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# Assessment and relative sustainability of common types of roadside noise barriers

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ABSTRACT

There is increasing legislative and public pressure for the design and build of road infrastructure schemes to achieve better sustainability performance. Roadside noise barriers (RNBs) form a major part of the growing road infrastructure system in mitigating undesirable road noise to impacted communities. However, the relative sustainability of common RNBs is little understood in the research and industry literature. This makes it difficult for stakeholders to make informed decisions with regards to the sustainable design and procurement of RNBs. This paper presents nowel research carried out to assess and rank the relative sustainability of 13 RNB types using three multi criteria analysis (MCA) techniques, i.e. Simple Additive Weighting (SAW), Preference Ranking Organisation MeTHod for Enrichment Evaluations (PROMETHEE), and Elimination et Choice Translating Reality (ELECTRE III). The paper concludes that the presented sustainability rankings of the main RNB types from least sustainable to most sustainable will support the relevant stakeholders, involved in the planning, design, and procurement stages, to evaluate the sustainability of RNB options as either part of a large highways scheme or standalone project. The presented results will save significant analysis time and costs in cases whereby it is unfeasible to conduct MCAs. The presented sustainability asssessment methodology may also provide the basis for an industry sustainability certification sceheme and in turn support advancing the sustainability transport agenda.



## 1. Introduction

There is a growing need resulting from various legislative and public pressures for the design and build of road infrastructure schemes (and their supporting systems) to achieve better sustainability performance (Commission of the European Communities, 2001; 2011). Roadside noise barriers-RNBs (also referred to in the literature as Transport Noise Reducing Devices-NRDs, Sound Walls, Noise Walls, or Acoustical Barriers) form a major part of the developing road infrastructure system in mitigating undesirable road noise to impacted communities. The consideration of their sustainability in parity with traditional road schemes (e.g. the design and build of a single carriageway) is becoming increasingly difficult to ignore as RNB projects alone need to: meet key technical requirements, balance and address social and environmental impacts, incur high levels of expenditure which need to be justified, and involves a level of utilization of raw materials comparable to the road scheme itself. Indeed, in some cases the roadside noise barrier forms a major visual and functional component of the overall road scheme.

The need for the selection and design of a RNB system occurs in one of two scenarios: (1) when the acoustic model for a potential road scheme predicts the generation of surface road noise emissions to be at levels considered unsafe or of serious annoyance to the impacted community, or (2) the conditions of an existing track of road are or become such that transport noise emissions are at levels now consideredharmful or of serious annoyance to affected residents. In either case, several noise abatements options are available (e.g. quieter road surfacing, double glazing solutions to impacted properties, etc.), but the placement of RNBs are the most effective as they block the sound transmission path from the source to the receiver. Moreover, the need for RNBs is unlikely to decrease in the near future as surface transport noise is projected to increase over the next two decades beside traffic growth (e.g. Boer and Schroten, 2007; Organisation for Economic Co-operation and Development-OECD, 2008).

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Oltean-Dumbrava et al. (2012a,b) further details the significance of their impact as a typical installation of noise barriers in the UK may be as much as 2 km, or 4 km if both sides of the carriageway are treated. A typical height is 4 m which means that the total area of the erected noise barrier is 16,000 $m^2$. At an average installed cost of approximately £100/$m^2$ for a timber option (Watts et al., 2006) this amounts to a total resource cost of £1.6 m. Note that aluminium, wood cement and acrylic barriers would be approximately double this cost. If the barrier contains covers over the road then costs would be at least an order of magnitude higher. A public funded expenditure of this scale underlines the need for the sustainability of RNBs to be considered at all stages and, in particular, during procurement where often the lowest installation cost has greatest weight in the decision process (Joynt and Kang, 2006). Fig. 1 highlights the complexity and typical scope of considering the sustainability of RNBs/NRDs. It shows the 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 RNBs/NRDs projects that have as their main functionthe reduction of noise pollution.

The careful selection of justifiable noise abatement solutions will continue to be an important factor when it comes to sustainably developing, upgrading, and maintaining national road networks in the foreseeable future. Even so, there are many types of RNBs available for selection to the decision maker (DM) in either of the two previously described scenarios. However, there is at present a worldwide lack of decision support for the relevant stakeholders (e.g. engineering managers, local authorities, transport planners, consultants, contractors, etc.) tasked with selecting or designing a sustainable RNB for a given road scheme. Although approaches for assessing RNBs' sustainability have been established by Oltean-Dumbrava et al. (2016), there exists no relative and generic sustainability assessment and ranking of the main RNB types used around the world, and thereby forms the central axis and novelty of this paper. The paper, therefore, provides an account of the first research carried out to assess and rank the relative sustainability of 13 main RNB types via the application of Multi criteria analysis (MCA) techniques that assumes and demonstrates the criteria independence. It is apparent there are multiple and conflicting issues (as shown in Fig. 1) which need be integrated and objectively evaluated for relatively assessing and ranking the sustainability of the said RNB types. MCA techniques are able to solve such problems and so form the principle area of investigation in this paper for assessing and ranking the said RNB types. The presented research will thus support making more sustainable decisions for transport noise reduction which is consistent with advancing the overall transport sustainability agenda.

The paper begins by asserting the scope and limitations of the study and the 13 RNBs inferred as being the most commonly used around the world and hence selected for assessment and ranking. Then, the definition of sustainability for RNBs is stated and discussed in order to clearly state the aim of the MCA for assessing and ranking the said RNB types. The paper then proceeds to present the overall methodology adopted and stages carried out to assess and rank the sustainability of RNBs. The next section after that implements the described methods using generic sustainability data and three MCA tools (SAW, PROMETHEE, and ELECTRE 3) to assess and generate relative rankings of the main RNB types from the point of view of their overall sustainability performance, and overall performance per sustainability factor (i.e. social, technical, environmental, and economic performance). The section thereafter contains a discussion on the study's results, and the final section draws some conclusions on the research presented and its implications for improving the sustainable procurement and design of RNB projects for the industry.

### 1.1. Noise barriers selected and scope of the study

The primary function of a noise barrier is to reduce or shield impacted communities from undesirable or harmful surface transport noise generated by road traffic. Noise barriers are comparatively unique in comparison to similar scale projects as there is a significant scope for maximising their sustainability primarily through material selection. This is realised specifically

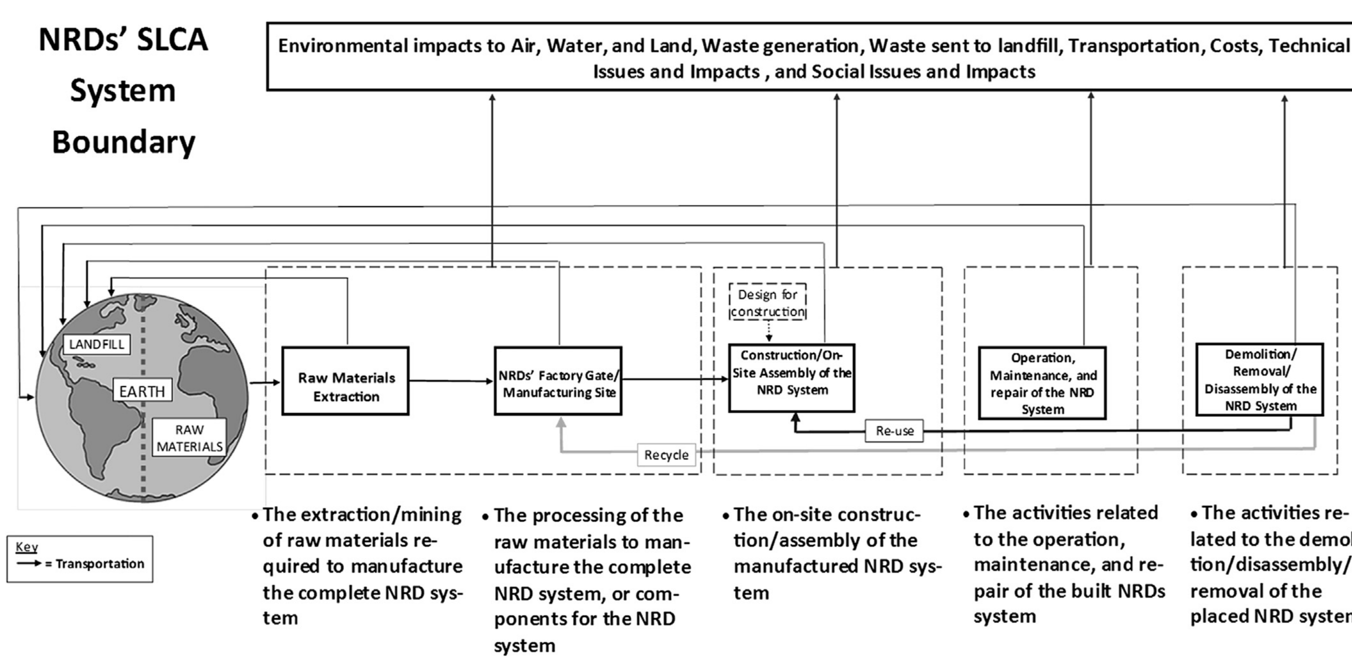


**Fig. 1.** The NRDs' sustainability life cycle assessment (SLCA) system boundary.
(Source: Oltean-Dumbrava et al., 2016).

