Guidebook to Noise Reducing Devices optimisation

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Guidebook to Noise Reducing Devices optimisation

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1 Introduction

The aim of this guidebook is to become a reference tool for noise mitigation through a better use of Noise Reducing Devices (NRD) (e.g.: Noise Barriers or sound Absorptive Claddings).

It targets all the stakeholders involved in NRD projects (designers, manufacturers, authorities, construction companies, maintenance companies…) and who are willing to optimise the products and their use, either for rail or road noise mitigation.

This guidebook is based on the final results and outcomes of the QUIESST research: it synthesizes this 3-years project and provides examples of best practices and recommendations on:

- The effect of sound reflections in the far field by the definition and the determination of intrinsic far field performance indicators ;
- A new method for in-situ measurements of sound reflection and airborne sound insulation of NRD;
- A better knowledge of the European NRD market through the first database comparing 400 different devices and their acoustic performances through more than 1400 test reports;
- The holistic approach on how to optimise NRD at 3 different levels:
  - Intrinsic (reflection, transmission and diffraction indices);
  - Extrinsic / holistic (acoustic, economic and environmental performances);
  - Global impact on typical dwellings;
- The NRD sustainability: how to design, build, maintain and decommission better sustainable NRD.

1.1 What types of Noise Reducing Devices (NRD) do we consider?

As defined in the appropriate European Product Standards EN 14388 for road application (Road traffic noise reducing devices — Specifications) and the corresponding prEN 16272 group of standards (Railway applications – Track – Noise barriers and related devices acting on airborne sound propagation) for railway applications, the term "Noise Reducing Devices" covers:

- **noise barriers**: noise reducing devices, which obstruct the direct transmission of airborne sound emanating from road or rail traffic (see Fig.1);

Figure 1: examples of road and railway noise barriers

- (sound absorptive) **claddings**: noise reducing devices, which are attached to a wall or other structure and reduce the amount of sound reflected (see Fig. 2);

Figure 2: examples of road and railway (sound absorptive) claddings

- **covers**: noise reducing devices which either span or overhang the traffic (see Fig.3);

Figure 3: example of a road cover

- a last type of device is also included in the NRD standards, the **added devices**: added components that influence the acoustic performance of the original noise-reducing device - acting primarily on the diffracted energy (see Figure 4).

Figure 4: examples of added devices

In this present guidebook, as in the QUIESST research, **only noise barriers and** (sound absorptive) **claddings are 100% covered**.

However, *some part of the results* can be also derived, as:

- to **covers**: the new in-situ measurement methods, the database of the European NRD and the sustainability;
- and to **added devices**: the sustainability.

1.2 What rules the acoustic performance of NRD?

The definitive answer to such a question is: the physics!
Whether it is for road or railway noise, the physical process is the following (see Fig.5):

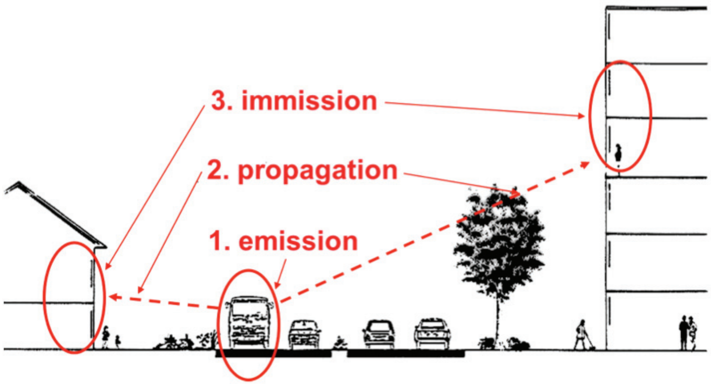


Figure 5: 3 steps between the noise source and the persons exposed to

1. **Emission**: the sound wave is emitted by the vehicles;
2. **Propagation**: the sound wave then propagates toward the environment;
3. **Immission**: finally, the sound wave reaches the façades of the buildings and penetrates inside those through their weakest components (e.g.: the windows..).

