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# Transport infrastructure: making more sustainable decisions for noise reduction

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ABSTRACT

There is a global and growing sustainability agenda for surface transport yet there are no specific means of assessing the relative sustainability of infrastructure equipment. Transport noise reduction devices are a significant part of the surface transport infrastructure: they specifically address environmental and social needs, have a high economic impact, and involve a wide range of raw materials raising multiple technical issues. The paper presents an account of the bespoke tool developed for assessing the sustainability of transport noise reduction devices. Regulatory standards for noise reduction devices and the relevant sustainability assessment tools and procedures adopted worldwide were reviewed in order to produce a set of pertinent sustainability criteria and indicators for NRDs projects, which were reviewed and edited during a stakeholder engagement process. A decision making process for assessing the relative sustainability of noise reduction devices was formulated following the review of the literature. Two key stages were identified: (1) collection of data for criteria fulfillment evaluation and (2) multi-criteria analysis for assessing the sustainability of noise reduction devices. Appropriate tools and methods for achieving both objectives are recommended.

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## 1. Introduction

Within surface transport infrastructure there is an urgent need for greater sustainability in noise reduction devices (NRDs), which include noise barriers, absorptive claddings and covers, as there is a current worldwide lack of support for practitioners in this area. An assessment framework approach and the research strategy used to define sustainability criteria and indicators for NRDs comprising primary and secondary research are described. The work described was carried out as part of the 'Quietening the Environment for a Sustainable Surface Transport' (QUIESST) project, co-funded by the European Community's Seventh Framework Programme (http://www.quiesst.eu/) and is a three year (2009–2012), multidisciplinary project involving 13 EU partners from 8 countries. Work package 6 (WP6) and its specialist research team are researching the sustainability of noise reducing devices (NRDs) across their whole lifecycle. A decision making process (DMP) is presented which includes recommended multi-criteria decision making analysis tools and data generation tools for sustainability assessment. This DMP is relevant to the scale and context of the NRD; it supports existing decision making processes utilized by national authorities and practitioners and was developed to meet the needs of the end user.

### 1.1. Noise reduction devices

Close to 80 million people in the European Union (around 20% of its population) have been estimated to suffer from the effects of noise at levels considered to be unacceptable, that is levels where most people become annoyed, where sleep is disturbed and where adverse health effects are to be feared (Nijland and Van Wee, 2008). Traffic noise is a typical area of conflict between individual mobility needs and legitimate societal aspirations for quieter lifestyles (European Union Road Federation, 2004). The reduction of transport noise (from any source) in Europe is a requirement of The European Parliament and the Council Directive (2002) relating to the Assessment and Management of Environmental Noise (also referred to as the 'Environmental Noise Directive' or 'END'). Surface noise produced by road and rail traffic is one of its main targets, with an expected reduction of 10–20 dB. Noise reduction can be made at the point of emission, propagation and/or reception. A holistic approach, targeting the whole process and optimizing the action taken is most effective, yet research to integrate the intrinsic characteristics of NRDs, i.e. characteristics of their production

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(mainly absorption and airborne sound insulation) and the extrinsic characteristics, i.e. performance *in situ* (final effectiveness) has been limited (Clairbois et al., 2010).

Many different types of NRDs are available throughout the world. The NRDs considered here are designed to control the spread of noise from roads and railways and include such devices as noise barriers, absorptive claddings and road covers. Some examples of NRDs are given in Table 1, as well as the added devices which are placed at the top of barriers in order to reduce sound diffracted into the protected zone and thereby decrease overall noise levels. The list is not exhaustive but represents the range of types of noise barrier currently in use.

NRDs are a growing part of Europe's transport infrastructure: a key objective of the Commission of the European Communities' (2001) White Paper on European transport policy was to promote the sustainability of surface transport and its respective infrastructure, but as yet there are no methods which allow for the specific assessment of the relative sustainability of NRDs.

### *1.2. The relative sustainability of noise reduction devices*

A review of existing research and technical information about the sustainability of NRDs (Oltean-Dumbrava et al., 2010, 2012) concluded that sustainability factors such as carbon footprint, whole life costs and design for climate change are not being fully considered across the whole lifecycle of NRDs (i.e. during construction, maintenance, repairs and demolition/removal). Furthermore, affected communities are rarely engaged in the decision making process. These findings were confirmed by a survey of key players and stakeholders in the NRD industry across Europe which found that 2/3 of respondents believed climate change would affect NRDs and over 90% did not calculate the carbon footprint of NRDs throughout their whole lifecycle and none of those surveyed considered the whole lifecycle costs of NRDs (ibid.).

Typical NRD projects are of a large scale; they use as many resources and have as much of an impact on the built environment as any other large built structure, hence the need for their sustainability to be considered by policy makers, designers and industry professionals. For all aspects of sustainability to be taken into account in decisions made at all stages within the NRD lifecycle, (design, construction, usage, maintenance and repair, demolition and removal) accurate data and a sound methodology are required.

There is general consensus amongst practitioners and academics that sustainability encompasses three main components; social, economic and environment (e.g. Carew and Mitchell, 2008; Spangenberg et al., 2010; Olewiler, 2008; British Standards Institute, 2010; Xing et al., 2009; Belof et al., 2009; Tsai and Chang, 2010). For civil engineering/infrastructure projects a fourth component, 'Technical' may take into consideration the performance and functional aspects of engineering projects (Oltean-Dumbrava, 2010a,b,c; Ashley et al., 2004). Fig. 1 illustrates how sustainability factors should be incorporated throughout the lifecycle of NRDs.

The term 'sustainability' is ubiquitous within the construction sector and has been adopted by most Governments worldwide (Rametsteiner et al., 2011; Augenbroe and Pearce, 1998; Brandon, 2005; Curwell et al., 1999; Halliday, 2008). However, despite being widely acknowledged in society and industry it is still an often misunderstood and misinterpreted concept (Hunt et al., 2008; Loucks and Gladwell, 1999; Cole, 2006). This may be because definitions of sustainability are numerous and the spatial and temporal scales in which it is considered are often not made explicit (Oltean-Dumbrava, 2010b).

