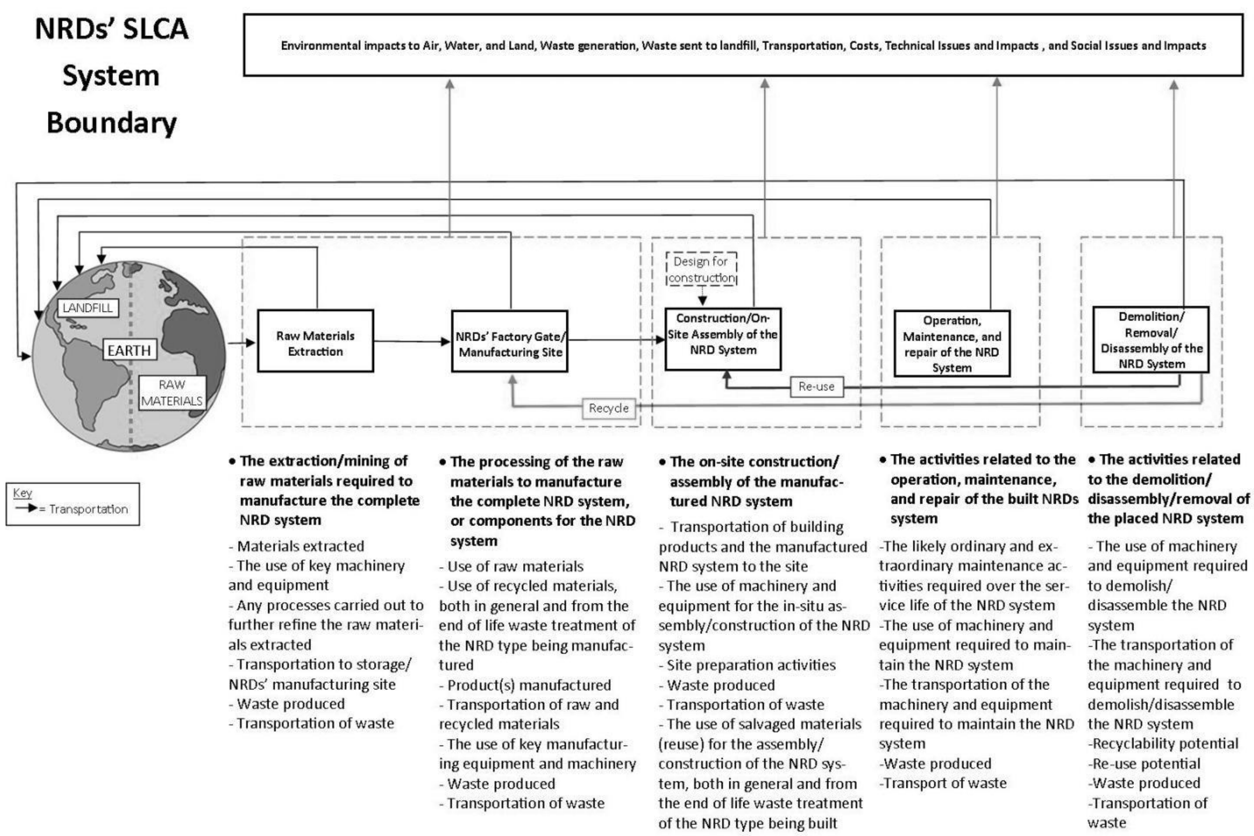

Figure 1: The NRDs' sustainability life cycle assessment (SLCA) system boundary

Clearly, assessing the sustainability of NRDs involves evaluating multiple and sometimes conflicting social, environmental, and economic objectives beside meeting key technical requirements (Oltean-Dumbrava et al., 2012). However, there is at present a current worldwide lack of support for practitioners wishing to carry out such assessments as no practical study of the aforementioned exists. Multi criteria Analysis (MCA) techniques claim to be able to solve such problems and so forms the principle area of investigation in this paper. The purpose of this paper is to provide a practical account of the study carried out to assess the absolute sustainability of two NRDs projects in Europe (i.e. one in Spain, and one in Italy) using the MCA methods and tools mentioned above. The presented research will thus support the relevant stakeholders (i.e. National road and rail authorities, transport planners, asset managers, acoustical engineers, consultants, contractors, manufacturers, etc.) make more sustainable decisions and provide a useful model for practitioners to adopt or amend to conduct their own assessments of NRDs' sustainability.

The paper first begins in Section 2 by asserting and discussing the importance of defining “sustainability” in order to clearly state the aim of any MCA with regards to assessing sustainability. Section 3 then presents the general stages for carrying out a sustainability assessment of NRDs, and describes the steps necessary for structuring and carrying out the MCA analysis. Prior to the case study, Section 4 discusses the importance of discerning the difference between conducting relative sustainability assessments and absolute sustainability assessments and the concept an Optimal Hypothetical Ideal Solution (OHIS) to assess the absolute sustainability of NRDs is introduced and discussed here.

The paper then proceeds using the procedure from Section 3 to present an assessment of the sustainability of two European NRD projects as a part of the EU project “*QUIetening the Environment for a Sustainable Surface Transport-QUIESST*”,. A brief description of the three MCA techniques selected for the purposes of the study is also presented.

A discussion of the study’s results is contained within Section 5, and Section 6 draws some conclusions on the research presented and its implications for improving the sustainable design and management of NRDs projects for the industry.