NRD are used in the *propagation part* of this whole process: they act as obstacles between the noise sources (the vehicles / trains) and the environment area to be protected (Fig.6).

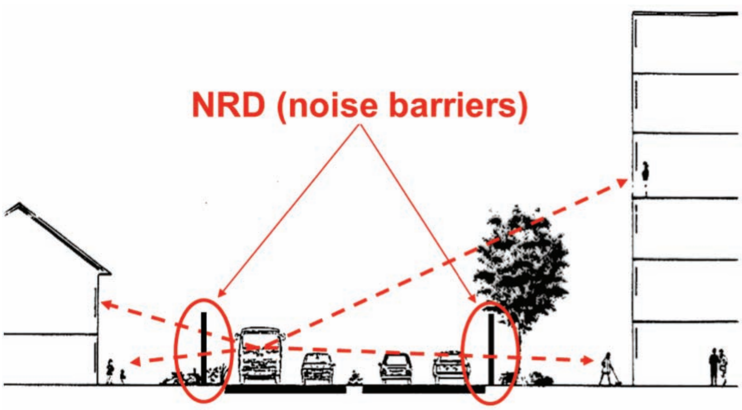


Figure 6: NRD (here: noise barriers) are placed to obstruct sound propagation from the vehicles to the persons exposed

When the sound wave reaches the NRD, 3 physical phenomena occur (Fig.7):

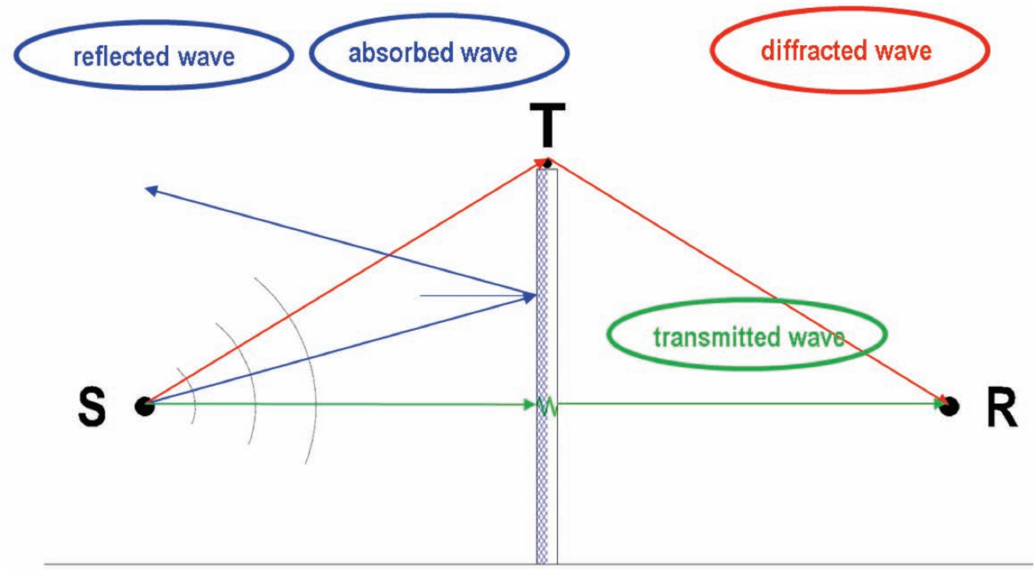


Figure 7: sound reflection / absorption, sound transmission and sound diffraction

1. **Reflection**: the sound wave reaching the exposed side of the NRD partly reflects on it: the reflected sound can the affect the facing areas;
2. **Transmission**: the sound wave reaching the exposed side of the NRD partly transmits through the device itself: the aim of the NRD being to play as an obstacle to the sound propagation, this transmitted energy has to be as low as possible;
3. **Diffraction**: the NRD acts as an obstacle to the sound propagation: however, a part of the sound wave passes over the devices: it diffracts on its top edge and then propagates to the protected side of the device.