According to Bell and Morse (2008) the most difficult, but equally important task is to define the time frame for the aim of achieving sustainability. Within the built sector *inter alia*, this can cause much confusion if one does not also identify the appropriate spatial scale one must work within (Joumard and Gudmundsson, 2010; Ashley et al., 2004; Gouda, 2004; Lélé, 1991; Loucks and Gladwell, 1999). From the spatial scales illustrated in Fig. 2, NRDs clearly fit within the project/small scale civil engineering project level to product level and a sustainability assessment methodology is required to suit this context.

The first ever, tailor made sustainability assessment tool for NRDs is presented. This will aid all stakeholders involved at all lifecycle stages of NRDs to make better informed decisions that should result in more sustainable NRDs.

### *1.3. The NRD sustainability framework*

The term 'Sustainability framework' has been defined as: *'The structure used to select and organize criteria, indicators and benchmarks'* (Oltean-Dumbrava, 2010b). A practical definition for sustainability in relation to NRDs is given by Oltean-Dumbrava et al. (2010): *'The optimal consideration of technical, environmental, economic and social factors during the design, construction, maintenance and repair, and removal/demolition stages of NRDs projects'*.

There are a number of sustainability frameworks for the assessment of environmental, economic and social factors in engineering and infrastructure projects but few address the technical elements separately (Foxon et al., 2002 and Ashley et al., 2004 are exceptions). Fig. 3 shows the proposed sustainability framework for NRDs and its cascading structure of criteria and indicator sets.

Indicators of sustainability should be carefully selected in order to be able to measure the comparative level of sustainability with accuracy (Yigitcanlar and Dur, 2010). Indicators can lead to better decisions and more effective actions by simplifying, clarifying and making aggregated information available to policy makers and practitioners (United Nations, 1992).

Much literature has been produced regarding development of criteria and indicators for sustainability (e.g. Joumard and Gudmundsson, 2010; Fernández-Sánchez and Rodriguez-Lopez, 2010; Hunt et al., 2008; Hurley et al., 2008; Hillyer and Purohit, 2007; Ugwu and Haupt, 2007; Atkisson et al., 2004; Sahely et al., 2004; Foxon et al., 2002; Häkkinen et al., 2002; Huovila, 2002; Segnestam et al., 2000; Bossel, 1999). The British Standards Institute (2010) (BSI) framework BS ISO 21929-1 summarizes the process and the European Environment Agency 'DPSIR framework'

**Table 1**
Some types of noise barrier currently in use.

| Main noise barrier | Added devices placed on top of main noise barrier |
|---|---|
| Steel supporting structure + metal panels | T-shape |
| Steel supporting structure + concrete panels | Cylindrical |
| Steel supporting structure + timber panels | Multiple edge |
| Steel supporting structure + transparent modules | Y-shape |
| Steel supporting structure with plastic panels | Sound interference louvers |
| Self supporting concrete or brick system | |
| Tunnel-concrete structure | |
| Tunnel-steel structure | |
| Tunnel with transparent panels | |
| Green barrier | |
| Gabion with stones | |
| Earth barrier (earth berm) | |
| Photovoltaic noise barrier | |

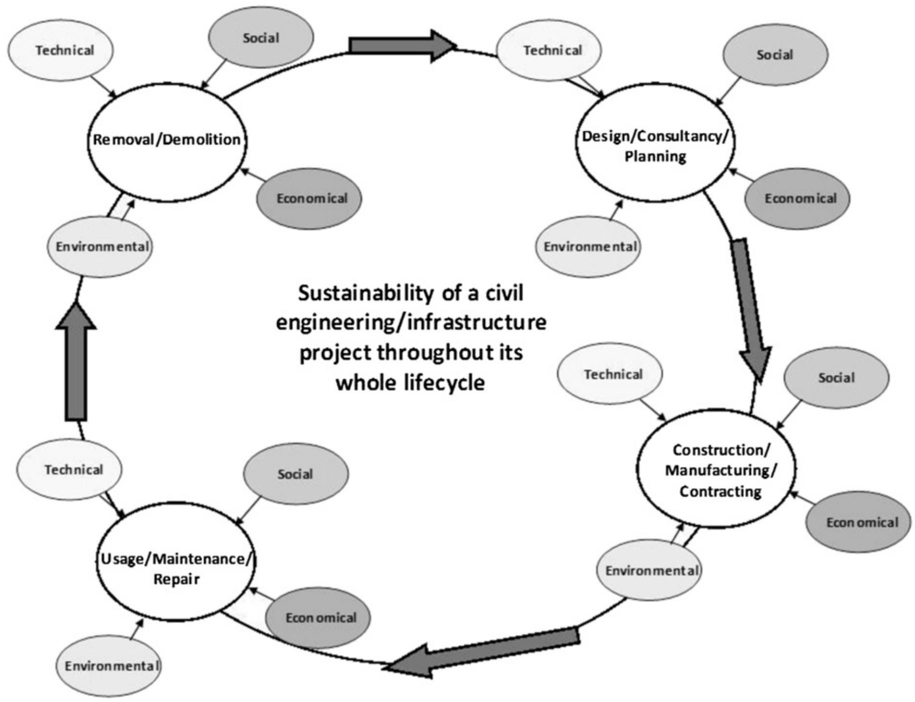


**Fig. 1.** Sustainability factors to be considered throughout the whole lifecycle of NRDs.

for reporting on environmental issues (driver, pressure, state, impacts, responses) enables categorization of indicators and modeling of cause-effect relationships (Table 2).