2. Defining Sustainability for Transport NRDs

It is essential to define “sustainability” as this provides the aim of the multi criteria analysis (MCA). Indeed, various commentators (e.g. Bell and Morse, 2008; Oltean-Dumbrava et al., 2012, to name but a few) remark on the importance of firstly affirming a contextually specific definition of sustainability for any MCA procedure in order to understand what one is trying to measure and so to carry out an assessment. There are many interpretations and definitions of sustainability (e.g. Carew and Mitchel., 2008; Spangenberg et al., 2010; Olewiler., 2008; British Standards Institute., 2010; Xing et al., 2009; Belof et al., 2009; Tsai and Chang, 2010; Holton et al., 2010; Labuschagne et al., 2005). In order to provide a practical and contextual definition that the relevant stakeholders involved with NRDs could utilize, the sustainability of NRDs has been broadly defined in Oltean-Dumbrava et al. (2013, 2014, 2012, 2011, 2010a) as: “*The optimal consideration of technical, environmental, economic and social factors during the design, construction, maintenance and repair, and removal/demolition stages of NRDs projects*”. Figure 2 illustrates how the aforementioned sustainability factors should be incorporated throughout the lifecycle of NRDs.

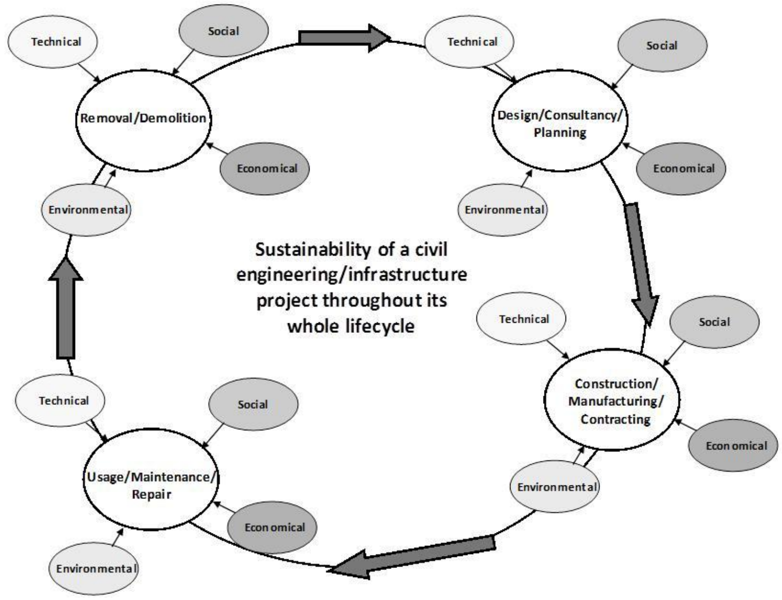

Figure 2: Sustainability factors to be considered throughout the whole lifecycle of NRDs (Source: Oltean-Dumbrava et al., 2012)

The proposed definition explicitly highlights the sub-objectives (i.e. social, technical, environmental, and economic) and the temporal and spatial scale for assessing NRDs sustainability.

3. Method: Stages for Assessing the Sustainability of NRDs

To date various methods have been developed and introduced to assess sustainability (e.g. UNEP, 2011; Ugwu et al, 2006; Ashley et al., 2004). A review of decision making processes (Oltean-Dumbrava et al., 2013), for example, found a common order of procedures summarized as: define the goal, select criteria and indicators, collect data required and carry out MCA. Figure 3 outlines the general process applicable to the assessment of the sustainability of NRDs.

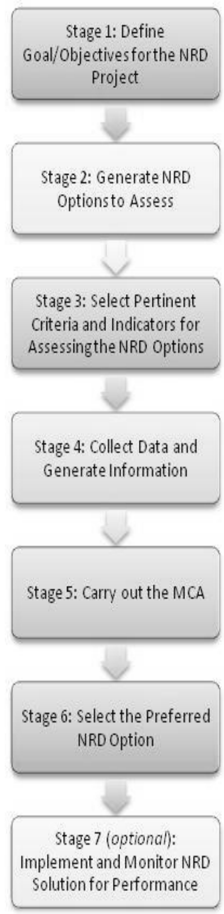

Figure 3: Decision Making Process (DMP) for assessing the sustainability of NRDs projects (Source: Oltean-Dumbrava et al., 2013)

This research has adopted the steps shown in Figure 3 to assess the sustainability of two built and operating European NRDs projects (one in Spain, and one in Italy). The results of implementing the stepwise procedure as shown in Figure 3 are presented as a case study in Section 5.

4. Absolute (Independent) vs. Relative Sustainability Assessments of NRDs Solutions: The Need to Define an Optimal Hypothetical Ideal Solution (OHIS)

It is necessary here to introduce and clarify the difference between absolute sustainability assessments and relative sustainability assessments. The assessment of sustainability is in general a relative concept. There are principally two relative assessment approaches: (1) the sustainability assessment is relative to the set of alternatives (i.e. options) and/ or criteria being considered, or (2) the sustainability assessment is relative to an absolute state/user defined baseline (detailed discussions of the aforementioned can be found in El-Haram et al., 2007, for example), but still relative to the set of criteria used for the assessment. Incidentally, two decision contexts, and thereby two assessment approaches, are foreseeable for NRDs: (1) the design and construction stage, and (2) the usage/built and operating stage. The particulars of the two assessment contexts are provided below:

1: Design stage assessment (Relative): here the decision maker (DM) considers a number of potential solutions (alternatives) relative to each other and aims to search, via applying relevant Multi Criteria Decision Making (MCDM) methods, for the best solution amongst the set of alternatives considered. A final relative ranking of the set of alternatives from most preferred to least preferred based on the criteria selected for the study is usually generated.

2: Usage stage assessment (Absolute): of a single built project in its operating state and not relative to any other projects (i.e. alternatives). The approach is synonymous to certification type assessments whereby the assessment is conducted in relation to a single project/alternative fulfilling specified and modeled objectives within the scheme (e.g. Building Research Establishment's Environmental Assessment Method-BREEAM, or Leadership in Energy and Environmental Design- LEED). This means that whilst there is only one existing project to be assessed (Absolute) the assessment is still relative to the criteria used as a baseline against which the assessment is being made (Relative). More so, the project is assessed relative to an actual or hypothetical "ideal" in place of a set of alternatives. A direct, one-on-one, independent assessment is thus carried out. A final "index score", rather than a ranking of the assessed solution, is generated to denote overall performance with respect to the modeled "ideal".