Keeping in mind all the physical phenomena listed here above, we can list all the parameters involved in the whole process:

- The **emission characteristics**: the directivity pattern of sound radiation around the vehicle and its associated sound power (cars, trucks, trams, trains, High Speed Trains…);
- The **dimensions**:
  - Height, length, volume of the obstacle made from the NRD;
  - Relative Source /Receiver location, topography, infrastructure profile;
  - Frequency domain, time domain;
- The **shape** of the objects:
  - The vehicles (cars, trucks, trams, trains, High Speed Trains…);
  - The barriers / walls built alongside the traffic (flat vertical, flat inclined, non-flat, volumic, added devices…);
- The NRD **intrinsic acoustic characteristics**:
  - Sound reflection/ absorption, sound transmission and sound diffraction.

ALL those parameters rule the global *acoustic* performance of the NRD.

1.3 What are the existing tools for assessing the NRD performances?

On the European market, NRD are mainly built from industrial products: it is of major importance to have *objective* tools in order to assess their performances, whatever the acoustic or the non-acoustic ones.
Two CEN standardisation working groups work on drafting standards to assess the NRD performance:

- For road traffic noise (see Figure 8):
  TC226 (road equipment) / WG6 (noise reducing devices);
- For railway noise(see Figure 9):
  TC256 (railway applications) / SC1 (railway infrastructure) / WG40 (noise barriers).

Each framework of standards includes several subsets of standards, targeting **acoustic and non-acoustic performance**.

Procedures for assessing the **long term performance**, that is how the initial product performance can be evaluated along years of use, has been also considered: for the coming future, thanks to the outcomes of this QUIESST research, the CEN working groups will start considering **sustainability** as a new characteristic to be objectively assessed.