### 1.4. Sustainability assessment tools

The relative sustainability of different solutions for a given project is tested by assessing fulfillment of a set of criteria that represent the goal of the most sustainable option. The solution which ranks first among the other alternatives in fulfilling the requirements of the criteria will be considered the most sustainable.

At present there exists no comprehensive, fully holistic sustainability assessment tool for NRD projects. 'Tools' here are considered as being: assessment guides; decision making systems; agendas; rating systems; sustainability methods; evaluation tools; appraisals, or any system that can measure the performance of a 'preferred solution'. The paradigm of measuring sustainability through the use of tools and indicators is not new. In 2003, the construction and city related sustainability indicators (CRISP) internet database contained more than 500 indicators gathered in 39 systems (Hunt et al., 2008; CRISP, 2001). Walton et al. (2005) reported more than 675 tools applicable to the assessment of sustainability in urban developments. For civil engineering projects, Fernández-Sánchez and Rodriguez-Lopez (2010) found 70 tools for assessing the sustainability of building projects.

Therivel (2004) found that there is no such thing as a 'good tool', but only a good match between a tool and the purpose for which it was intended. Thus, it could not be assumed that any existing tools were directly applicable to noise barrier projects without modification, but a review of already developed primary and secondary criteria and indicators was carried out; Fernández-Sánchez and Rodriguez-Lopez (2010) believe this is particularly useful in identifying transferrable/adaptable criteria because of the feedback already received about tools in use.

The selection of methods and tools for assessing the overall sustainability of NRDs is a Multi-Criteria Analysis (MCA) problem and involves the development of three key elements:

1. The decision making process (DMP) for assessing the sustainability of NRDs and where the implementation of various sustainability tools should be applied;
2. Selection of a Multi-Criteria Decision Making (MCDM) tools(s) to carry out the Multi-Criteria Analysis (MCA) to assess the sustainability of NRDs; and
3. Selection of analytical/data generation tools which could be used to provide data for the MCA.

Decision making is widely researched e.g. Foxon et al. (2002), Atkisson et al. (2004), Fernández-Sánchez and Rodriguez-Lopez (2010), Bossel (1999), Sahely et al. (2004), Segnestam et al. (2000), Häkkinen et al. (2002), Joumard and Gudmundsson (2010), Ugwu et al. (2006), Fenner and Ryce (2008), Hunt et al. (2008), Huovila (2002), Hillyer and Purohit (2007), and many MCDM methods and tools are recommended for approaching multiple criteria problems. Selection of a suitable MCDM tool for

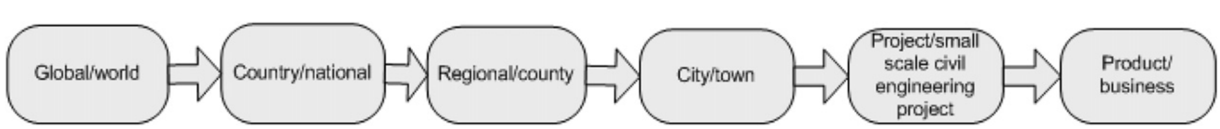


**Fig. 2.** Spatial scales of sustainability assessment.

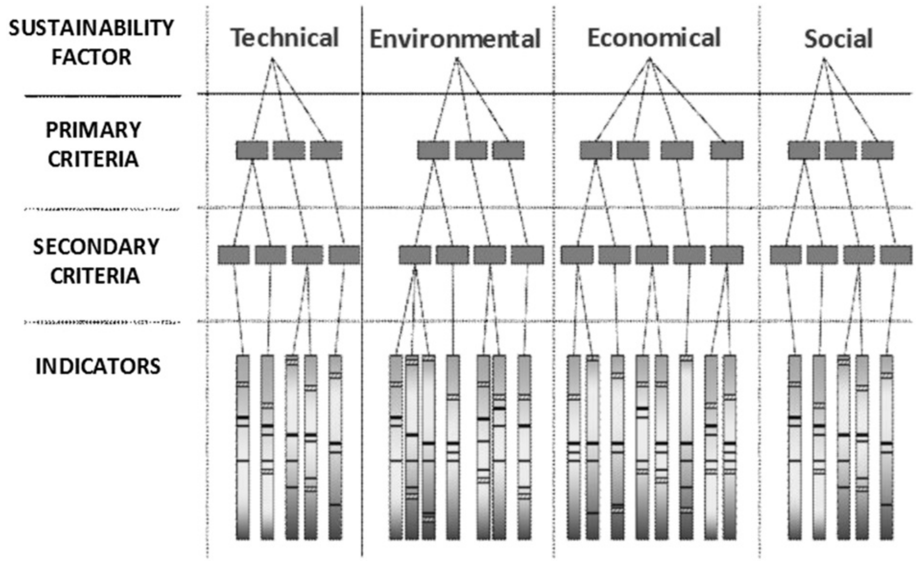


**Fig. 3.** Sustainability framework for noise reduction devices (adapted from Ashley et al., 2004).

MCA, and of the tools for generating criteria (attribute) data, is important as this can determine whether or not the sustainability procedural tool/framework is widely utilized.

### 1.5. Research aims and objectives

The main aim of this research was to develop a decision making tool to enable assessment of the relative sustainability of different NRDs. It is intended that various stakeholders involved in the NRDs industry will utilize this tool in order to make better decisions that result in more sustainable NRDs. To achieve this end, the key research outcomes of WP6 and so the final bespoke sustainability assessment framework and method for assessing the whole life sustainability of NRDs will form part of the 'Guidebook to NRD optimization in a sustainable way' aiming to be the future reference source for noise mitigation by NRDs. It was essential therefore that feedback was sought during tool development from potential end users.