through the acoustical design of the noise barrier system. . Good sound insulating materials are typically uniformly dense and heavy materials without air gaps, such as: cast concrete, brickwork, and sheet metal. It is important that the noise barrier system as a whole does not contain air gaps as this will degrade the airborne sound insulation. As such there are many noise barrier types used around the world. Table 1 presents the most common types used and identified for the study following a review of the relevant literature (e.g. Kotzen and English, 2009; U.S. Department of Transport and Main Road, 2010) and discussions with key players such as transport engineers, urban/transport planners, manufacturers, designers and other stakholders.

The barrier types selected are not exhaustive, but represent the most common types in use around the world. It is the aim of this study to rank the RNB types shown in Table 1 from the point of view of their sustainability. However, due to practical constraints it is not possible to research all aspect of their sustainability. It is therefore important that this paper states the scope and limitations of the presented study, which are as follows:

#### *1.1.1. Rail side noise barrier systems omitted*

Although they serve the same purpose, discrepancies do exist for example in calculating acoustic performance due to differences in source characteristics (distribution of sources and typical spectra). Other issues where differences arise are sizing, material selection, placement, maintenance requirements, structural stability, etc. Therefore the paper exclusively researches the sustainability of RNBs, although there is scope to extend the work presented here to rail noise barriers.

#### *1.1.2. Support for design and selection problems*

All life cycle stages of the noise barrier systems have been researched. However, this paper places emphases on those results supporting the stakeholders involved with the design and selection of noise barrier systems as this stage is considered as exerting the greatest influence in promoting sustainable noise barriers.

#### *1.1.3. Site specific and layout issues omitted in the sustainability research*

The layout of the site and consideration of site-specific issues (i.e. location, logistics, access, topography, population, weather, urban character, etc.) is complex and has the potential to improve/detract the sustainability performance of the set of noise barrier types studied, or favour certain types. Further information and discussions regarding the consideration of site specific issues and data in the sustainability assessment of RNBs can be found in Oltean-Dumbrava et al. (2016). In order to carry out a consistent and site-independent study, only the sustainability of the intrinsic characteristics of the material selected for the noise barrier system were researched by the authors. This will provide results per main barrier type that are dissociated from the sustainability performance of a specific site or project. The results are thus largely based on the type of the noise barrier.

**Table 1**
List of the main noise barriers identified for the study.

| Noise barrier Types identified for research | | |
|---|---|---|
| No. | Key | Type |
| 1 | SM | Steel supporting structure + Metal panels |
| 2 | SC | Steel support structure + Concrete panels |
| 3 | ST | Steel supporting structure + Timber panels |
| 4 | SG | Steel supporting structure + Transparent modules |
| 5 | C | Self-supporting concrete or brick system |
| 6 | SP | Steel supporting structure with plastic panels |
| 7 | CT | Tunnel-concrete structure |
| 8 | STu | Tunnel-steel structure |
| 9 | GT | Tunnel with transparent panels |
| 10 | GB | “Green” barrier (containing vegetation) |
| 11 | GA | Gabions (wire cage filled with graded stones) |
| 12 | EB | Earth barrier (earth mound or berm) |
| 13 | PVNB | PVNB (photovoltaic noise barrier) |

### *1.2. Defining sustainability for road noise barriers*

Oltean-Dumbrava et al. (2016) highlight the importance of defining “sustainability” to clearly state the goal of the MCA and for the DM/stakeholders involved in the assessment to clearly: (1) understand the aim and scope of the assessment, (2) the aspects to measure, and (3) guide sustainability criteria and indicator selection for structuring the assessment model (e.g. Oltean-Dumbrava et al., 2014; Singh et al., 2009). There are many reported interpretation and definitions of sustainability available (e.g. Wang, 2009) with many tending to be vague, or centering around the notion of protecting ones progeny and living within the carrying capacity of the planet. However in order to provide a practical definition the relevant stakeholders could utilize, Oltean-Dumbrava et al. (2014) provide the following definition of sustainability as suitable to RNB projects: “*The optimal consideration of technical, environmental, economic and social factors during the design, construction, maintenance and repair, and removal/demolition stages of civil engineering/infrastructure projects*”.

## 2. Method: stages for assessing the sustainability of roadside noise barriers

To date several methods have been developed and introduced to assess sustainability (e.g. Herva and Roca, 2013; Spengler et al., 1998). However, a review of sustainability decision making processes, methodologies, assessment stages, etc., by 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. Fig. 2 outlines the general process applicable to the assessment of the sustainability of RNBs.

This paper follows the methodology as proposed by Oltean-Dumbrava et al. (2013) in Fig. 2 to assess and relatively rank the sustainability of the 13 main RNB types identified. The description and results of implementing the stepwise procedure as shown in Fig. 2 is presented in the following Section. The practical implications of completing such work are also highlighted throughout.

## 3. Results: application of methods and tools to assess and rank the relative sustainability of 13 main noise barrier types

### *3.1. Stage 1: define goal/objectives for the assessment*

The aim of the study was to affirm an indicative, relative, generic, and site-independent sustainability ranking of 13 RNBs according to the definition of sustainability given earlier in this paper. The given definition therefore represents the goal of the study. It is important to note that this study assesses and ranks the overall sustainability performances of the set of RNB types identified in relation to each other, and not in absolute terms. An absolute sustainability assessment would require the specification of a baseline solution (or ideal hypothetical solution) for carrying out such an assessment. A relative sustainability assessment over an absolute sustainability assessment was specifically chosen as such a baseline solution does not exist for assessing the sustainability of RNBs in absolute terms.