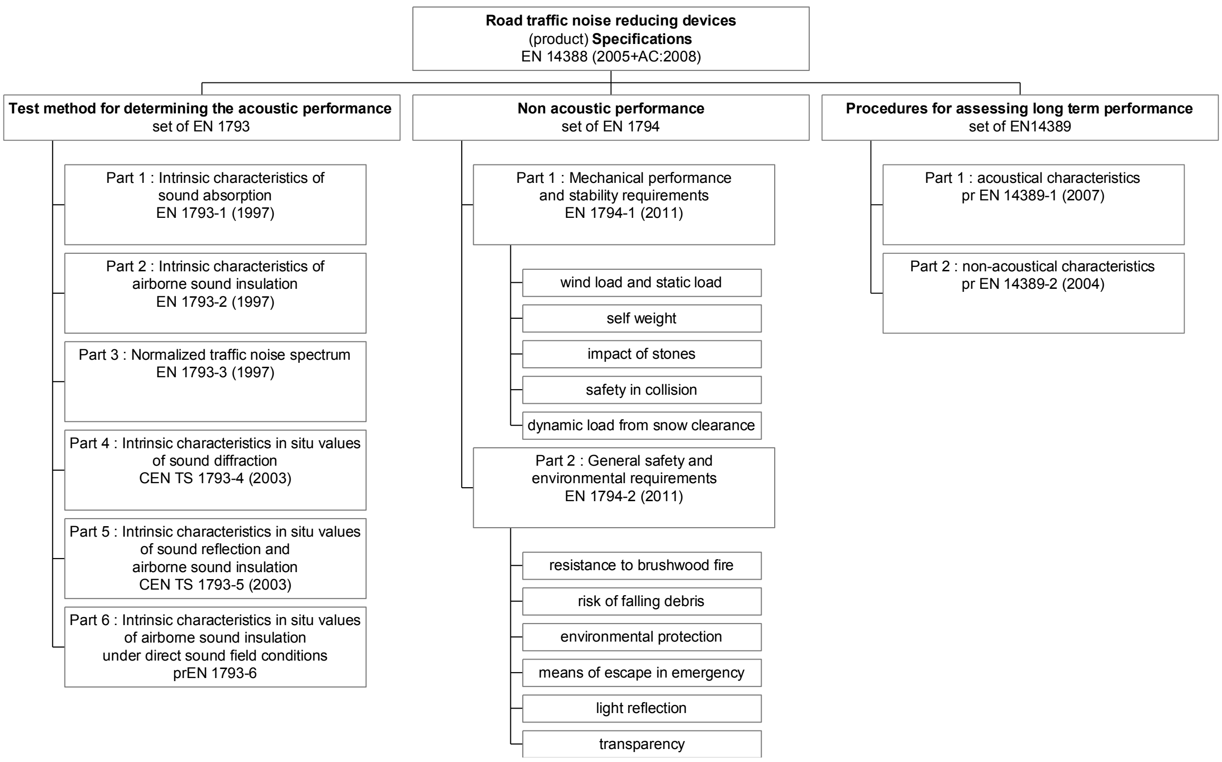


Figure 8: the framework of standards for road traffic noise reducing devices

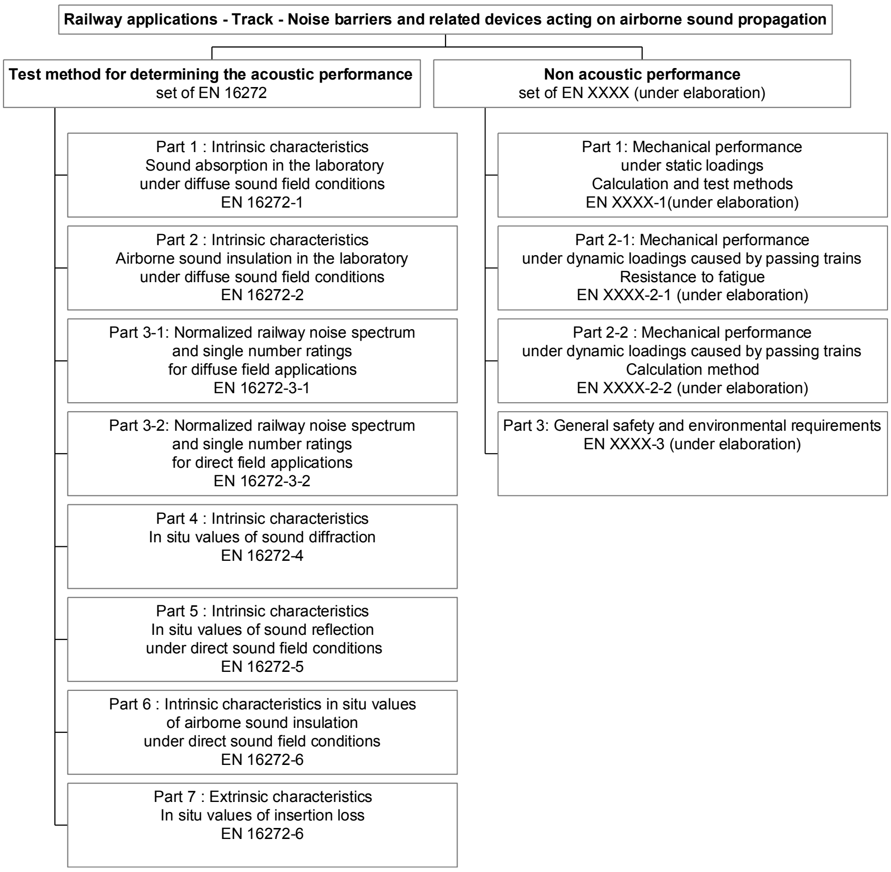


Figure 9: the framework of standards for railway noise barriers and related devices acting on airborne sound propagation

1.4 How QUIESST improves the way toward a better use of NRD?

When we place a NRD, as a noise barrier for example here in Figure 10, alongside a road or a railway line, the sound propagates to the whole environment, whatever it is on the protected (diffraction) zone, or on the opposite side, the reflection zone, both zones are important in the global NRD performance.