The objectives were to:

- Compile a sustainability criteria and indicators database for the selection of the most relevant/adaptable criteria for the sustainability assessment of noise barrier projects;
- Create a 'sustainability framework' for structuring relevant criteria and indicators to use in assessing the sustainability of noise barrier projects;
- Define a decision making process for assessing the sustainability of NRDs;
- Comprehensively evaluate and recommend the best MCDM tool(s) to assess the sustainability of NRD projects; and to
- Identify and compile a list of sustainability 'tools' which can be practically used for assessing the overall sustainability of NRD projects.

## 2. Methods

### 2.1. Defining criteria and indicators

Existing research strategies for defining potential criteria and indicators are not suitable for NRD projects without modification. This led to the development of a research strategy for NRD projects, whereby, a 'Top-Down-Bottom-Up' approach was taken to create and validate the set of environmental, social economic criteria and technical criteria that characterize the sustainability of NRDs throughout the whole lifecycle.

The 'Top-Down' approach comprised secondary research in the form of a literature review of the regulatory framework and standards relating to NRDs and information regarding sustainability. Sustainability factors, criteria, indicators, frameworks and tools were collated, along with existing indicator sets such as the UK Government Quality of Life Counts indicators and the CRISP (Construction and City Related Sustainability Indicators), and analysis was made of how they represent the relative sustainability of NRDs throughout the whole lifecycle. From this an initial set of criteria and indicators was produced for review and amendment during a stakeholder engagement process. Table 3 lists the standards and Table 4 lists the assessment tools that were reviewed.

'Bottom-Up' primary research was used to validate the proposed set of sustainability criteria, to determine whether any criteria

**Table 2**
Sustainability indicator development requirements (adapted from British Standards Institute, 2010).

| Main types of indicators | Criteria and indicators should be: | Information about an indicator should contain at least: |
|---|---|---|
| - Driving force indicators<br>- Pressure indicators<br>- State indicators<br>- Response indicators | - Informative and significant<br>- Clearly related to one or several dimensions of sustainability<br>- Transferrable<br>- Interpretable and understandable<br>- Based on data that are available and easy to obtain<br>- Flexible to allow for future development<br>- Agreed upon by stakeholders | - A title<br>- A description/definition<br>- A unit of measurement (where applicable)<br>- Data availability and sources<br>- Organizations involved in the development<br>- References and further resources |

**Table 3**
International Standards Organization Standards in relation sustainable aspects of buildings and their indicators (Source: British Standards Institute, 2010; Fernández-Sánchez and Rodriguez-Lopez, 2010).

| Standard | Standard title | Year |
|---|---|---|
| ISO 21929-1 | Sustainability in building construction – Sustainability indicators – Part 1: Framework for development of indicators and a core set of indicators for buildings | 2006 |
| ISO 21930 | Sustainability in building construction-environmental declaration of building products | 2007 |
| ISO 21931-1 | Sustainability in building construction-framework for methods of assessment for environmental performance of construction works. Part 1: buildings | 2008 |
| ISO 21932 | Sustainability in building construction-terminology | 2005 |
| ISO 15392 | Sustainability in building construction-general principles | 2008 |
| CEN EN 15643-1 | Sustainability of construction works-integrated assessment of building performance. Part 1: general framework | Draft |
| CEN EN 15643-2 | Sustainability of construction works-integrated assessment of building performance. Part 2: framework for the assessment of environmental performance | Draft |
| CEN EN 15643-3 | Sustainability of construction works-integrated assessment of building performance. Part 3: framework for the assessment of social performance | Draft |
| CEN EN 15643-4 | Sustainability of construction works-integrated assessment of building performance. Part 4: framework for the assessment of economic performance | Draft |
| ISO 14001 | Environmental management systems – Specification with guidance for use | 1996 |
| ISO 14004 | Environmental management systems – General guidelines on principles, systems and supporting techniques. | 1996 |
| ISO 14010 | Guidelines for environmental auditing – General principles | 1996 |
| ISO 14011 | Guidelines for environmental auditing – Audit procedures – Auditing of environmental management systems | 1996 |
| ISO 14031 | Environmental management – Environmental performance evaluation – Guidelines | 1999 |
| ISO/TR 14032-1 | Environmental management – examples of environmental performance evaluation (EPE). | 1999 |
| ISO 14040 | Environmental management – Lifecycle assessment – Principles and framework. | 1997 |

**Table 4**
Sustainability assessment tools tailor made for civil engineering projects.

| Acronym | Brief description |
|---|---|
| LA21 | Local Agenda 21: not a tool but an agenda for change created by the United Nations; provides rationale for many tools and policies worldwide |
| SWARD | Sustainable Water industry Asset Resource Decisions: developed in conjunction with UK water industry professionals (Ashley et al., 2004); the only tool to directly acknowledge the 'technical factor' in assessing sustainability |
| BREEAM | Building Research Establishment's Environmental Assessment Method: developed in the United Kingdom in 1990, becoming known internationally as the measure for best practice in environmental design and management |
| SPeAR | Sustainable Project Appraisal Routine: developed by Arup, informs decision making at all stages of design and development |
| LEED | Leadership in Energy and Environmental Design: developed in the U.S. in 1998 as a consensus-based building rating system based on the use of existing building technology |
| CEEQUAL | Civil Engineering Environmental Quality Assessment and Audit Scheme: UK assessment & awards scheme for improving sustainability in civil engineering and public realm projects |
| HK-BEAM | Hong Kong, Building Environmental Assessment Method: established in 1996 with two assessment methods for new and existing office buildings. Also three categories for global, local and indoor impacts, respectively (BRE, 2006) |
| CASBEE | Comprehensive Assessment System for Building Environmental Efficiency: developed in Japan in 2001, it is a method for assessing the environmental performance of buildings |
| GREEN STAR | An Australian national, voluntary environmental rating system that evaluates the environmental design and construction of buildings with tailored tools to suit a range of building types (based on BREEAM & LEED) |
| SUSAIP | Sustainability Appraisal in Infrastructure Projects: analytical decision model and a structured methodology for sustainability appraisal; the only one of those considered to evaluate infrastructure projects |
| HQE | Haute Qualité Environnementale (High Quality Environmental Method): a French method for sustainable buildings, based on the principles of sustainable development |
| SBA | Sustainable Building Alliance Method: a pan-European sustainable assessment method, based on the different national approaches and developed at the initiative of the United Kingdom's Building Research Establishment (BRE) and the French CSTB (Centre Scientifique et Technique du Bâtiment) |

should be added or removed from the set, and to rank/rate each criterion by means of:

- A survey of key stakeholders involved in the NRD industry across Europe,
- Group workshops of key stakeholders involved throughout the whole life of NRDs, and
- Interviews with key stakeholders and experts.