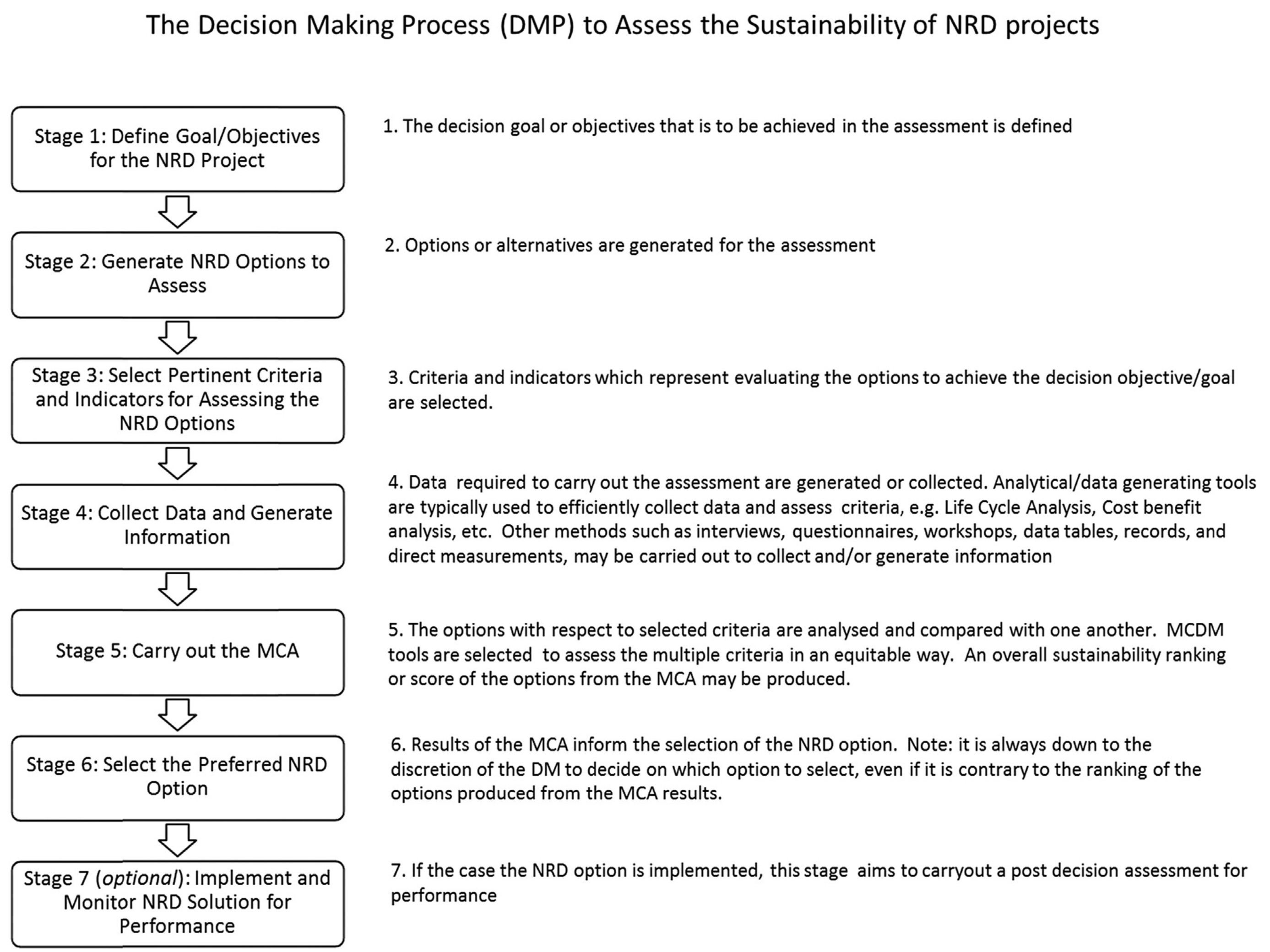


**Fig. 2.** Decision Making Process (DMP) for assessing the sustainability of NRDs projects. (Source: Oltean-Dumbrava et al., 2013).

### *3.2. Stage 2 and stage 3: generate noise barrier options to assess, and select pertinent sustainability criteria and indicators for assessing the noise barrier options*

The relative sustainability of 13 RNB types as shown in Table 1 were selected as options to assess. There are a limited number of sets of criteria available for broadly assessing the sustainability of various project types and scales within the literature (e.g. Construction and City Related Sustainability Indicators (CRISP) database; Sustainable Building Alliance (SBA) database of criteria). However, a research informed and industry validated generic set of criteria for assessing specifically the sustainability of RNBs is reported by Oltean-Dumbrava et al. (2014). The resulting set of 126 criteria suggested are spread across the four factors (technical, environmental, social and economic) that define sustainability, whereby 96 are quantitative and directly measurable and the other 30 are qualitative. Of course, not all of the 126 generic set of criteria are relevant to the aims of this study, some criteria are site specific. Fig. 3 below shows the considerations taken for selecting criteria pertinent to the study, i.e. intrinsic.

By using the considerations shown in Fig. 3, a manageable and applicable set of criteria that could be used for assessing the 13 noise barriers' sustainability was selected. Primarily, the availability of data, site-independent criteria, and relevance drove criteria selection. Table 2 presents the final set of criteria selected for the study as being an indicative and non-site specific means of assessing the social, technical, environmental, and economic factors of RNBs' sustainability. The ensuing sections present the data collection techniques and the subsequent MCA carried out using the aforementioned criteria to assess and rank the RNBs from the point of view of their sustainability.

### *3.3. Stage 4: collect and generate criteria assessment data*

Table 3 present the performance of 13 RNBs against selected sustainability criteria. Since it was impractical to consistently generate specific, site-independent, data for 13 RNB types with regards to the criteria selected, the QUIetening the Environment for a Sustainable Surface Transport (QUIESST) decision support database of generic sustainability criteria values for common RNB types was used to generate criteria performance data for the MCA. The said database contains the results of a concerted research effort by the QUIESST team (Oltean-Dumbrava et al., 2012b) to support improving the sustainability of the RNBs industry by providing general and indicative: technical information, costs/economic impacts, social impacts, health and safety issues, and environmental

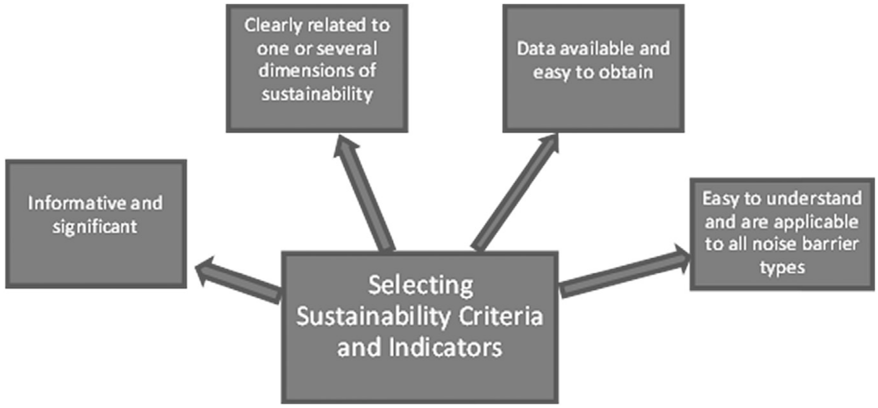


**Fig. 3.** Considerations for selecting sustainability criteria and indicators for noise barriers. (Adapted Source: BS ISO 21292-1).

performance and impacts, across the whole life of common noise barrier types. The database also contains a mixture of site-dependant and site independent criteria data per main noise barrier type which the user can utilise from the results of surveys, records, interviews, site visits, observations, expert workshops, analytical calculations, environmental life cycle analyses (LCA) and life cycle cost analyses (LCCA). Full details of the scope, limitations, and meta data of the QUIESST sustainability decision support database can be found in Oltean-Dumbrava et al. (2012b).

While it may appear unusual to utilise generic data from a database for carrying out MCAs or assessing sustainability, the practice is commonplace for LCA studies. For example, the ECOINVENT database (the world's leading database with consistent and transparent, up-to-date, Life Cycle Inventory data) is routinely and confidently used by practitioners to "generically" evaluate the whole life environmental impacts of products, processes, and services (e.g. Dale et al., 2011; Singh et al., 2011). The QUIESST's decision support data base is somewhat similar in that utility. However, unlike the ECOINVENT database, QUIESST's database is the result of a one-time research project. It needs to be mentioned that there is at present no company, system, recognizable user community, or willing cohort, dedicated to maintaining and updating the said database. Nonetheless the generic sustainability criteria performance matrix of the 13 main RNB types is thus presented in Table 3 for the readers' information.

### 3.4. Stage 5: carry out the MCA

Multi criteria decisions making (MCDM) tools have been demonstrated by a number of practitioners (e.g. Fuente et al., 2016; Tsamboulas et al., 1999) to be effective for quantifying and objectively evaluating sustainability or complex decisions in a number of project settings. The focus of MCA 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 (Oltean-Dumbrava et al., 2016). A wid range MCA tools are available within the literature. 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. Additionally, from a pedagogical point of view, the three MCA tools were also selected to triangulate the assessments final rankings. A brief overview of the SAW, PROMETHEE, and ELECTRE 3 MCA tools is given in Table 4. It is not the purpose of this paper to provide a detailed account of the methodology for implementing SAW, PROMETHEE, and ELECTRE 3 respectively. Detailed treatments of the aforesaid can be examined in Oltean-Dumbrava et al., 2013.

In short, however, SAW adopts a compensatory approach to the decision problem whilst PROMETHEE and ELECTRE adopt a no-compensation between criteria performance approach and provides the rationale for their selection. SAW is a linear additive method in which its calculations are based on summing normalized criteria values within the decision matrix per alternative to generate an index value in the range 0–1 to denote overall preference with respect to the criteria selected. The higher the generated index value is, the more it is preferred within the SAW method.