Figure 10: NRD protects the diffraction zone but also reflects sound to the reflection zone

Today, many efforts have been done on both sides of the characteristics that made the NRD effective: the product side, and the in-situ side.
The QUIESST approach integrates both sides, because the true final noise reduction clearly depends on both (in a true holistic approach).

To achieve its objectives, QUIESST clearly identified the 5 following mains topics:

1. The relationship between the **near field and the far field** acoustic performances.

2. A new measurement method for measuring the intrinsic “true” sound absorption and airborne sound insulation properties of NRD (**near field measurement method**).

3. The first **European product database** of the intrinsic acoustic properties of NRD.

4. A comprehensive strategy on how to **optimise NRD within a true holistic approach**.

5. The first study done yet about **NRD sustainability**, referring to relevant parameters and generic sustainability criteria, with associated assessment methods.

2 Work Package 2 (WP2) “Near field - far field” relationship for sound reflectivity

2.1 Significance of near field and far field reflectivity

Sound reflectivity is one of the major intrinsic acoustic characteristics for NRD: it describes how an incident sound field is reflected back towards the opposite side of the road. The reflectivity is a function of the absorption properties of the material of the NRD, as well as of its geometrical shape that may enhance or reduce sound reflections toward some directions. **The reflectivity effect in the far field is thus not only related to the barrier and its design, but also to the location of the receiver position in the far field.**

“Diffuse” sound field conditions

Until now, the reflectivity of NRD is derived as the inverse of their intrinsic sound absorption. This last quantity is tested in the reverberation room of an acoustic laboratory (see Fig.11), according to the European standard EN 1793-1(methodology derived from the ISO 354):

Figure 11: a laboratory reverberation room

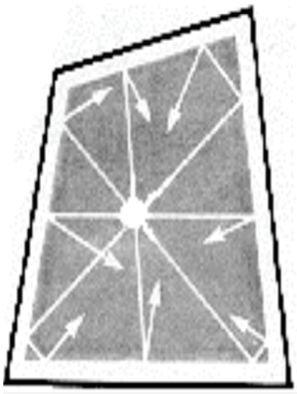


Figure 12: principles of a diffuse sound field (sound comes from everywhere with the same energy)

Under such conditions, NRD are tested within a diffuse sound field (sound waves come from any direction with the same energy: see Fig.12) that corresponds to enclosed reverberant spaces. This method gives relevant results for applications where the NRD are used in diffuse or semi-diffuse sound field conditions, like tunnels or deep trenches: in such conditions, the influence of the NRD shape on the reflectivity characteristics are disregarded.

“Open” sound field conditions

However, NRD are more often placed along motorways or railways, locations that better correspond to “open sound field”: the incident sound field cannot be considered as diffuse anymore, but rather as a combination of directional sound waves under varying angles of incidence. With such a directional sound fields, the **NRD shape may be used to control the reflection contributions to the far field**.

Therefore, in order to test the sound absorptive performance of NRD alongside motorways or railways, the tests should be performed with directional incident sound waves: measuring that reflectivity, including the NRD sound absorption and its shape effects, would require testing in the far field, at considerable distances (greater than 20 to 30 m) from the reflecting noise barrier. This way of testing is very difficult because the reflected sound is normally less powerful than the direct sound and will be completely mixed with it. On the other hand, ambient “background” noise and contributions of reflections from the ground and other obstacles are likely to disturb far field reflection measurements.

These problems can only be controlled by measuring the reflected sound in the near field of the device (at 0,25 m from the barrier surface): the EU “Adrienne” project (1995 – 1997), developed such a reflection test method (see Fig.13).