Primarily a questionnaire-based survey was developed containing the proposed set of generic sustainability criteria, whereby the responded were asked to: rate, rank, add, and remove criteria, and validate/comment on the generic set of sustainability criteria for NRDs projects. A copy of the sustainability criteria validation questionnaire survey can be found in Oltean-Dumbrava et al. (2010). The questionnaire survey allowed the researchers to engage with a large range of relevant stakeholders involved throughout the whole lifecycle of NRDs in a short space of time. The survey was conducted over a 5 week period from 4th October 2010 to 5th November 2010. The QUIESST consortium and their available network(s) were fully utilized in order to gain meaningful responses from a wide range of organisations/individuals that include: national road and rail authorities, planning authorities, contractors, manufacturers, consultants, designers, acoustical engineers, asset managers, researchers and so on, across Europe. A total of 34 questionnaires was returned which, given the small niche market size of NRDs and the general historic reluctance of stakeholders to participate and the wide range of stakeholders represented, was considered a good sample size to perform meaningful statistical analysis. Kendall's co-efficient of concordance for the ranking data and the average ratings for each criterion together with their standard deviation were used to analyze the data collected in determining the stakeholders' agreement for the said criteria.

### 2.2. Selection of multi-criteria decision making tools for multi-criteria assessment

A shortlist of MCA tools for detailed consideration in executing the MCA for assessing the sustainability of NRDs was compiled from a review of those available (listed in Table 7).

For each method shortlisted, desk studies of implementation were undertaken, within which the perspective of potential stakeholders was assumed (i.e. non decision making specialists) and the likelihood of the method being adopted was assessed. The most important factors for selection of a tool, and so the likelihood of it being adopted, were considered to be: the complexity of the mathematical calculations; the cognitive strain of following the procedures, and the time taken overall to implement the MCDM tool.

### 2.3. Data generating tools

The benefits of adopting analytical/data generating tools are twofold: (1) they provide criteria values required for assessment, and (2) they can generate data for more than one criterion or analyze key aspects of sustainability giving a greater insight into identifying and understanding the issues. In many cases, analytical/data generating tools can be used individually to provide decision support. A review was carried out to identify analytical and data generation tools which could be used to assess the sustainability of NRDs and provide criteria data for a performance matrix.

## 3. Results

### 3.1. Existing sustainability assessment tools

Even though the evidence suggests that sustainability principles are considered in the design of road and rail traffic NRDs, overall these considerations lack the depth to evaluate sustainability throughout the whole lifecycle of NRDs.

**Table 6**
Primary criteria for assessing the sustainability of noise barrier projects.

| Sustainability factor | Primary criteria |
|---|---|
| Technical | - Material selection<br>- Ease of building/construction<br>- Flexibility and adaptability |
| Economic | - Lifecycle cost<br>- Green value<br>- Financial sources<br>- Compensation cost<br>- Effect on local residential/commercial property prices<br>- Contractual and procurement type |
| Social | - Safety and security<br>- Health and wellbeing<br>- Severance/separation<br>- Social acceptance<br>- Architectural design and local context<br>- Community engagement<br>- Local employment and engagement with local business |
| Environmental | - Energy<br>- Land use<br>- Air quality and climate change<br>- Flora and fauna<br>- Water |

Furthermore, it is clear from analysis of design guides from around the world, that different priorities exist, dependent on geographical location. For example, even though all countries consider general technical design and acoustic performance as the main priority, in the USA the focus is on technical design and cost; in the UK it is on visual design and cost; in Australia social aspects are the focus and in China a brief overview approach is taken to all sustainability factors.

**Table 5**
Current sustainability factors for noise reduction devices identified from EN standards and design manuals.

| | Sustainability factors | | | |
|---|---|---|---|---|
| Whole life cycle stage | Technical | Economic | Social | Environmental |
| Design/Consultancy/Planning | - Material selection<br>- Acoustic performance<br>- Service life<br>- Minimal maintenance<br>- Service life of structural elements<br>- Full compliance to EN standard<br>- Ease of construction | - Construction cost<br>- Compensation cost | - Safety and security<br>- Health and comfort<br>- Severance<br>- Socio-economic wellbeing<br>- Community engagement<br>- Architecturally in context with local surroundings | |
| Construction/Manufacturing/Contracting | Ease of construction | - Construction cost per m or m$^2$<br>- Cost of noise barrier being built as part of a large construction project (cheaper)<br>- Cost of noise barrier being built as a sole construction project (more expensive)<br>- Transportation of material, equipment and work force<br>- Influence on cost due to: Quantity of barriers, material availability, weather, traffic protection and detours, limitation of construction hours, labor costs | - Access<br>- Land property issues<br>- Disruption of everyday life | Pollution control |
| Usage/Maintenance/Repair | Access for maintenance | Maintenance cost per m or m$^2$ | - Access<br>- Traffic protection<br>- Aesthetics of barrier and site | - Physical or chemical impacts under natural conditions over time<br>- Physical or chemical impacts under fire conditions<br>- Fauna movements<br>- Drainage requirements |
| Demolition/Removal | | | Community engagement strategy for noise barrier removal or replacement | End of life re-use/recycling |

Table 5 shows the current most common factors identified for sustainability evaluation throughout the whole lifecycle of noise barriers from a review of the European (EN) standards and design manuals used throughout the world.