Of course, the above assessment approaches are not limited to the two described assessment contexts. Potential solutions at the design stage could indeed be assessed in absolute terms, and built and operating projects could be assessed relative to other built and operating projects. However, practices of the latter are considered particularly uncommon due to the difficulty in obtaining data for other built projects in particular if these were not built by the same company. As the aim of the present study is to assess the absolute sustainability of two NRDs case studies (i.e. not relative to each other), the assessment context 2 is applicable. As such, an "ideal" reference solution needs to be specified with regards to the criteria selected. However, defining a "hypothetical ideal solution" is an emerging concept, which has been rarely explored in the sustainability MCA literature. The concept with respect to NRDs is thus expounded upon in what is to follow.

The 'Optimal Hypothetical Ideal Solution (OHIS)' is introduced by this paper and defined by the authors of this study as: "*the optimal hypothetical ideal solution (OHIS) is the ideal reference solution for the absolute sustainability assessments of <u>all</u> alternatives or built projects of the same type. The performance of the optimal hypothetical ideal solution, therefore, represents the sustainability objectives/goals all projects should strive for*". Please note that defining the OHIS for an assessment procedure is synonymous with other terms such as specifying the baseline solution, reference solution, benchmark solution, preferred solution, and so on. This means built projects are assessed relative to a user <u>defined baseline</u>, i.e. to the OHIS, in order to generate an absolute sustainability performance score. To achieve this end, raw OHIS criteria values (i.e. un-normalised criteria values) will need to be defined as a part of this case study. The set of raw OHIS criteria defined following the selection of criteria and collection of data for this study (See Section 5) can be found in Table 1.

The case studies have therefore been assessed with reference to the OHIS in order to assess their sustainability in absolute terms. The OHIS is thus used to perform pairwise comparisons against and/or used to benchmark solutions relative to it. The application of the methods described to two case studies is presented hereinafter.

5. Case Study: the Absolute Sustainability Assessment of Two Built and Operating European Transport NRDs Projects for EU Project QUIESST

Quietening the Environment for a Sustainable Surface Transport (QUIESST) European Union(EU) grant was a three year, inter and multi-disciplinary project undertaken by 13 EU partners from 8 countries, which began late November 2009. Work package 6 (WP6) and its specialist research team were researching the sustainability of noise reducing devices (NRDs) across their whole life cycle. Further details of the QUIESST project and its research outcomes to date can be found in QUIESST (2013).

The main aim of WP6 was to provide a bespoke sustainability assessment framework and method for assessing the whole life sustainability of NRDs, was part of the '*Guidebook to NRD optimization in a sustainable way*' aiming to be the future reference source for noise mitigation by NRDs. This tool will assist the relevant stakeholders (e.g. decision makers, transport engineers, urban/transport planners and other relevant stakeholders involved with NRDs) to assess the sustainability of each major life cycle stage and so make more sustainable decisions. However, no practical case study example of assessing the absolute sustainability of NRDs exists for the relevant stakeholders to utilize.

This section therefore describes and discusses the research undertaken to assess the absolute sustainability of two built and operating European transport NRDs projects (one in Spain, and One in Italy) according to the procedure shown in Figure 3, as a part of the QUIESST research project. The practical implications of completing such work are also highlighted throughout.

5.1. Stage 1: Define Goal/Objectives for the Assessment

The goal of the QUIESST study was to assess the absolute sustainability of selected built and operating NRDs projects across Europe according to the definition of NRDs' sustainability as given in Section 2 of this paper.

An absolute sustainability assessment was specifically requested for a number of reasons: (1) the selected cases were built and operating, so assessment context two was applicable, (2) the end user partners felt that such a study, provided that the same MCA parameter are applied, could be useful to build an asset database of the sustainability of built and operating NRDs projects across Europe with respect to the OHIS, (3) it was more practical to carry out in the long term. That is, the introduction of assessing other built and operating projects will only need to be assessed relative to the OHIS, and so the results of this assessment could be compared against the pool of other independent and absolute sustainability assessments of built and operating projects. The alternative of conducting relative sustainability assessment would require the need to assess all considered projects relative to each other or to an agreed baseline reference. This was considered clearly impractical by the partners involved in the study as in the long term this could mean assessing tens, or hundreds, of built NRDs projects in relation to each other in order to determine the relative sustainability of other built NRDs projects as they are introduced in to the pool, and finally (4) the completion of such a procedure would provide the partners and stakeholder involved in the study a useful model to tailor to independently assess numerous built NRDs projects in isolation.

Therefore an emphasis was placed in this study to select MCDM methods that are able to generate “Index scores” of overall sustainability performance rather than a ranking. The reason for this was that the OHIS will invariably rank 1st and so provide little insight into the sustainability analysis. However, although not the principle aim, the generated independent scores could be used to rank the sustainability of built NRDs projects.

5.2. Stage 2: Generate Noise Barrier Options to Assess

The assessment of the sustainability of two European case studies was requested and provided by the QUIESST partners. Basic details of the two NRDs projects studied are illustrated in Figure 4 below:

Spanish Case Study

- **Type =** Mainly transparent type**, Location =** M406 - Alcorcon, **Length =** 604m, **Average height =** 4m, **Total cost =** €576,022.00

Italian Case Study

- **Type =** Mainly steel type with transparent modules, **Location =** A14 – Senigallia, **Length =** 356m, **Average height =** 5.5m, **Total cost =** €1,245,000.00

Figure 4: Details of the Spanish and Italian cases selected for sustainability assessment

The rationale for this was to assess two NRDs projects from two different countries, two different environments and of two different types in order to cover a variety of situations from the technical, environmental, social, and economic points of view. This allowed the possibility to undertake a both deep (for each case study) but also wide (completely different case studies) sustainability assessment which would cover hopefully a wide range of situations. In so doing, demonstrate the robustness and flexibility of the overall MCA approach by allowing the end user to select and model criteria pertinent to them.