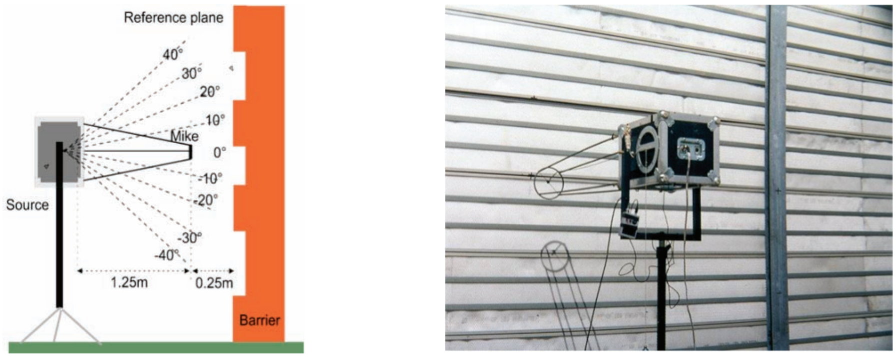


Figure 13: principles and application of the “ADRIENNE” method (CEN TS 1793-5)

In WP 3 of the present QUIESST research, an improved version of the near field reflection test method has been developed (see chapter 3). However, for signal analysis reasons, the measuring test distance is still kept 0,25 m from the NRD: at such short distances, the measurements will only give a measure of the *total reflected sound energy within the measured area*. Any surface unevenness has a direct effect on the reflected sound field, and could lead to very complex radiated sound fields: those effects could not be completely considered in the near field tests (e.g.: directive effects).

“Far field” propagation

For instance, for “non-flat” NRD, results of the near field reflection tests cannot be directly used to compute the reflectivity at larger distances (i.e.: in the far field): as the geometrical shape of barrier elements can significantly influence the reflection contributions in the far field, it is relevant to take these geometrical parameters into account for the assessment of the **intrinsic performance of NRD in the far field**.

Therefore Work Package 2 developed an engineering method for the extrapolation of the NRD near field reflectivity test results toward its far field effect.

2.2 Engineering extrapolation method: the final outcome of WP 2

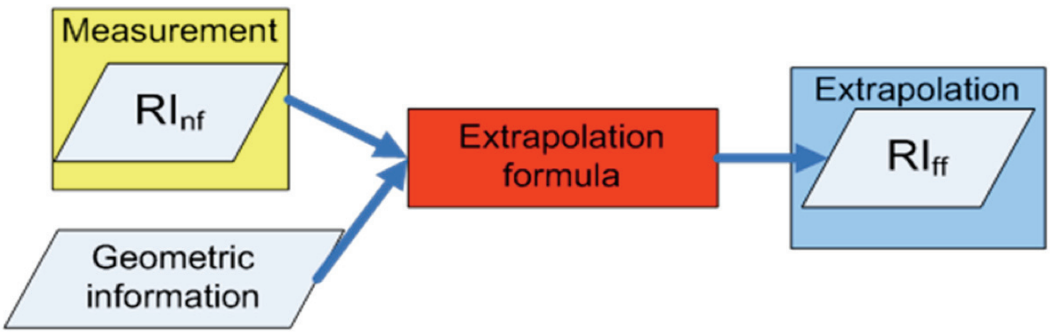


Figure 14: principles of the QUIESST engineering extrapolation method

The final outcome of WP 2 is an engineering computation method that gives the values of **two far field performance indicators** (for high rise and low rise buildings as shown in Fig.15) for different kinds of NRD.

As shown in Fig.14, the method uses, as **inputs**, the results of the new WP 3 near field reflection test method: the ⅓rd octave band values of the averaged Reflection Index (RI_{nf}) are used. The barrier type and the geometrical shape parameters are also relevant **inputs**.