The state of the art NRDs' sustainability gap analysis through the review of legal frameworks and design guides highlighted the need for updating or for a new, specialist design guide focused on developing standards for more sustainable NRDs (Oltean-Dumbrava et al., 2012). This gap in the guidance hinders the implementation of effective and efficient NRDs that meet new and potential assessments such as carbon footprint, water footprint and adaptability to climate change.

Over one thousand primary, secondary and tertiary criteria and sustainability indicators were compiled; not all were applicable for NRD projects, and many were variations of similar methods. No methodology exists within the standards for creating and selecting appropriate criteria and indicators to suit the project in context. There is clear bias toward the assessment of buildings rather than for civil engineering projects evidenced by the use of indicators such as 'indoor air quality'. Nonetheless, Fernández-Sánchez and Rodriguez-Lopez (2010) believe that step changes are being made in the industry to move away from this focus.

For NRDs all appropriate technical standards must be taken into account to ensure optimization of technical and acoustic performance and any assessment method must integrate existing standards.

Key observations regarding existing tools include:

1. None of the reviewed tools were effective sustainability tools or directly applicable to NRD projects with the exception of SWARD (Ashley et al., 2004). Methods were not true sustainability tools in terms of being inclusive, holistic, multi-dimensional and capable of simultaneously addressing the social, economic and environmental principles of sustainability together with other factors such as political, technical or legal constraints. Means to address key technical issues such as primary technical/functional requirements and mitigation against the impacts of climate change were lacking. These findings support those of Therivel (2004).
2. Social issues were poorly covered; the majority of tools reviewed had little to no coverage of the social dimension of sustainability.
3. There was a heavy focus on the environmental aspect of sustainability, whilst neglecting the social and economic dimensions. This observation supports the findings of others such as BRE (2006) and Therivel (2004).
4. Rating tools are restrictive and promote points chasing: users are forced to conform to practice in a certain way to gain points

**Table 7**
Evaluation of MCDM tools for conducting the MCA for assessing the sustainability of NRDs.

| Evaluation of MCDM methods | | |
|---|---|---|
| MCDM tool/Technique for carrying out the MCA | Pros | Cons |
| SAW/WSM (Simple Additive Weighting/ Weighted Sum Method) | - Easy to follow<br>- No complicated calculations<br>- Results are easy to understand<br>- Audit trail easy to follow<br>- Internal consistency and logical soundness<br>- Non expert friendly<br>- Realistic time and manpower resource requirements for the analysis process<br>- Can be easily set up in MS Excel<br>- High likelihood of being adopted by industry | - Limited scope to modeling criteria<br>- Criteria must be independent of each other to avoid double counting |
| AHP (The Analytical Hierarchy Process) | - Simple model to build<br>- Logical process<br>- Efficiently handles qualitative and quantitative attribute values<br>- Results are easy to understand | Doubts have been raised over its theoretical foundation. There is a strong view that the underlying axioms on which AHP is based are not sufficiently clear as to be empirically tested. |
| SMART/SMARTS/SMARTER (Simple Multiple Attribute Rating Technique) | - True tree structure independent of alternatives<br>- Results not affected by the introduction of new alternatives<br>- Software not required | Similar cons to SAW |
| TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) | - Internal consistency and logical soundness<br>- Easy to follow<br>- Intuitively appealing<br>- No complicated calculations<br>- Can be easily set up in MS Excel<br>- Results are easy to understand<br>- Simple index value given<br>- Results can be easily shown graphically | - Large number of procedures<br>- Large number of computations<br>- Provides an overall result |
| Dominance Method | - Little to no mathematical calculations required<br>- Low time and manpower resources requirements for the analysis process<br>- Easy to follow<br>- No need for software<br>- Results can be shown graphically | - Criteria are not weighted<br>- Audit trail may be difficult to follow<br>- Unlikely that any option will dominate all others |
| ELECTRE (Elimination et Choice Translating Reality) | - Proponents argue that its outranking concept is more relevant to practical situations than the restrictive dominance concept<br>- Can be used to choose, rank, and sort alternatives | - High cognitive strain<br>- Not transparent<br>- Most likely will require an MCA expert to aid/carry out the analysis |
| PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) | - Encourages more interaction between the decision maker and the model in seeking out good options<br>- Proponents argue that its outranking concept is more relevant to practical situations than the restrictive dominance concept | High cognitive strain |

rather then examining projects holistically for opportunities to maximize sustainability.

### 3.2. Primary research

Following the review of NRD sustainability literature; analysis of the compiled potential criteria and indicators database; and the stakeholder engagement process; 22 primary criteria for assessing the sustainability of noise barrier projects were selected by the authors and are shown in order of ranked importance in Table 6. Within these primary criteria are more detailed secondary and tertiary criteria. The primary criteria highlight all the major issues to consider and assess for each sustainability factor (i.e. the technical, economic, environmental and social aspects of noise barrier projects).

There was general consensus among stakeholders in support of the initial set of criteria as evidenced by the relatively high Kendal's co-efficient of concordance value for determining the level of agreement in the ranking data from the questionnaire. Where criteria were rated, it was found that 93% of the total criteria proposed by the authors were considered “very important” to “moderately important” by the stakeholders, which had a low standard deviation and hence a high agreement amongst the stakeholders. However, the final presented list of 22 primary criteria – and the numerous secondary and tertiary criteria related to it – is not definitive; it is presented as a modifiable set of criteria. If required, users can develop and add further criteria as appropriate based on the ‘Top-Down-Bottom-Up’ strategy for identifying pertinent sustainability criteria and indicators for NRDs.

### 3.3. Multi-criteria decision making tool selection

All MCDM tools claim to solve MCA problems, yet it is recognized that selection of an appropriate MCDM tool is a decision making problem in itself. Fig. 4 summarizes the MCDM tool selection requirements for assessing the sustainability of NRDs.