5.3. Stage 3: Select Pertinent Criteria and Indicators for Assessing the Noise Barrier Options

The first systematic study to define a pertinent set of sustainability criteria and indictors specifically for NRDs was reported by Oltean-Dumbrava et al. (2010b and 2011). These affirmed a research informed and industry validated generic set of 141 sustainability criteria, of which 92 are directly measurable, for NRDs projects. No other cogent generic set of sustainability criteria are available for NRDs, and so for the reasons mentioned were initially considered for the selection of sustainability criteria in the present study.

Through a combination of email exchanges, interviews, group meetings, and workshops held around Europe, the relevant partners were asked to specify for each criterion if information is currently available, or could be made available at a later date through implementing analytical tools, in the form requested. The results of this process for both projects were cross examined and the set of criteria common to both case studies were identified. In total, 63 measurable criteria spread across the four factors of sustainability were selected, and considered sufficient by the researchers to demonstrate the overall method and perform meaningful analyses with. The selected criteria were also weighted at this stage to reflect the priorities of the QUIESST partners. The final set of criteria, indicators, and weights selected for the study can be found in Table 1.

5.4. Stage 4: Collect and Generate Criteria Assessment Data

The collection and generation of information necessary for the study took 6 months to complete. A wide range of techniques were used to collect the criteria information required, including Environmental Life Cycle Assessment (ELCA); Life Cycle Cost Analysis (LCCA); interviews, telephone discussions, meetings, workshops, and email exchanges with the QUIESST partners and the relevant key stakeholder (i.e. senior engineers, consultants, asset managers, contractors, and manufacturers involved with the two projects); and the review of acoustical models and compliance to standards data. Additionally, site visits and in-situ measurements were carried out to collect the necessary data. The results of the data gathering techniques for the Spanish and Italian case study are respectively presented in Table 1. The task of specifying raw OHIS criteria values for the study are discussed separately as part of “Stage 5: Carry out the MCA”, presented in the next Section.

5.5. Stage 5: Carry out the MCA

Multi criteria decisions making (MCDM) tools have been demonstrated by a number of practitioners (e.g. Herva and Roca, 2013; Cheng and Chang, 2011; Ahmad et al., 2013; Elghali et al., 2008; Pires et al., 2011; Spengler et al., 1998; to name but a few.) to be effective for quantifying and objectively evaluating sustainability or complex decisions in a number of project settings. The focus of MCDM tools/MCA techniques is to support the decision maker (DM) to identify the best alternative among the set of alternatives considered via ranking or rating the overall performances of alternatives with respect to the selected criteria. Following a review of MCDM tools suitable for assessing the sustainability of NRDs, Oltean-Dumbrava et al. (2013)

recommend the following based on their characteristics and for triangulating results, presented in Table 2.

Table 2: Recommended MCDM tools for assessing the sustainability of noise barriers and triangulating results (Adapted source: Oltean-Dumbrava et al., 2013)

MCDM Tools for Assessing the Sustainability of Noise Barriers		
Simple	**Medium**	**Complex**
Simple Additive Weighting/ Weighted Sum Method (SAW/WSM)	Analytical Hierarchy Process (AHP)	Preference Ranking Organisation MeTHod for Enrichment Evaluations (PROMETHEE)
Simple Multiple Attribute Rating Technique (SMART, also SMARTS and SMARTER)	Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)	Elimination et Choice Translating Reality (ELECTRE 3)
-Simple -Compensatory method -Low MCA parameters required -No specialist software required or can be easily set up MS Excel	⟷	-Complex -Non-compensatory method -Multiple MCA parameters required -Specialist software required to pragmatically implement

Please note that this study refers to the triangulation of results by checking the level of agreement between applying three discrete MCDM tools or criteria weighting schemes to the same problem data/information presented in the decision matrix. Any one of the above MCDM tools presented in Table 1 can be selected to solve the MCA problem. However, this study decided to select SAW, PROMETHEE, and ELECTRE 3, as each method offers a different approach to assessing the multiple sustainability criteria selected for assessment and vary in their complexity. In short, SAW adopts a compensatory approach to the decision problem whilst PROMETHEE and ELECTRE adopt a no-compensation between criteria performance approach and thereby provides the rationale for the authors' selection. Additionally, from the research point of view, the three MCDM tools were also selected to triangulate the case studies results and validate these.

A brief overview of the SAW, PROMETHEE, and ELECTRE 3 MCDM tools is given in Table 3; however, focus is given in their presentations on identifying outputs which generate an index score or rating to denote the absolute sustainability preference of the studied NRDs. It is not the purpose of this paper to provide a detailed account of the methodology and calculations for implementing SAW, PROMETHEE, and ELECTRE 3 respectively, and detailed treatments of the aforesaid can be examined through the highlighted references.

Table 3: Overview of MCDM tools selected

Overview of the three MCDM tools selected to assess the multiple sustainability criteria selected for the two case studies			
	SAW	**PROMETHEE**	**ELECTRE 3**
Complexity (Simple, medium, complex)	Simple	Complex	Complex
MCDM tool classification	Compensatory/trade-off method	Non-compensatory/non-trade off method	Non-compensatory/non-trade off method
Produces a score to denote preference? (Yes/no)	Yes, [0,1] Index	Yes, [-1,1] Phi Net Flow	Yes, [0,1] Concordance index
Brief description of preference score	An index score of "1" means the assessed solution 100% mimics the OHIS	A multi criteria Phi net flow score of "1" means the assessed project is totally preferred in comparison to the OHIS	A Concordance index score of "1" means the assessed project is totally preferred in comparison to the OHIS
Software essential? (Yes/no)	No	Yes (Visual PROMETHEE or D-Sight Software	Yes (LAMSADE's ELECTRE 3 Software)
Criteria modeling requirements for the study	Specification of OHIS raw criteria values, min/max values, and selection and application of normalization techniques	Specification of one of 6 PROMETHEE criteria types, OHIS raw criteria values, and indifference and preference thresholds for the selected criteria	Specification of OHIS raw criteria values, indifference, preference, and veto thresholds for the selected criteria
Example references to detailed treatments	Yoon and Hwang, 1995; Triantaphyllou, 2000.	Brans and Vincke, 1985; Brans and Mareschal, 1994; Anand and Kodali, 2008.	Roy, 1971&1991; Yoon and Hwang, 1995; Triantaphyllou, 2000; Buchanan and Vanderpooten, 2007.