The **output** is an estimated contribution of the reflected sound to the sound level in the far field, expressed as the **single number rating for the far field reflection index: $DL_{RI,ff}$.**

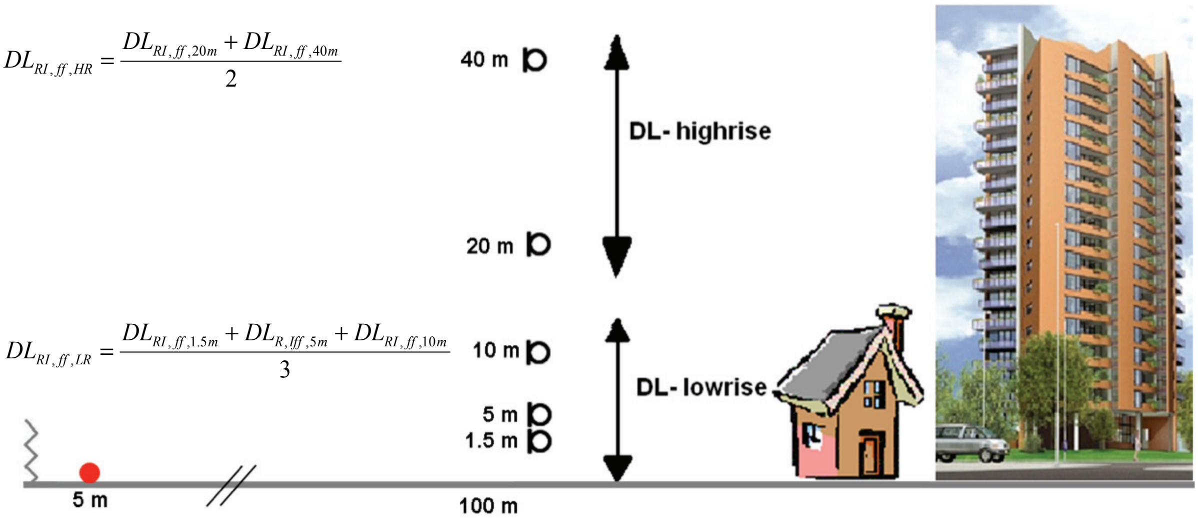


Figure 15: locations that are considered for the sound source, the NRD and the receivers definitions of $DL_{RI,ff,HR}$ and $DL_{RI,ff,LR}$

This single number rating, expressed in dB(A), is computed at five different receiver positions: at a distance of 100 m from the NRD, and at heights of 1.5, 5, 10, 20 and 40 m above the ground (see Fig.15).

The far field reflection index *RI_{ff}* is defined as the ratio between the amount of energy which is reflected by the device and the energy that would be reflected by a *reference* barrier (as a reference, a flat rigid vertical barrier of the same height as the test sample **-** usually 4 m **-** is chosen).

In order to obtain a compact description of the reflection effects in the far field the single number ratings at the five positions are then clustered and averaged in two groups (see Fig.15): the average of the single number ratings of the three lowest positions $DL_{RI,ff.LR}$ is considered to be representative for low rise buildings and the average of the single number ratings of the highest two $DL_{RI,ff,HR}$ is considered representative for high rise buildings.

In this way, those **two far field indicators characterise the far field reflectivity of NRD**.

2.3 Basis of the engineering extrapolation method

The basis for the method is formed by the use of two data bases filled with results of numerical simulations.

2.3.1 Near field data base

The first database consists of results of simulations under the near field reflection tests conditions for different NRD variants representing the majority of the European NRD market. Five different NRD families were selected (see Fig.16).