PROMETHEE is based on the calculation of positive flow ($\Phi^{+}$) and negative flow ($\Phi^{-}$) 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. $\Phi^{+}$ 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. $\Phi^{-}$ out to 0) the better the alternative. The PROMETHEE II complete ranking is based on calculating the net outranking flow value ($\Phi$), 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 overall, and so ranked according to these values (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 concordance, discordance, and credibility indices to express in what measure alternatives are dominated by or dominate other alternatives to establish outranking relationships (Yoon and Hwang, 1995). The concordance index expresses in what measure the performances of the actions 'a' and 'b' are in concordance with the assertion "a outranks b" or "a is at least as good as b". That is, let (a, b) be a pair of actions, the concordance index, C (a, b), is a fuzzy index in the range 0–1 measuring whether "action a is at least as good as action b" for the set of criteria considered. The discordance index, D (a, b), a fuzzy index in the range 0–1, on the other hand, expresses to what degree the opposition to the assertion "a out ranks b". The credibility index is merely the comprehensive concordance index weakened by the discordance indices and provides a better indication of the acceptability of "a outranking b" and is some cases omitted or replaced by the comprehensive concordance index (Buchanan and Vanderpooten, 2007). The overall preference rankings of the alternative are derived through applying

**Table 2**
The set of sustainability criteria selected and MCA parameters for assessing and ranking the relative sustainability of common RNB types (please note the highest and lowest values amongst the set of RNB options considered per criterion is given. Key: Nr = Not required, Ex = Excluded, Δ = Difference).

| Noise barriers' sustainability assessment criteria | Aim to improve sustainability/ preference (maximize/Minimize) | Indicator | MCA Parameters | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | SAW | | | PROMETHEE/ELECTRE 3 | | ELECTRE 3 |
| | | | Highest value | Lowest value | Δ | Indifference threshold | Preference threshold | Veto threshold |
| Psycho-acoustic impacts | Maximize | 1-10 rating | 9 | 6 | 3 | Nr | Nr | Nr |
| Heat island impacts | Maximize | 1-10 rating | 9 | 3 | 6 | Nr | Nr | Nr |
| Work related sicknesses | Maximize | 1-10 rating | 9 | 4 | 5 | Nr | Nr | Nr |
| Resistance of the barrier to vandalism | Maximize | 1-10 rating | 9 | 2 | 7 | Nr | Nr | Nr |
| Glare control for road users | Maximize | Yes(1)/No(0) | 1 | 0 | 1 | Nr | Nr | Nr |
| Loss of view for residents and road users | Maximize | 1-10 rating | 9 | 1 | 8 | Nr | Nr | Nr |
| Loss of daylight for residents and road users | Maximize | 1-10 rating | 9 | 1 | 8 | Nr | Nr | Nr |
| Glare control for residents | Maximize | Yes(1)/No(0) | 1 | 0 | 1 | Nr | Nr | Nr |
| Community art use possible on the noise barrier | Maximize | Yes(1)/No(0) | 1 | 0 | 1 | Nr | Nr | Nr |
| Use of new materials | Minimize | % new (virgin) material content/m3 | 99 | 1 | 98 | 10 | 80 | Ex |
| Use of recycled materials | Maximize | % recycled material content/m3 | 99 | 1 | 98 | 20 | 80 | Ex |
| Sound insulation of the NRD | Maximize | dB | 30 | 24 | 6 | Nr | Nr | Nr |
| Whole barrier service life | Maximize | Years | 50 | 30 | 20 | 5 | 10 | Ex |
| Structural elements service life | Maximize | Years | 30 | 30 | 0 | 5 | 10 | Ex |
| Removability of the noise barrier at the end of its life | Maximize | 1-10 rating | 9 | 1 | 8 | Nr | Nr | Nr |
| Acoustic elements service life as stated by the manufacturer | Maximize | Years | 50 | 15 | 35 | 5 | 10 | Ex |
| Acoustic durability in-situ | Maximize | Years | 50 | 14 | 36 | 5 | 10 | Ex |
| Constructed technologies for easy maintenance | Maximize | 1-10 rating | 10 | 3 | 7 | Nr | Nr | Nr |
| Buildability/constructability of the noise barrier | Maximize | 1-10 rating | 10 | 1 | 9 | Nr | Nr | Nr |
| Climate change (i.e. durability) | Maximize | 1-10 rating | 10 | 7 | 3 | Nr | Nr | Nr |
| Ability to change existing noise barrier as required (e.g. increase height if needed) | Maximize | 1-10 rating | 10 | 3 | 7 | Nr | Nr | Nr |
| Loss of land | Maximize | 1-10 rating | 8 | 5 | 3 | Nr | Nr | Nr |
| Ecotoxicity of soil | Minimize | m3 of water/NRD $m^2$ | 58739.1 | 6380.01 | 52359.09 | 10000 | 25000 | Ex |
| Non-dangerous waste production | Minimize | kg/$m^2$ | 1097.52 | 67.13 | 1030.39 | 100 | 300 | Ex |
| Dangerous waste production | Minimize | kg/$m^2$ | 20.57 | 0.03 | 20.54 | 5 | 15 | Ex |
| Recyclability potential | Maximize | % recyclable/$m^2$ | 1 | 0.41 | 0.59 | 15 | 30 | Ex |
| Re-use potential | Maximize | % re-usable/$m^2$ | 0.544 | 0 | 0.544 | 15 | 30 | Ex |
| Global warming potential (whole life cycle) | Minimize | kg CO2equivalent/ $m^2$ | 251.38 | 69.8 | 181.58 | 50 | 100 | Ex |
| Acidification potential | Minimize | kg SO2 equivalent/ $m^2$ | 10.63 | 0.33 | 10.3 | 3 | 6 | Ex |
| Embodied water content (whole life cycle) | Minimize | litre/$m^2$ | 6216.76 | 1023.8 | 5192.96 | 2000 | 4000 | Ex |
| Ecotoxicity for water | Minimize | m3/$m^2$ | 58739.06 | 6380.01 | 52359.05 | 20000 | 40000 | Ex |
| Use of primary energy resources (whole life cycle) | Minimize | MJ/$m^2$ | 9729.24 | 1392.8 | 8336.44 | 3000 | 6000 | Ex |
| Renewable energy production (Photovoltaic/ small scale wind turbines) | Maximize | Yes(1)/No(0) | 1 | 0 | 1 | Nr | Nr | Nr |
| Cost of land | Minimize | €/$m^2$ | 62.5 | 6.3 | 56.2 | 10 | 30 | Ex |
| Design costs including consultants | Minimize | €/$m^2$ | 95.6 | 62.5 | 33.1 | 8 | 15 | Ex |
| Labor cost | Minimize | €/$m^2$ | 89.7 | 35.5 | 54.2 | 10 | 20 | Ex |
| Equipment hire cost | Minimize | €/$m^2$ | 54 | 13.2 | 40.8 | 10 | 20 | Ex |
| Fabrication/manufacturing + installation | Minimize | €/$m^2$ | 562.5 | 108 | 454.5 | 40 | 100 | Ex |
| In-situ civil works | Minimize | €/$m^2$ | 229.7 | 106.6 | 123.1 | 30 | 60 | Ex |
| Maintenance cost | Minimize | €/$m^2$ | 250 | 43.1 | 206.9 | 30 | 80 | Ex |
| Removal/demolition cost | Minimize | €/$m^2$ | 190 | 18.2 | 171.8 | 30 | 70 | Ex |

the applicable algorithms to generate downward and upward distillations. The two distillations are then combined to produce either a median or final preorder (i.e. ranking) of the set of alternative considered (see Roy, 1991; Buchanan and Vanderpooten, 2007; for detailed expositions).

Furthermore, critical to the MCA study at hand was defining the MCA parameters for implementing SAW, PROMETHEE, and ELECTRE 3 respectively. This mainly included defining min/max preferred values, and indifference, preference, and veto thresholds for the set of criteria considered. The final allocation of the MCA parameters for the selected criteria and MCA tools can be found in Table 2. The results of the MCAs are given in the next section.