As this study is concerned with providing index values to denote overall sustainability performance with respect to the OHIS rather a ranking of the assessed solutions, Table 3 has highlighted the computable index values/scores which achieve that utility per MCDM tool selected. In short, SAW is a linear additive method. Its calculations are based on summing normalized criteria values within the decision matrix per alternative to generate an index value in the range 0 to 1 to denote overall preference with respect to the criteria selected. PROMETHEE is based on the calculation of positive flow (Φ^+) and negative flow (Φ^-) for each alternative according to the given weight for each criterion. The positive outranking flow expresses how much each alternative is outranking all the others. The higher the positive flow (i.e. Φ^+ up to 1), the better the alternative. The negative outranking flow expresses how much each alternative is outranked by all the others. The smaller the negative flow (i.e. Φ^- out to 0) the better the alternative. The PROMETHEE II complete ranking is based on calculating the net outranking flow value (Φ), which is given in the range -1 to +1, and represents the balance between the positive and negative outranking flows. Therefore the higher the net flow, the better the alternative (Brans and Mareschal, 1994; Anand and Kodali, 2008).

Lastly, ELECTRE 3 is an outranking method like PROMETHEE and based on making pair-wise comparisons. ELECTRE 3 calculates discordance and concordance indexes to express in what measure alternatives are dominated or dominate other alternatives. The concordance index expresses in what measure the performances of the actions ‘a’ and ‘b’ are in concordance with the assertion “a outranks b”. That is, let (a, b) be a pair of actions, the concordance index, C(a, b), is a fuzzy index in the range 0 to 1 measuring whether “action a is at least as good as action b” for the set of criteria considered. The higher the concordance index, the better the alternative.

Furthermore, critical to the MCA study at hand was defining the necessary notional OHIS as the user defined baseline for implementing SAW, PROMETHEE, and ELECTRE 3. The OHIS represents the best performing/best solution. Thereby, the case studies were individually assessed relative to the OHIS in order to assess their sustainability in absolute terms. However, due to the novel nature of the study, no evidence base for carrying out such a task in relation to NRDs exists for the selected criteria. As such, an evidence based approach (where available) or an axiomatic based approach was taken to define the raw OHIS criteria values for the purposes of benchmarking the sustainability performances of the two selected projects. The final allocation of the raw OHIS criteria values and MCA parameters for the selected criteria following group consensus are presented in Table 1.

5.6. MCA Results: SAW, PROMETHEE, and ELECTRE 3 MCA Results for Assessing the Absolute Sustainability of the Spanish and Italian NRDs Projects

Through using the relevant software, the SAW, PROMETHEE, and ELECTRE 3 multi-criteria analysis of the sustainability criteria selected for the two case studies using the modeled criteria parameters and performance data as shown in Table 1 has been carried out using equal weightings. Table 4 presents the respective MCA results and the subsequent generation of absolute sustainability performance scores/index values of interest to this study.

Table 4: NRDs’ sustainability preference index scores generated by the SAW, PROMETHEE, and ELECTRE 3 multi criteria sustainability analysis for the Spanish and Italian case study with respect to the OHIS.

	NRDs Sustainability Preference/Index Scores for the Two Selected Case Studies		
	OHIS	Spanish Case Study	Italian Case Study
SAW	1	0.43	0.41
PROMETHEE	n/a	-0.721	-0.736
ELECTRE 3	n/a	0.22	0.21

Table 5 compares the absolute sustainability performance scores shown in Table 4 and ranks the OHIS, and Spanish and Italian NRDs projects. Please note that the rankings of the Spanish and Italian NRDs projects are non-transitive as they were assessed relative to the OHIS rather in comparison to each other.

Table 5 Triangulation of the SAW, PROMETHEE, and ELECTRE 3 Rankings

Triangulation of the SAW, PROMETHEE, and ELECTRE 3 Rankings			
	SAW	PROMETHEE	ELECTRE 3
OHIS	1st	1st	1st
SPAIN	2nd	2nd	2nd
ITALY	3rd	3rd	3rd

A Sensitivity Analysis (SA) was performed in order to test the robustness and reliability of results obtained from the decision model. A SA generally involves observing the variation in output from a model with respect to changes in the values of the model's inputs. Many SA methods of varying complexities are available to achieve this end depending on the priorities of the decision maker (DM) and purpose of the SA (for a detailed overview of SA methods please see Saltelli et al, 2004; for examples). Therefore, there is no one universal SA method applicable to all decisions problems/contexts. Typically, it is accepted that the criteria evaluations cannot be changed because these represent fixed facts related to the assessment. Thereby criteria weights are clearly the only variables which can be manipulated (Rothley, 1999; Herath, 2004; Redpath et al, 2004; Ashley et al, 2004, Janssen et al, 2005; to name but a few). As such, 3 sets of criteria weightings in the range [0, 1] are normally applied to triangulate the final rankings produced by a single applied MCDM tool to the decision problem and compared (ibid). The 3 sets of criteria weightings used to perform the SA were as follows:

(1) Normal weighting: as specified by the relevant stakeholders for the two case studies at the outset of this report;
(2) Equal weightings: all criteria were given equal weighting of 1, and;
(3) Inverse weighting: or random weights, the normal weights applied were inversed (e.g. Normal weight = 0.21 -> inversed weight= 0.12) in order to generate a fair and random set of weights - to input into the three MCDM tools selected to assess the sustainability of the two case studies.