A review of decision making processes found a common order of procedures summarized as: define the goal – select criteria and indicators – collect data required – carry out MCA. Fig. 5 illustrates a process applicable to assessment of the sustainability of NRDs.

The correct selection of a viable MCDM tool affects how likely it is that the sustainability assessment process is adopted by industry, even if it is well founded in robust research. Those methods that do not require specialist software and/or an expert to carry out the MCA are most judiciously adopted.

A wide range of MCA methods was considered at the outset in relation to the requirements shown in Fig. 4. This included the use of fuzzy, interval, probabilistic methods used individually or combined with the common MCDM tools, such as that considered by Chang et al. (2008); and Pires et al. (2011), but were ultimately omitted from further evaluation as they were deemed unlikely to be easily understood by the relevant stakeholders. Table 7 shows the shortlist of MCDM tools and the subsequent pros and cons analysis performed. The MCDM tools evaluated have large variances in terms of the complexity of the computations, the cognitive strain of following the procedures and the time required to carry out the analysis. It is possible to use a hybrid of MCDM tools, to optimize the MCA e.g. Mahmoodzadah et al. (2007) advise combining AHP with TOPSIS as the best method to select industrial


**Fig. 4.** MCDM tool selection requirements for assessing the sustainability of NRDs (Adapted from DETR, 2000; and Stewart, 1991).

projects. Bell et al. (2001) use a hybrid Swing/AHP method based on the rationale of combining AHP's ease of use with Swing weightings more precise notion of attribute importance as the best method for evaluating policies for preventing global warming. Babic and Plazibat (1998) use a hybrid integration of Analytical Hierarchy Process (AHP) and PROMETHEE as the method to rank enterprises according to the achieved level of business efficiency. Within the sphere of engineering for sustainable development, Ugwu and Haupt (2007) use a hybrid of WSM and the AHP in order to determine an index value which denotes the relative sustainability of the alternative considered.

There are many ways to combine different MCDM methods in order to utilize their best features. All of the above MCDM methods solve multi attribute decision making problems; however researchers such as Zanakis et al. (1998) point out that different techniques may yield different results when applied to the same problem; such inconsistencies would have major implications for DMs if only one method is utilized. Therefore it is often recommended that more than one method, typically three, is used to triangulate the validity of the results.

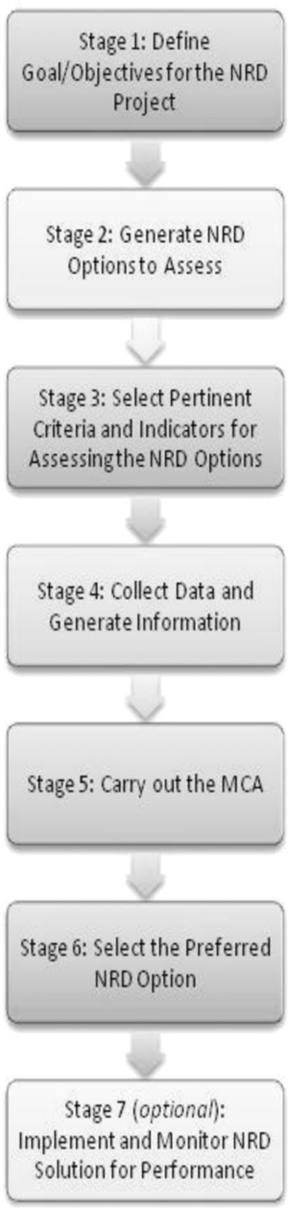


**Fig. 5.** Decision making process (DMP) for assessing the sustainability of NRDs projects (Adapted from: DETR, 2000; and Ashley et al., 2004).

**Table 8**
MCDM tools recommended for assessing the sustainability of NRDs.

| MCDM Tool | Comment |
|---|---|
| SAW/WSM | Simple intuitive approach and not time consuming |
| SMART (also SMARTS and SMARTER) | Simple approach and not time consuming |
| AHP | Simple approach and slightly more difficult and time consuming than SMART and SAW/WSM |
| TOPSIS | Slightly more difficult and time consuming than SMART and SAW/WSM |

Janić and Reggiani (2002) utilized the SAW, TOPSIS and the AHP method discretely for the selection of a new Hub Airport, and found the results produced were the same from each method when procedures used to assign weights to criteria were identical. This implies the results are dependent on the criteria weights and not the MCDM method adopted (e.g. Venek and Albright, 2008; Janić and Reggiani, 2002). This is a logical conclusion as the total alternative value is determined by the multiplication of the weight assigned to criteria by the criteria score. The SWARD case study (Ashley et al., 2004) used more than one MCDM method to triangulate results. In this case, the MCDM tools used were: SMART, ELECTRE and PROMETHEE and again, the results produced were similar.

In practice the use of three different MCDM tools is not practical as each method may require different input and DMs may not have time to conduct three analyses. Sensitivity analysis may be sufficient to test the robustness and reliability of the results obtained from a selected MCDM tool. If the obtained solutions are not sensitive to the parameter values, the analyst has obtained a good set of results (Vincke, 1999).

If the choice of MCDM tool(s) has little effect on the final decision reached, priority should be given to the needs of the end user and the likelihood of the tool being adopted by the industry for the benefit of building more sustainable NRDs. As proposed by Stewart (1991) the most simplistic and intuitive, yet reliable approach to selecting a MCDM method and tool that is easy to use and understand should be taken and feedback should be sought from stakeholders. Table 8 gives the recommended MCDM tools for assessing the sustainability of NRDs.