**Table 3**
Generic sustainability performance matrix of the 13 roadside noise barriers.

| Noise barriers' sustainability assessment criteria and Indicators | Indicator | Roadside noise barrier type | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SM | SC | ST | SG | C | SP | CT | Stu | GT | GB | GA | EB | PVNB |
| Psycho-acoustic impacts [1–10 rating] | 1-10 rating | 6 | 6 | 6 | 6 | 6 | 6 | 9 | 9 | 9 | 6 | 6 | 6 | 6 |
| Heat island impacts | 1-10 rating | 3 | 3 | 4 | 4 | 3 | 4 | 3 | 4 | 4 | 9 | 6 | 9 | 6 |
| Work related sicknesses | 1-10 rating | 4 | 4 | 4 | 5 | 6 | 6 | 4 | 5 | 5 | 8 | 6 | 9 | 6 |
| Resistance of the barrier to vandalism | 1-10 rating | 2 | 2 | 3 | 2 | 3 | 3 | 5 | 5 | 2 | 8 | 8 | 9 | 2 |
| Glare control for road users | Yes(1)/No(0) | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 0 |
| Loss of view for residents and road users | 1-10 rating | 2 | 2 | 2 | 9 | 2 | 2 | 1 | 1 | 8 | 5 | 3 | 3 | 2 |
| Loss of daylight for residents and road users | 1-10 rating | 5 | 5 | 5 | 9 | 5 | 5 | 1 | 1 | 8 | 5 | 5 | 7 | 5 |
| Glare control for residents | Yes(1)/No(0) | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 0 |
| Community art use possible on the noise barrier | Yes(1)/No(0) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Use of new materials | % new (virgin)material content/m3 | 99 | 99 | 99 | 99 | 99 | 95 | 99 | 99 | 99 | 5 | 5 | 1 | 99 |
| Use of recycled materials | % recycled material content/m3 | 1 | 1 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 95 | 95 | 99 | 0 |
| Sound insulation of the NRD | dB | >24 | >24 | >24 | >24 | >24 | >24 | >30 | >30 | >30 | >24 | >24 | >24 | >24 |
| Whole barrier service life | Years | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 50 | 30 |
| Structural elements service life | Years | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| Removability of the noise barrier at the end of its life | 1-10 rating | 2 | 1 | 9 | 6 | 2 | 3 | 1 | 1 | 1 | 3 | 5 | 3 | 4 |
| Acoustic elements service life as stated by the manufacturer | Years | 30 | 40 | 20 | 20 | 30 | 20 | 40 | 30 | 20 | 15 | 20 | 50 | 20 |
| Acoustic durability in-situ | Years | 30 | 40 | 20 | 20 | 30 | 20 | 40 | 30 | 20 | 15 | 20 | 50 | 20 |
| Constructed technologies for easy maintenance | 1-10 rating | 9 | 10 | 8 | 5 | 10 | 7 | 10 | 10 | 5 | 7 | 10 | 10 | 3 |
| Buildability/constructability of the noise barrier | 1-10 rating | 3 | 3 | 4 | 3 | 3 | 3 | 5 | 10 | 5 | 3 | 3 | 1 | 3 |
| Climate change (i.e. durability) | 1-10 rating | 10 | 10 | 8 | 9 | 10 | 9 | 10 | 10 | 9 | 7 | 10 | 10 | 9 |
| Ability to change existing noise barrier as required (e.g. increase height if needed) | 1-10 rating | 4 | 3 | 9 | 7 | 8 | 7 | 10 | 10 | 10 | 8 | 8 | 10 | 6 |
| Loss of land | 1-10 rating | 8 | 7 | 7 | 8 | 7 | 8 | 5 | 5 | 5 | 4 | 6 | 1 | 6 |
| Ecotoxicity of soil | m3 of water/NRD $m^2$ | 25559.01 | 12107.8 | 7988.91 | 20335.55 | 8798.75 | 25443.05 | 17089.84 | 58739.06 | 29936.98 | 10277.28 | 13881.38 | 6380.01 | 50901.2 |
| Non-dangerous waste production | $kg/m^2$ | 241.83 | 187.85 | 175.03 | 289.97 | 85 | 210.08 | 102.26 | 1097.52 | 730.93 | 108.86 | 300.13 | 67.13 | 341.97 |
| Dangerous waste production | $kg/m^2$ | 0.11 | 0.07 | 20.57 | 0.14 | 0.04 | 0.07 | 0.06 | 0.45 | 0.26 | 0.05 | 0.11 | 0.03 | 0.78 |
| Recyclability potential | % recyclable/$m^2$ | 0.56 | 1 | 0.41 | 0.98 | 1 | 0.87 | 1 | 0.84 | 0.68 | 1 | 1 | 1 | 0.43 |
| Re-use potential | % re-usable/$m^2$ | 0 | 0 | 0 | 0.34 | 0 | 0 | 0 | 0 | 0 | 0 | 0.54 | 0 | 0 |
| Global warming potential (Total) | kg CO2equivalent/$m^2$ | 170.29 | 103.61 | 69.81 | 162.31 | 175.7 | 120.29 | 208.44 | 483.47 | 240.43 | 212.58 | 191.84 | 128.09 | 251.38 |
| Acidification potential | kg SO2 equivalent/$m^2$ | 2.24 | 1.82 | 1.69 | 3.04 | 0.45 | 1.91 | 0.55 | 10.63 | 6.83 | 0.54 | 2.67 | 0.33 | 1.81 |
| Embodied water content (Total) | litre/$m^2$ | 1644.68 | 1523.7 | 1023.8 | 2028.11 | 2323.68 | 1287.3 | 2738.61 | 6216.76 | 3737.35 | 2810.19 | 3857.16 | 1724.09 | 2052.66 |
| Ecotoxicity for water | $m3/m^2$ | 25559.01 | 12107.8 | 7988.91 | 20335.55 | 8798.75 | 25443.05 | 17089.84 | 58739.06 | 29936.98 | 10277.28 | 13881.38 | 6380.01 | 50901.2 |
| Use of primary energy resources (Total) | $MJ/m^2$ | 3728.6 | 2272.13 | 1625.46 | 3094.19 | 2944.22 | 2728.67 | 3420.11 | 9729.24 | 4563.66 | 2404.15 | 2799.67 | 1392.8 | 4445.55 |
| Renewable energy production (Photovoltaic/small scale wind turbines) | Yes(1)/No(0) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Cost of land | €/$m^2$ | 12.50 | 15.6 | 12.5 | 12.5 | 27.5 | 12.5 | 6.3 | 6.3 | 6.3 | 31.3 | 31.3 | 62.5 | 17.5 |
| Design costs including consultants | €/$m^2$ | 62.5 | 62.5 | 62.5 | 62.5 | 67.5 | 62.5 | 95.6 | 95.6 | 95.6 | 68.5 | 68.5 | 68.5 | 67.5 |
| Labor cost | €/$m^2$ | 35.5 | 41.3 | 35.5 | 55.3 | 44.6 | 35.5 | 89.7 | 89.7 | 89.7 | 55.3 | 55.3 | 53.6 | 35.5 |
| Equipment hire cost | €/$m^2$ | 13.2 | 14 | 13.2 | 15.4 | 14.2 | 13.2 | 58.5 | 54 | 54 | 34.2 | 29.9 | 34.2 | 13.2 |
| Fabrication/manufacturing + installation | €/$m^2$ | 143.7 | 135.3 | 125.3 | 183.7 | 123 | 158.7 | 292 | 466.9 | 562.5 | 108 | 129.4 | 167.6 | 140.3 |
| In-situ civil works | €/$m^2$ | 106.6 | 108.6 | 106.6 | 106.6 | 126.7 | 106.6 | 229.7 | 143.4 | 143.4 | 126.7 | 134.2 | 135.7 | 108 |
| Maintenance cost | €/$m^2$ | 85 | 60 | 85 | 125 | 125 | 85 | 46.3 | 43.1 | 100 | 250 | 60 | 175 | 85 |
| Removal/demolition cost | €/$m^2$ | 19.3 | 51.3 | 31 | 28 | 90.8 | 20.2 | 190 | 149.1 | 120 | 86.5 | 60.8 | 18.3 | 19.3 |

**Table 4**
Overview of MCA tools selected.

| Overview of MCA tools selected to assess and rank the relatives sustainability of the selected roadside noise barriers | | | |
|---|---|---|---|
| | SAW | PROMETHEE | ELECTRE 3 |
| **Complexity** (Simple, medium, complex) | Simple | Complex | Complex |
| **MCDM tool classification** | Compensatory/trade-off method | Non-compensatory | Non-compensatory |
| **Able to produce a final preference ranking of the set of alternatives?** (Yes/no) | Yes | Yes | Yes |
| **Produces a score to denote overall relative preference?** (Yes/no) | Yes, [0,1] Index score | Yes, [-1,1] Phi Net Flow | No overall score relative to the set of alternatives is computable |
| **Software essential?** | No | Yes (Visual PROMETHEE or D-Sight Software) | Yes (LAMSADE's ELECTRE 3 Software) |
| **Criteria modelling requirements for the study** | Min/Max values and specification of normalisation functions for the selected criteria | Specification of one of 6 PROMETHEE criteria types, and indifference and preference thresholds for the selected criteria | Specification of 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. |

### *3.5. MCA results: SAW, PROMETHEE, and ELECTRE 3 final overall sustainability rankings and rankings per sustainability factor (i.e. social, economic, environmental, and economic) of the main RNB types*

Through using the relevant software, the SAW, PROMETHEE, and ELECTRE 3 multi-criteria analysis of the sustainability criteria selected for ranking the relative sustainability of 13 roadside noise barriers using the MCA parameters (as shown in Table 2) have been carried out using equal weightings. Table 5 present the final overall relative sustainability rankings of the 13 RNB types generated by each MCA tool. Please note that the SAW, PROMETHEE, and ELECTRE 3 MCAs are able to generate many different tables, figure, and graphs which provide different insights to the decision problem. However this paper is concerned with complete rankings as these are considered most useful to the aims of the study and so are presented in following sections for discussion.