Given the above, Table 6 shows the sensitivity analyses results for the three MCDM tools selected to assess the sustainability of the two case studies with respect to the OHIS.

Table 6: Overall rankings for the all comparison following the sensitivity analyses for SAW, PROMETHEE, and ELECTRE 3

Triangulation Table Following the Sensitivity Analyses									
	SAW			**PROMETHEE**			**ELECTRE 3**		
Weighting									
	Normal	Equal	Inverse	Normal	Equal	Inverse	Normal	Equal	Inverse
OHIS	1st	1st	1st	1st	1st	1st	1st	1st	1st
SPAIN	2nd	2nd	2nd	2nd	2nd	2nd	2nd	2nd	2nd
ITALY	3rd	3rd	3rd	3rd	3rd	3rd	3rd	3rd	3rd

6. Discussion

SAW, PROMETHEE, and ELECTRE 3 was implemented using the presented decision data to assess the absolute sustainability of two built NRDs projects in Europe**.** Each method was successfully able to generate an absolute sustainability assessment index score in the range 0 to 1 or -1 to +1 for the case studies in relation to the OHIS. The following ranking has been consistently produced by the three methods: OHIS (1ST), Spanish case study (2nd), and Italian case study (3rd), and shown to be robust and reliable in the SA performed. In each method, the OHIS has, as expected, ranked or scored considerably higher than the Spanish and Italian case study as this solution, based on OHIS raw criteria values defined by the QUIESST partners and relevant stakeholders, represents the best performing/best solution. As such, the OHIS will always be ranked first and achieve scores close to being perfect.Although it was not the purpose of this paper, the SA results have demonstrated that the Spanish case study consistently marginally outperforms the Italian case study with regards to the sustainability criteria selected.

Because the research required an absolute assessment of the two case studies over a relative one, it was necessary to define an OHIS as the reference solution/baseline. This approach is common to most rating tools, such as BREEAM and LEED, albeit their analysis of criteria is a strictly rating/score based one and so different to the MCA approach taken by the authors in this paper. A detailed description and discussion on the weakness of taking a rating approach over a MCA approach can be found in Oltean-Dumbrava et al. (2013). Given that the same set of criteria and modelled parameters are used, other projects could be assessed relative to this OHIS and a data bank of the overall sustainability performance of all built and operating NRDs projects around the world could be built. The said database would provide a convenient sustainability profile of built NRDs and support design and management decisions with regards to NRDs' sustainability. Thereby the work presented here will therefore provide a useful reference for achieving such a task.

Incidentally, the generation of index values to denote the overall sustainability in the range 0 to 1] or -1 to +1 (depending on the MCDM tool selected) is a useful feature as it will allow the relevant stakeholders to test solutions and conduct 'what-if' analyses for: design and build NRD projects, built and operating NRDs, and construction products related to NRD projects in the aim of improving/maximizing the "overall score". This effectively allows one to test integrating issues of designing and implementing low carbon strategies to mitigate against the effects of climate change in parallel to considering social, economic, and technical related issues and select the 'best solution'. Conversely, solutions which aim to be technically proficient, such as having a high service life, low maintenance requirement, durable against extreme weathering, etc., can be compared against achieving low carbon and energy related objectives in a fair and unbiased way based on how criteria are selected. As such, many decision priority contexts could be generated using the generic set of sustainability criteria established for NRD. However, the results of the study need to be interpreted with caution as the MCA is based on: a finite set of criteria, criteria performance values which are both actual and hypothetical, subjective evaluations, evaluations relative to a user defined OHIS, and MCA parameters specified by the QUIESST partners, although these are normal limitations of interpreting results from any MCA model. As such, it is possible the results presented in this paper could change if any of the mentioned variables are manipulated. Further implications of the study are given below.

Because the two case studies are the only ones that considered a high level of consideration for sustainability assessment as part of the research, the results should not be taken as indicative of general practices for each country. Indeed, it should be noted that it is most likely that at the time when these projects were built the serious consideration of sustainability, as defined by the researchers, in the public or private domain, or top down pressure from governments or local legislators, did not exist to the extent it does today. As such, it is unfair to assume or expect performance remotely close to the OHIS and this has been subsequently reflected in the results respectively. However, the results obtained for the two case studies could be used by the relevant stakeholders to benchmark progress and strategize options for improving their overall sustainability.

One should be mindful that the SAW methodology is a compensatory method and the weak performance in one criterion could be compensated by a strong performance in another. Thus the SAW normalised decision matrix should be analysed carefully to identify any major trade-offs before accepting the final index score definitively. Indeed, such an assessment procedure could be criticized as being inherently against the fundamental principles of sustainability, which demands an optimal and fair consideration of all relevant criteria be taken. Therefore, a compromised solution is invariably identified as preferable in the adoption of compensatory methods such as SAW. It is the view of the authors that methods which do not allow for compensation in criteria performance should be selected as this reflects the principles of sustainability (i.e. optimizing and integrating the consideration of social, technical, environmental, and economic related objective).

Outranking methods, such as PROMETHEE and ELECTRE 3, offer possible methods to achieve this end as they do not allow for criteria compensation and have been subsequently implemented to triangulate the SAW rankings. The PROMETHEE and ELECTRE 3 methodology implemented took into account the indifference and preference thresholds defined for the set of criteria considered and so generated a non-compensated score. Thereby the approach is more in line with considering the principles of sustainability as it implements a method to not allow for unacceptable trade-offs and optimally consider all criteria. This in turn provides a richer value in comparison to the index value generated by the SAW method. However, the understanding and interpretation of pair-wise comparison degrees was found to be initially difficult for the stakeholders involved with the study to understand as they were not familiar with outranking theories. As such, this led to the relevant stakeholders to question the applicability of these methodologies and so the reliability of the results produced despite their theoretical basis being well founded. Indeed, a large part of the MCA study was spent explaining outranking theories and guiding stakeholders to define their MCA parameters (e.g. selecting criteria types in PROMETHEE and defining thresholds).