SAW/WSM, SMART, and AHP have been selected because of their prevalence in the literature and being the most widely used in industry. AHP has the benefit of quickly performing a cost-benefit analysis (CBA), which may be useful to stakeholders. Each of the selected methods is an 'additive utility model', which involves intuitive scoring and has an easy to follow method and criteria can be modeled accordingly to prevent trade-offs. Each also can provide an easy to follow audit trail which is important in justifying decisions with stakeholders. More importantly, the results are transparent and understandable with the provision of an index value and rank of the alternatives. Sophisticated software is not required and each MCDM tool can be set up in a spreadsheet, though the time and manpower resource requirements vary per MCDM tool. TOPSIS can provide a more sophisticated analysis which has an intuitive appeal and novel approach. It is possible to use a hybrid of these methods for a more robust and reliable approach.

**Table 9**
MCDM tools to triangulate results for assessing the sustainability of NRDs.

| Simple | Medium | Complex |
|---|---|---|
| SAW/WSM | AHP | PROMETHEE |
| SMART/SMARTS/SMARTER | TOPSIS | ELECTRE |

**Table 10**
Initial recommendations of analytical/data generating tools for assessing the sustainability aspects of NRD projects.

| Environmental | Economic | Social | Technical |
|---|---|---|---|
| E-LCA (Environmental LifeCycle Analysis) | LCC (LifeCycle Cost) | S-LCA (Social LifeCycle Assessment) | Relevant EN Standards related to NRDs |
| EIA (Environmental Impact Assessment) | CBA (Cost-Benefit Analysis) | SIA (Social Impact Assessment) | – |

Outranking methods were not included because of the difficulties which may be experienced by the end user in quickly understanding and interpreting the calculations and their results. Kangas et al. (2001) believe that it is more important to understand the method and to apply it correctly, rather than pondering over the choice of the MCDM tool. Should it be necessary to triangulate the results it is advisable to select contrasting MCDM tools ranging from simple to complex as shown in Table 9. PROMETHEE or ELECTRE methods can be used here to confirm that the results for the stakeholders do not change in a major way irrespective of the MCDM tool selected.

### 3.4. Data generating tools

The tools shown in Table 10 can be used to generate data for sustainability assessment. The selection of suitable tools depends on the criteria selected, and the principal decision objectives defined for assessing the sustainability of NRDs. The uses of data generating/analytical tools are most helpful in generating multiple criteria information at once related one particular factor of NRDs' sustainability for MCDM evaluation. For example, much of the information generated in conducting a LCC analysis would align with criteria defined for assessing NRDs economic factor. Such an approach is more efficient than individually collecting criteria information. Of course, the efficiency of such an approach is entirely dependent on the set of criteria selected for assessment. The use of data generating/analytical would support stage 4 of the DMP shown in Fig. 4.

Each tool has varying levels of data requirements and different strengths and weaknesses. Analytical tools in combination or in isolation are not likely to provide information for all criteria, particularly for unique sustainability criteria related to NRDs such as the accommodation of water flow through a NRD barrier, the obstruction of fauna movements by the NRD, the ability of the barrier to reduce roadside pollution, or the flexibility to adapt to changes (such as an increase in height). However, many discrete and combined uses of the recommended tools shown in Table 10 can be found in the literature on a wide range of project types to inform decisions and sustainability analysis' (see for instances Utne, 2008; Cheng and Chang, 2011; Bolin and Smith, 2011).

A data collection methodology should be developed to combine the most suitable tools, along with the other data collection methods, to efficiently collect data and information for the performance matrix.

## 4. Discussion/conclusion

Despite the large number of sustainability assessment tools available, and the construction sector being in agreement that action must be taken to support sustainability, there is little evidence to show any real influence in policies or on current practices (IIED, 2007; Hunt et al., 2008). This is likely to be due to overcomplicated, overarching decision making systems and a lack of understanding of the fundamentals of sustainability criteria and indicators.

Public authorities are the most likely key DMs to assess the whole life sustainability of NRDs as they have majority control (approx 90%) of the NRD market. As a result, other stakeholder groups directly and indirectly affected by decisions taken by public authorities (e.g. consultants, contractors, manufacturers and affected communities) must be taken into account in the interest of satisfying the sustainability agenda throughout the whole lifecycle of NRDs. In order to promote sustainable behavior and for key businesses to remain competitive and adapt to new market conditions, the development of sustainability key performance indicators (KPIs) is crucial for all stakeholders and lifecycle stages in order for all key players to understand their role in achieving sustainable NRDs.

This paper has presented the 'Top-Down-Bottom-Up' research strategy undertaken to define a generic set of relevant sustainability criteria for NRDs projects. The top down and bottom up research strategy ensured transparency in criteria selection. As a result of implementing the said strategy, a validated set of criteria and an appropriate assessment framework that characterizes assessing the whole life sustainability of NRDs has been achieved. Hitherto, such as set of relevant sustainability criteria specifically for NRDs projects was previously un-available to the relevant stakeholders. This will now allow the relevant stakeholder to seriously consider NRDs' sustainability equitably and so support the sustainability agenda. However, the set of criteria proposed is ultimately the researchers' recommendation and thus not definitive, albeit the pertinent issues to consider in assessing NRDs sustainability have been sufficiently explored through reviewing the relevant literature and engaging with the stakeholders.

Furthermore, the DMP presented here is the result of a robust review of regulatory standards for NRDs and existing relevant sustainability assessment tools and procedures worldwide. The DMP highlights the logical order and key stages to follow in assessing the sustainability of NRDs. Careful consideration of the end user in the recommendation of data gathering tools to provide criteria information and MCDM tools to carry out a MCA should ensure a DMP that is transparent and useable.

Overall, the paper has provided for the first time the theoretical basis for assessing the sustainability of NRDs. The authors are now in an almost ready state to conduct a sustainability assessment of NRDs for any decision context by applying the methods and tools developed and described here. The forthcoming trials of the DMP will provide a valuable critique of this first tailor made tool for sustainability assessment of NRDs and provide a useful model for the stakeholders to consult in conducting their own assessments.

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