It should be noted that within SAW a same rank is shared when the total normalised scores are the same, and within ELECTRE 3 a same rank is shared when the alternatives are considered to be equally as good each other/incomparable at that ranking level. The rankings produced by SAW are a compensated ranking of the alternatives, and the rankings produced by PROMETHEE and ELECTRE 3 are a non-compensated ranking of the alternatives.

The results of the MCAs carried out to generate the relative rankings of the main RNBs' overall performance per sustainability factor (i.e. social, technical, environmental, and economic), per MCA tool, are presented in Tables 6–9 respectively. A sustainability performance profile of the main RNB types can then be built up using these results. However, note that the ELECTRE 3 method does not produce overall scores to denote preference, but is able to produce (as previously mentioned) an overall preference score in the pairwise comparison of two alternatives in the form of calculating Concordance, Discordance, and Credibility indices. The overall relative sustainability preference rankings of the main RNB types are derived through applying the applicable algorithms to generate downward and upward distillations. The two distillations are then combined to produce either a median or final preorder (i.e. ranking) of the set of RNB types considered (See Roy, 1991; Buchanan and Vanderpooten, 2007; for detailed treatments). The median preorder provides a more complete ranking by using the sum of ranks from the ascending and descending distillations, whereas the final preorder is the average of the two intermediate (ascending and descending) distillations. The ELECTRE 3 final preorders are given for the following results.

**Table 5**
The overall relative sustainability rankings of common roadside noise barrier types produced per MCA tool selected.

| Overall relative sustainability rankings of the main RNB types | | | | | | | |
|---|---|---|---|---|---|---|---|
| SAW | | | PROMETHEE | | | ELECTRE 3 | |
| Key | Rank | Summed index score | Key | PROMETHEE II ranking | Phi net flow score | Key | Rank (median preorder) |
| EB | 1 | 0.725 | EB | 1 | 0.223 | EB | 1 |
| ST | 2 | 0.616 | GA | 2 | 0.146 | GA | 2 |
| C | 3 | 0.597 | SC | 3 | 0.060 | SC | 3 |
| SC | 4 | 0.580 | SG | 4 | 0.052 | C | 4 |
| GA | 5 | 0.579 | C | 5 | 0.051 | SG | 5 |
| GB | 6 | 0.572 | ST | 6 | 0.037 | SM | 6 |
| CT | 7 | 0.555 | GB | 7 | 0.019 | ST | 7 |
| SG | 8 | 0.527 | SP | 8 | 0.004 | GB | 8 |
| SP | 9 | 0.526 | CT | 9 | −0.028 | SP | 9 |
| SM | 10 | 0.499 | SM | 10 | −0.042 | CT | 10 |
| PVNB | 11 | 0.461 | PVNB | 11 | −0.128 | PVNB | 11 |
| Stu | 12 | 0.449 | GT | 12 | −0.177 | Stu | 12 |
| GT | 13 | 0.441 | STu | 13 | −0.217 | GT | 13 |

**Table 6**
Comparison of the relative generated ranks for overall social performance per MCA tool selected.

| SAW | | | PROMETHEE | | | ELECTRE 3 | |
|---|---|---|---|---|---|---|---|
| Key | Rank | Summed index scores | Key | Rank | Phi net flow score | Key | Rank (final preorder) |
| EB | 1 | 0.753 | EB | 1 | 0.098 | EB | 1 |
| GB | 2 | 0.728 | GB | 2 | 0.075 | GT | 2 |
| GA | 3 | 0.642 | GA | 3 | 0.051 | GB | 2 |
| C | 3 | 0.642 | SG | 4 | 0.028 | SG | 3 |
| ST | 4 | 0.630 | GT | 5 | 0.020 | GA | 3 |
| CT | 5 | 0.617 | ST | 6 | −0.000 | C | 4 |
| SC | 6 | 0.605 | C | 7 | −0.016 | CT | 4 |
| GT | 7 | 0.556 | CT | 8 | −0.018 | Stu | 4 |
| SG | 8 | 0.543 | SP | 9 | −0.024 | ST | 5 |
| SP | 9 | 0.432 | SC | 10 | −0.035 | SP | 6 |
| Stu | 10 | 0.420 | Stu | 11 | −0.039 | SC | 7 |
| SM | 11 | 0.383 | PVNB | 12 | −0.053 | PVNB | 7 |
| PVNB | 12 | 0.333 | SM | 13 | −0.087 | SM | 8 |

**Table 7**
Comparison of the relative generated ranks for overall technical performance per MCA tool selected.

| SAW | | | PROMETHEE | | | ELECTRE 3 | |
|---|---|---|---|---|---|---|---|
| Key | Rank | Summed index scores | Key | Rank | Phi net flow score | Key | Rank (final preorder) |
| EB | 1 | 0.828 | EB | 1 | 0.132 | CT | 1 |
| STu | 2 | 0.661 | CT | 2 | 0.087 | EB | 1 |
| CT | 3 | 0.653 | STu | 3 | 0.073 | STu | 2 |
| GA | 4 | 0.643 | GA | 4 | 0.045 | GA | 2 |
| ST | 5 | 0.568 | C | 5 | 0.010 | ST | 3 |
| GB | 6 | 0.558 | SC | 6 | −0.006 | C | 3 |
| C | 7 | 0.554 | SM | 7 | −0.024 | GT | 4 |
| GT | 8 | 0.536 | ST | 8 | −0.024 | SC | 5 |
| SC | 8 | 0.536 | GB | 9 | −0.028 | GB | 5 |
| SM | 9 | 0.512 | GT | 10 | −0.028 | SM | 6 |
| SG | 10 | 0.499 | SG | 11 | −0.069 | SG | 6 |
| SP | 11 | 0.491 | SP | 12 | −0.077 | SP | 7 |
| PVNB | 12 | 0.455 | PVNB | 13 | −0.089 | PVNB | 7 |

**Table 8**
Comparison of the relative generated ranks for overall environmental performance per MCA tool selected.

| SAW | | | PROMETHEE | | | ELECTRE 3 | |
|---|---|---|---|---|---|---|---|
| Key | Rank | Summed index scores | Key | Rank | Phi net flow score | Key | Rank (final preorder) |
| EB | 1 | 0.689 | SG | 1 | 0.065 | SC | 1 |
| C | 2 | 0.576 | SC | 2 | 0.049 | SG | 2 |
| ST | 3 | 0.526 | SP | 3 | 0.047 | SP | 3 |
| SC | 4 | 0.488 | C | 4 | 0.041 | C | 4 |
| GB | 5 | 0.487 | GA | 5 | 0.038 | GA | 4 |
| GA | 6 | 0.451 | EB | 6 | 0.021 | EB | 5 |
| CT | 7 | 0.437 | SM | 7 | 0.010 | SM | 6 |
| SP | 8 | 0.431 | CT | 8 | 0.010 | CT | 6 |
| SG | 9 | 0.430 | GB | 9 | 0.005 | GB | 6 |
| SM | 10 | 0.347 | ST | 10 | 0.003 | ST | 7 |
| PVNB | 11 | 0.328 | PVNB | 11 | −0.044 | PVNB | 7 |
| GT | 12 | 0.238 | GT | 12 | −0.077 | GT | 8 |
| Stu | 13 | 0.191 | STu | 13 | −0.168 | STu | 9 |

## 4. Discussion

The SAW, PROMETHEE, and ELECTRE 3 MCA tools have been implemented to assess and rank the relative sustainability of common types of RNBs. A ranking of the overall relative sustainability (and overall performance per social, technical, environmental, and economic factor) of the common RNB types used around the world has therefore been achieved in this paper. These rankings will provide a useful reference for supporting the sustainable design and procurement practices of RNBs for road schemes by indicating the generic sustainability performances of the main RNB types available that can be used as benchmarks. Such a set of rankings will particularly favour situations where it is considered impractical for the DM/stakeholder tasked with selecting a RNB system to carry out their own complex sustainability MCA, and so save significant analysis time and costs.