However, PROMETHEE and ELECTRE 3 are promoted by their proponents as being 'user-friendly' and being able to provide a greater insight to the decision problem in comparison to trade-off methods instinctively adopted by most professionals when attempting to analyse a decision problem. Indeed, the implementation of the PROMETHEE and ELECTRE 3 MCA methodology and use of the relevant software package(s) is a relatively straight forward, inexpensive, and time efficient to conduct sustainability analyses for NRDs projects, once a member of staff is fully trained in these. The capital cost to do this is very comparable to consulting a MCA expert, and so is considered a worthwhile investment. As such, it is evident industry training is required not only for applying MCA methods to assess NRDs sustainability, but also for the end-users of such assessments for confidently interpreting MCA results, as a driver towards advancing the sustainability agenda for the NRDs industry.

7. Final Conclusion and Recommendations

This paper has provided an account of the first study carried out to assess the absolute sustainability of two built and operating NRDs projects in Europe (i.e. one in Spain, and one in Italy). A relevant procedure and demonstration of applying three MCDM tools, i.e. SAW, PROMETHEE, and ELECTRE 3, to assess the sustainability of built NRDs has been presented. These methods can be similarly applied to assess potential solutions (e.g. at the design stage) in absolute terms. The demonstration has shown how multiple and conflicting objectives of NRDs' sustainability, i.e. social, technical, environmental, and economic, can be equitably assessed through applying MCA techniques.

An emphasis within the paper was placed on generating index values to denote overall sustainability preference as this was considered most conducive to meeting the long-term requirements of the relevant stakeholders. To this end, the selected methods were able to generate an absolute sustainability assessment index score in the range 0 to 1 or -1 to +1 for the case studies in relation to the OHIS. These generated index values can be used to succinctly communicate the sustainability performances of constructed NRDs to a broad range of stakeholders, and conduct "what-if" analyses. Such a study into assessing the sustainability of NRDs previously did not exist for the NRDs industry. Therefore, the case study contained in this paper will support the relevant stakeholders involved with NRDs by providing a useful model that can be used or amended to conduct their own assessments. These guidelines will assist the relevant stakeholders, such as transport/noise policy makers and national road and rail authorities - and consultants, contractors, asset managers, and the relevant manufacturers prepare tenders and bids in procurement related activities - show a demonstrable commitment to achieving sustainability related objectives with respect to NRD in the near future.

Surface transport noise pollution and so the carefull selection of justifiable noise abatement solutions will continue to be an important factor when it comes to sustainably developing, upgrading, and maintaining national road and rail networks in the foreseable future. The NRDs industry faces a number of novel challenges as pressure to achieve better overall sustainability performance and stricter product regulations (e.g. The new Construction Product Regulation: 305/2011/EU -CPR) continues to come into play. At present, the performance of NRDs are largely dictated and regulated by compliance to standards and product regulations. These standards are largely technically based and are limited in their scope of integrating and assessing specifically the social, environmental, and economic impacts of NRDs projects accross their whole life. No specific standard or certification scheme for assessing the sustainability of NRDs exists for the relevant stakeholders. Various analytical tools have been applied within this research project to generate data for sustainability assessment, and some MCDM tools have been recommended and applied. The approach has been considered to be flexible in order to meet the needs of various stakeholders.

Development of standards for the sustainability assessment of products, therefore, introduced into the market will then help the NRD industry but will also be an essential tool for Public Authorities and Road Managers when implementing public procurement techniques. Further research in to affirming a fixed core set of sustainability criteria and method which reflects the principles of sustainability would be required. This paper offers significant findings and the basis for possibly achieving both ends. Overall, the work completed here will allow for a universal approach to assessing the sustainability of NRD projects that will be consistent with the overall global transport sustainability agenda.

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Table 1: Selected criteria and indicators, RAW OHIS criteria values, and SAW, PROMETHEE, ELECTRE 3 MCA parameters for the case studies

(Key: (S) =criterion related to the social factor, (T) = criterion related to the technical factor, (En)=criterion related to the environmental factor, (Ec)=criterion related to economic factor, (L) = low weighting, (M) = medium weighting, (H) = high weighting, Scp = performance of the Spanish case study, and Lcp = performance of the Italian case study, Nr = not required, and Ex = excluded)