Several lessons can be learnt from the applied tools and results. The decision maker has now the evidence based sustainability related information that is not site specific. As such the decision-maker can choose the best option that suits his/her brief for that particular site knowing fully well the advantages and disadvantages from the sustainability point of view that solution will have. More so the decision maker can choose a combination of solution that meet his/her brief for the same reasons explained above.

**Table 9**
Comparison of the relative generated ranks for overall economic performanceper MCA tool selected.

| SAW | | | PROMETHEE | | | ELECTRE 3 | |
|---|---|---|---|---|---|---|---|
| Key | Rank | Summed index scores | Key | Rank | Phi net flow score | Key | Rank (final preorder) |
| SM | 1 | 0.838 | SM | 1 | 0.059 | SM | 1 |
| SP | 2 | 0.824 | SP | 2 | 0.059 | SC | 1 |
| PVNB | 3 | 0.812 | ST | 3 | 0.058 | ST | 1 |
| ST | 4 | 0.808 | PVNB | 4 | 0.058 | SP | 1 |
| SC | 5 | 0.757 | SC | 5 | 0.053 | PVNB | 1 |
| SG | 6 | 0.698 | SG | 6 | 0.028 | SG | 2 |
| C | 7 | 0.643 | C | 7 | 0.015 | C | 2 |
| GA | 8 | 0.605 | GA | 8 | 0.013 | GA | 3 |
| EB | 9 | 0.592 | EB | 9 | −0.027 | STu | 4 |
| Stu | 10 | 0.549 | GB | 10 | −0.032 | GB | 4 |
| GB | 11 | 0.546 | Stu | 11 | −0.083 | CT | 5 |
| CT | 12 | 0.517 | GT | 12 | −0.092 | EB | 5 |
| GT | 13 | 0.477 | CT | 13 | −0.108 | GT | 6 |

An expanded discussion on the results of the MCA is given in the next section.

Furthermore, the application of the sustainability assessment framework clearly demonstrates that ‘green’ in relation to a product does not necessarily translate as the most sustainable option. As demonstrated by this research, the green noise barrier does not rank highly from an overall sustainability perspective. This raises an important point about greewashing and products marketed as “green” without evidence backed claims. Without considering all factors of sustainability, the selection of so called “green products” may mislead the decision maker to make less sustainable decision.

SAW, PROMETHEE, and ELECTRE 3 were particularly chosen as they offered different approaches to the decision problem: they ranged from simple to complex, the level of detail that could be considered in analysing the decision problem data, have a high prevalence of use within the literature, and to triangulate the results. As can be seen from Table 6, the SAW, PROMETHEE, and ELECTRE 3 MCA found overall the Earth Berm noise barrier type (based on the criteria selected and data used) as clearly the most sustainable noise barrier type. This result was not completely unexpected, which, in comparison to the set of RNB types considered, can be attributed to exceptional performance in the following criteria across the four factors of sustainability (see Table 3 for performance data):

**Technical:** Use of new materials, recycled materials, and service life.

**Social:** Resistance to vandalism, and health risk to workers.

**Environmental:** Recyclability potential, global warming potential, embodied water content, and use of primary energy resources.

**Economic:** removal/demolition cost.

Thus one could deduce that the relative sustainability ranks of the other RNB types could improve if their sustainability performances were to emulate (or be better than) the Earth Berm noise barrier type on the majority of the selected criteria. Indeed this notion of emulating an identifiable system in a positive way is somewhat similar to the principles of Biomimicry which aims to emulate natural systems rather than man-made products and systems. Of course, this paper acknowledges that noise barrier products are not naturally occurring systems, and so to consider them in such a fashion belies the principles of Biomimicry and may invite criticisms by practitioners. However, such a case is not uncommon, and one can find many cases of asserted man-made structures, or hypothetical models (in particular in the building sector) for industry practitioners to emulate either: (1) physically, or (2) performance wise, for sustainability. For example, within the housing sector, examples of best sustainability practices and builds (both actual and hypothetical) may be given to industry to imitate or seek to achieve. For instance, the Building Research Establishment Environmental Assessment Method (BREEAM) tool, a popular environmental assessment tool for buildings, rates the performances of buildings against hypothetical performances. Thus the notion of considering the Earth Berm noise barrier type as the “positive ideal” (also referred to in the literature as the Optimal Hypothetical Ideal Solution-OHIS, baseline solution, reference solution, benchmark solution, preferred solution, and so on), for the purposes of sustainable design is tenable. Therefore in order to extending and emulating the sustainability attributes of the top ranked RNB types with regards to sustainability the following recommendations should be considered for improving the overall relative sustainability of the manufactured RNB types. Additionally, as noise barriers' sustainability is an aggregation of technical, environmental, social, and economic performance, recommendations per factor are given.

**Social Factor:** use of natural looking materials, vegetation, or artificial cladding or finishes that give a natural appearance ought to be maximized to improve its overall social performance and acceptance.

**Technical Factor:** maximize use of recycled materials and minimize use of virgin materials. The service life of the main material elements of the noise barrier system ought to be extended by considering the following: the application of coatings; changing the mechanical processing of materials using techniques that increase service life; surface treatments; sacrificial material elements and weather resistant claddings, to improve its overall technical performance.

**Environmental Factor:** maximize designing noise barrier systems and selecting material which have a high recyclability or reuse potential at the end of its life. Additionally a broad approach to minimizing the carbon footprint, embodied energy content, and embodied water content of noise barrier systems through either: (1) material selection or (2) improvements to material processing techniques should be taken to enhance its overall environmental performance.

**Economic Factor:** although capital costs are generally the single largest cost throughout the whole life of a constructed asset, the combined maintenance and removal cost of a system could be higher in some cases. Therefore, barrier systems which are easy to maintain, repair, replace, and expand as and when required (and so time and cost efficient), ought to be maximized to improve its overall economic performance.

Therefore it is possible that the low overall sustainability rankings of the RNB types presented in this study (e.g. SP, CT, SM, GT, PVNB, and Stu) could significantly increase following implementing the above recommendations and also considering additional criteria and weighting criteria to reflect the priorities of the project.

Additionally, the analysis of the 13 RNB types per sustainability factor (i.e. social, technical, environmental, and economic) provides a convenient "Sustainability performance profile", and so a deeper insight into their sustainability performances. These ranking per sustainability factor could further support cases where the stakeholder(s) may lack the expertise or not have the resources available to conduct such complex sustainability assessments for design and procurement related activities. Nonetheless, a number of caveats need to be noted regarding the present study. The results of the MCA need to be interpreted with caution because the results are based on: evaluating largely site-independent sustainability criteria, using generic (average) sustainability data, using equal weightings for the selected criteria, and axiomatically defined indifference and preference thresholds for the MCA parameters. As such the presented rankings are not definitive but only serve to inform decisions. This does not diminish the value and novelty of the research since the data used whilst generic and average can be used as benchmarks for the respective RNB by DM to ascertain the sustainability of their own RNB for a certain criteria or category of criteria and identifying the need for improvement in the design or manufacturing stages.

Nevertheless, the relatives sustainability rankings of the main RNB types presented in this study could alter significantly when: additional and site dependent criteria are selected, criteria are weighted to reflect the priorities of the DM/context, alternative MCA parameters are selected for the three respective MCA tools, and specific data instead of generic data are used for assessing the precise and accurate sustainability of noise barriers, as presented in Oltean-Dumbrava et al. (2016). Therefore it is arguable that a case-by-case approach to the sustainable selection of RNBs, rather than a generic one, should be taken. The layout of the site and consideration of site-specific issues (i.e. location, logistics, access, topography, population, weather, urban character, etc.) has the potential to improve/reduce the sustainability performance of the set of RNB types studied. The consideration of additional criteria which reflect these issues could therefore increase or decrease the relative sustainability rankings of the barrier types considered in this paper. It is possible that certain RNB types which have performed poorly in this study may perform better when site related issues and priorities of the assessor are taken into further consideration. This supports the notion that there is no such thing as an absolutely sustainable noise barrier, but only a good match between the barrier type, the location and the purpose it was intended for.

The rankings produced by SAW are a compensated ranking of the alternatives, and the rankings produced by PROMETHEE and ELECTRE 3 are a non-compensated ranking of the alternatives. Note: similarities between the PROMETHEE and ELECTRE 3 rankings are due to the same indifference and preference thresholds being respectively applied for each method. A discrepancy between the rankings of the relative sustainability of the studied noise barrier types from the applications of compensatory methods (i.e. SAW) and non-compensatory methods (i.e. PROMETHEE and ELECTRE 3) are observable. Except for the Earth Berm noise barrier type, average deviations of $\pm$ 2 to 3 in the relative ranks of the remaining 12 RNB types can be seen between the SAW, and PROMETHEE and ELECTRE 3 overall relative sustainability ranks. This suggests a large amount of "trade-offs" if the calculation of the overall relative sustainability was carried out with SAW. That is, a weak performance in one criterion was compensated for by a strong performance in a different criterion. This compensation of criteria performance could be argued as opposing the fundamental principle of sustainability which generally state an optimal and fair consideration of the conflicting objectives related to sustainability is taken. It would thereby be unwise to base decisions on an "overall sustainability ranking/index" from the application of compensatory methods, such as SAW, as these methods could hide unacceptable solutions. Such decision making practices should be considered with caution as they might not promote sustainability (e.g. a strong performance in economic related objectives could compensate for a weak performance in environmental related objectives), and indicate the need for applying non-compensatory methods for the sustainable design and procurement of RNBs as these assessment methods reflect the principles of sustainability.

The results of the SAW, PROMETHEE and ELECTRE 3 MCA are transitive. As the results are relative to the set of noise barrier types considered in this study, adding or deleting a noise barrier type could significant alter the relative positions of the types of RNBs assessed here. Therefore should a relevant stakeholder wish to compare the sustainability of a new type of noise barrier (e.g. one composed entirely of shredded recycled rubber from old car tyres, or a hybrid RNB such as a metal noise barrier type with transparent modules) against the results shown in this study, the stakeholder will have to repeat implementing the data and methods presented in this report (i.e. 13 + 1 assessments per MCA tool). Such an assessment may well be challenging for the stakeholder as a significant amount of time in this study was spent setting up the MCA problem, collecting that data and running the analyses. Budget constraints may also limit the time and resources available to stakeholders wishing to carry out such evaluations. This observation, therefore, suggests that a simpler outranking approach or method that produces non-transitive rankings/ratings is required in order for one to practically compare the introduction of "new types" of noise barriers' sustainability in comparison to the 13 types studied in this report.

The problem of transitive rankings could be overcome by conducting "absolute" instead of "relative" sustainability assessment by specifying a "Positive Ideal Solution" (also referred to in the literature as the Optimal Hypothetical Ideal Solution-OHIS, baseline solution, reference solution, benchmark solution, preferred solution, and so on). In this case a direct "one-to-one" absolute sustainability assessment against the positive ideal solution could be carried out in place of relative assessments against multiple RNB types, as described in this paper. However, the challenges of defining a positive ideal solution lay in the subjectivity of postulating such a solution and gaining industry acceptance. Neither task is easy to achieve and will require further research. However, this study has shown evidence that the Earth Berm noise barrier type is the most sustainable type, and hence provides the rationale to initially consider this type as the "positive ideal solution" for either: (1) direct "one-to-one" comparisons, or (2) as the basis for developing a hypothetical ideal solution for the purposes of conducting absolute sustainability assessments. The research and results presented will be directly useful to the surface transportation and RNBs industry. As these results are based on industry averages across Europe, the results will provide useful information to manufacturers to benchmark sustainability performance of their own products against these results and in doing this drive innovation. However, the principles and theory applied to assess the sustainability of a "product" presented in this paper will be of use to other industries and manufacturers from other industries in several ways:

- **To score and rank the sustainability of product category groups in their own industries:** the learning and notion of ranking the relative sustainability of common products within a product category using MCA could be applied to other product category groups and industries (e.g. automobile industry, building materials, consumer products, etc.), and thus providing information to decision makers for making informed decisions regarding sustainability. The decision-makers will then know if their products are or not competitive from the sustainability point of view. This knowledge will drive innovation in designing better products.

- **For developing a product sustainability scheme for all product categories:** the methods applied to generate an "overall product sustainability score" could provide the theoretical basis for a sustainability product labelling scheme for all product categories. The widespread use of such a sustainability label is missing from the market place. Currently, Environmental Product Declarations (EPDs) are used to support decisions, but these are limited as they provide only environmental information. Expanding the system to include all sustainability factors (i.e. social, economic, and technical) will provide the full set of product sustainability information to stakeholders, and in turn support advancing the sustainability agenda.

## 5. Final conclusion and recommendations

This paper has provided an account of the first study carried out to assess and rank the relative sustainability of 13 RNB types via the application of three MCA techniques (i.e. SAW, PROMETHEE, and ELECTRE 3). After implementing the methods and MCA tools described in this paper, the relative sustainability rankings and ranking per sustainability factor (i.e. social, technical, environmental, and economic) of the 13 RNB types (see Tables 6–9) have been presented and discussed. The results of the MCAs in this paper have shown evidence that the Earth Berm noise barrier types is generally the most sustainable, and so provides the rationale for emulating its sustainability attributes for informing the sustainability designs of RNBs. The analysis and rankings of the main RNB types per sustainability factor provides a convenient "Sustainability performance profile", and so a deeper insight in to the sustainability performances of the said RNBs for the stakeholders. The consideration of RNBs' sustainability will be an important factor as increasing pressure on the relevant stakeholders (e.g. public authorities, transport planners, engineering/asset managers, consultants, contractors, investors, etc.) for sustainably developing, upgrading, and maintaining national road networks in the foreseeable future continues to increase. The findings presented in this paper, therefore, offer a significant contribution to the stat of the art of roadside noise barriers' sustainability, and will help support practitioners in the planning, design, and procurement stages evaluate the sustainability of noise barrier options as either part of a large highways scheme or standalone project.

SAW, PROMETHEE, and ELECTRE 3 were chosen to achieve the aim of this study mainly because of their prevalence of use by practitioners and contrasting approaches to solving MCA problems. That is, SAW is a compensatory/trade-off method, and PROMETHEE and ELECTRE 3 are a non-compensatory/non-trade off methods.

Additionally many popular certification schemes and MCA tools like SAW are compensatory in their approach to assessing criteria. This is against the fundamental principles of sustainability, which implies that trade-offs in criteria performance are unacceptable unless the aim is to achieve a global minimum then trade-offs might well be one way of achieving this in a real system incorporating interdependencies among the variables. An assessment method or certification scheme which mirrors the above view is thus required for assessing the sustainability of potential or constructed assets. The adoption of non-compensatory or out-ranking based methods to achieve this end are the most judicious as they generally do not allow for trade-offs between criteria performance, and aim to find the most optimised solution/acceptable compromise with regards to achieving sustainability objectives. While various commentators have highlighted that there is no such thing as a "one size fits all" set of criteria or an unified method of approach to the problem of assessing sustainability, it is the authors' view that such approach is required in order to: (1) provide a harmonised approach to assessing the different levels of the civil engineering infrastructure systems, and (2) move towards making decisions which explicitly address conflicting objectives, do not accept trade-offs, and promote achieving the global goal of "sustainability".

The development and application of certification systems have been shown to be effective tools in promoting regulation, exchange of information, and a common approach to design and decision making, and offer a viable mechanism for achieving this end. Given the above, it is recommended that future work be carried out to develop a "non-compensatory certification scheme" for commonly assessing the sustainability of all RNB types and projects as such a certification scheme currently does not exist for the industry, as well as other industries. The said scheme should embody the principles of sustainability by preferring solutions which best meet the conflicting objectives of sustainability (i.e. social, technical, environmental, and economic performance) and reward projects for doing so accordingly. The research work completed in this paper would therefore provide the basis for such an undertaking and support advancing the transport sustainability agenda.

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