				MCA Parameters			
				SAW	**PROMETHEE/ELECTRE 3**		**ELECTRE 3**
NRDs' Sustainability Assessment Criteria	**Indicator**	**Scp**	**Lcp**	**Final Raw OHIS criteria values (also applicable to PROMETHEE and ELECTRE 3)**	**Indifference Threshold**	**Preference Threshold**	**Veto Threshold**
Psycho-acoustic impacts (S) (M)	1-10 rating	8	6	10	Nr	Nr	Nr
Resistance of the barrier to vandalism (S) (H)	1-10 rating	8	6	10	Nr	Nr	Nr
Glare control for road users (S) (M)	Yes(1)/No(0)	1	1	1	Nr	Nr	Nr
Shading impacts for road users (S) (M)	1-10 rating	9	10	10	Nr	Nr	Nr
Drivers' stress (S) (M)	1-10 rating	10	6	10	Nr	Nr	Nr
Use of crash/safety barriers for road users (S) (H)	Yes(1)/No(0)	0	0	1	Nr	Nr	Nr
Crossing facilities such as footbridges/ underpasses (S) (L)	Yes(1)/No(0)	0	0	1	Nr	Nr	Nr
Access doors (S) (H)	Yes(1)/No(0)	1	1	1	Nr	Nr	Nr
Landscape architecture (S) (H)	1-10 rating	7	8	10	Nr	Nr	Nr
Architectural design of the NRD (S) (H)	1-10 rating	9	7	10	Nr	Nr	Nr
Loss of view for residents and road users (S) (H)	1-10 rating	8	6	10	Nr	Nr	Nr
Loss of daylight for residents and road users (S) (H)	1-10 rating	10	8	10	Nr	Nr	Nr
Enclosure effects for residents and road users (S) (M)	1-10 rating	9	9	10	Nr	Nr	Nr
Glare control for residents (S) (M)	Yes(1)/No(0)	1	1	1	Nr	Nr	Nr
Shading impacts for residents (S) (M)	1-10 rating	10	8	10	Nr	Nr	Nr
More litter due to noise barrier's presence (S) (L)	1-10 rating	9	9	10	Nr	Nr	Nr
Barrier design/type via public consultation (S) (H)	Yes(1)/No(0)	1	0	1	Nr	Nr	Nr
Community art used on noise barrier (S) (L)	Yes(1)/No(0)	0	0	1	Nr	Nr	Nr
Local social identity enhancement (S) (L)	1-10 rating	5	3	10	Nr	Nr	Nr
Use of new materials (T) (H)	% new(virgin) material content	97.5	88	10	10	80	Ex
Use of recycled materials (T) (H)	% recycled material content	1	11	90	20	80	Ex
Use of hazardous materials (T) (H)	Yes(0)/No(1)	1	1	1	Nr	Nr	Nr
Sound insulation of the NRD (T) (H)	dB	27	32	1 (High pass, normalized)	2	5	Ex
Sound absorption of the NRD (T) (M)	dB	1	10	1(Highly absorbing, normalized)	5	9	Ex
Whole barrier service life (T) (H)	Years	20	15	50	3	9	Ex
Structural elements service life (T) (H)	Years	30	30	50	2	8	Ex
Removability of the noise barrier at the end of its life (T) (M)	1-10 rating	8	10	10	Nr	Nr	Nr
Acoustic elements service life as stated by the manufacturer (T) (M)	Years	20	15	50	5	10	Ex
Buildability/constructability of the noise barrier (T) (H)	1-10 rating	9	8	10	Nr	Nr	Nr
Ability to change existing noise barrier as required (e.g. increase height if needed) (T) (M)	1-10 rating	5	8	10	Nr	Nr	Nr
Loss of land (En) (L)	The average 'Footprint' (m2) of the NRD/m	0.8	1.5	0.5	0.5	3	Ex
Ecotoxicity of soil (En) (L)	m3 of water/NRD m^2	*26.40*	*44.77*	0.01	10	20	Ex
Accommodating water flow through barrier under normal conditions (En) (M)	Yes(1)/No(0)	1	1	1	Nr	Nr	Nr
Special drainage considerations to address flood risk (En) (L)	Yes(1)/No(0)	0	0	1	Nr	Nr	Nr

Noise barriers obstructing fauna/wildlife corridors (En) (L)	Yes(0)/No(1)	0	0	1	Nr	Nr	Nr
Non-dangerous waste production (En) (H)	kg/m²	4.44	13.98	0.01	3	6	Ex
Dangerous waste production (En) (M)	kg/m²	0.041	0.03	0.01	0.01	0.05	Ex
Inert waste production (En) (M)	kg/m²	23.10	45.27	0.01	10	20	Ex
Radioactive waste production (En) (L)	kg/m²	0.006	0.004030	0.001	0.001	0.004	Ex
Materials for energy recovery (En) (M)	% recoverable for energym²	1	10	95	10	50	Ex
Recyclability potential (En) (H)	% recyclable/m²	99	90	100	10	50	Ex
Re-use potential (En) (M)	% re-usable/m²	20	10	80	5	30	Ex
Global warming potential (whole life cycle) (En) (M)	kg CO2equivalent/m²	225	102.45	0.01	50	100	Ex
Global warming potential due to transport (En) (M)	kg CO2equivalent/T.km	8.610	6.58	0.01	2	4	Ex
Acidification potential (En) (L)	kg SO2 equivalent /m²	0.80	0.51	0.01	0.1	0.3	Ex
Dust and particulate matter (En) (L)	m3/m²	16800	27500	0.01	3000	5000	Ex
Materials that trap or deflect pollution (En) (M)	Yes(1)/No(0)	0	0	1	Nr	Nr	Nr
Ozone layer destruction/depleter (En) (L)	kg CFC-R11 equivalent /m²	0.00000001480	0.000000450	0.00000001	0.00000001	0.00000003	Ex
Embodied water content (whole life cycle) (En) (M)	litre/m²	1800	1030	0.01	200	400	Ex
Ecotoxicity for water (En) (L)	m3/m²	*26.40*	44.77	0.01	10	20	Ex
Use of primary energy resources (whole life cycle) (En) (M)	MJ/m²	2930	1680	0.01	500	1000	Ex
Use of primary energy resources for transport (En) (H)	MJ/T.km	145	111	0.01	15	30	Ex
Renewable energy production (Photovoltaic/small scale wind turbines) (En) (M)	Yes(1)/No(0)	0	0	1	Nr	Nr	Nr
Cost of land (Ec) (H)	€/m²	5.05	25.25	3.00	2.00	4.00	Ex
Design costs including consultants (Ec) (L)	€/m²	20.20	102.53	5.00	8.00	15.00	20.00
Labour cost (Ec) (H)	€/m²	14.04	22.69	8.00	2.00	4.00	Ex
Equipment hire cost (Ec) (M)	€/m²	11.63	19.24	6.00	3.00	5.00	Ex
Fabrication/manufacturing + installation (Ec) (H)	€/m²	139.90	210.35	80.00	15.00	40.00	80.00
In-situ civil works (Ec) (H)	€/m²	47.60	248.79	30.00	5	10	40
Green value of the noise barrier (Ec) (M)	1-10 rating	5	8	10	Nr	Nr	Nr
Sustainable/green procurement (Ec) (M)	Yes(1)/No(0)	0	0	1	Nr	Nr	Nr
Public financing (Ec) (H)	% of total financing	100	5	1	5	20	Ex
Private financing (Ec) (M)	% of total financing	1	95	100	5	20	Ex

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