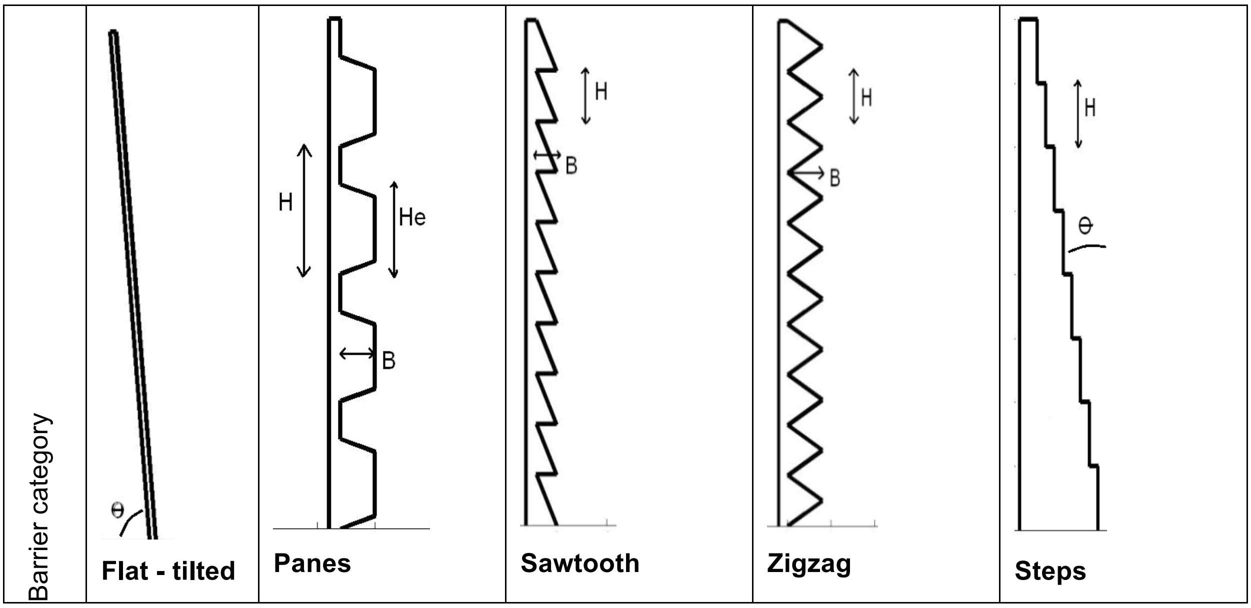


Figure 16: NRD families

For each NRD type, 3 different types of *absorptive material* were applied:

1. Rigid: all materials with an acoustically hard surface (100 % reflective; 1 variant)
2. Porous concrete (6 variants)
3. Perforated metallic or plastic cassettes filled with mineral wool (6 variants)

The total number of variants in the near field data base is 1196. For each variant, the spectral values of RI_{nf} (near field Reflection Index) and the corresponding single number rating $DL_{RI\ nf}$, averaged over three receiver positions are stored in combination with the material and geometrical parameter values.

2.3.2 Far field database

The second database contains the results of Boundary Element Model (BEM) simulations of the far field reflection index RI_{ff} values, for the same series of NRD variants as for the near field data. In this case, the values were computed for the five different receiver positions in the far field (Fig.15). For each receiving position, the far field single number indicators $DL_{RI,ff}$ have been also computed.

2.3.3 Step-wise extrapolation

The extrapolation is carried out in a two-step approach:

1. the result of a near field reflection test is matched to the best fitting simulated variant in the database, following a 2 steps matching procedure;
2. then, the *material parameters* (type of absorption material, flow resistivity and porous layer thickness) are used as input data for the computation of an estimate of the far field effects of the NRD: this estimate is computed with a polynomial approximation of the contents of the far field database. This enables a fast computation with the possibility to interpolate between the simulated variants.
   The *geometrical shape parameters* are also used as input and these values can be interpolated between the values of the originally simulated variants in the database.

The final outputs of this far field extrapolation method are the two far field indicators $DL_{RI,ff,LR}$ and $DL_{RI,ff,HR}$.

2.4 Uncertainty of the method

The engineering extrapolation method is a heuristic method, based on an approximation of the data that were computed with numerical simulation models for 1196 barrier variants: the approximations can deviate, to a certain extent, from the original simulated data.

Within the first step of the approximation process, the matching of the near field test results to the best fitting simulated variant was tested against the results of the WP 3 Round Robin Test: the differences between the single number ratings of the tests and the single number ratings of the fitted variants were always smaller than 1 dB, except for one very unusual design (absorbing zigzag - see Fig.17).

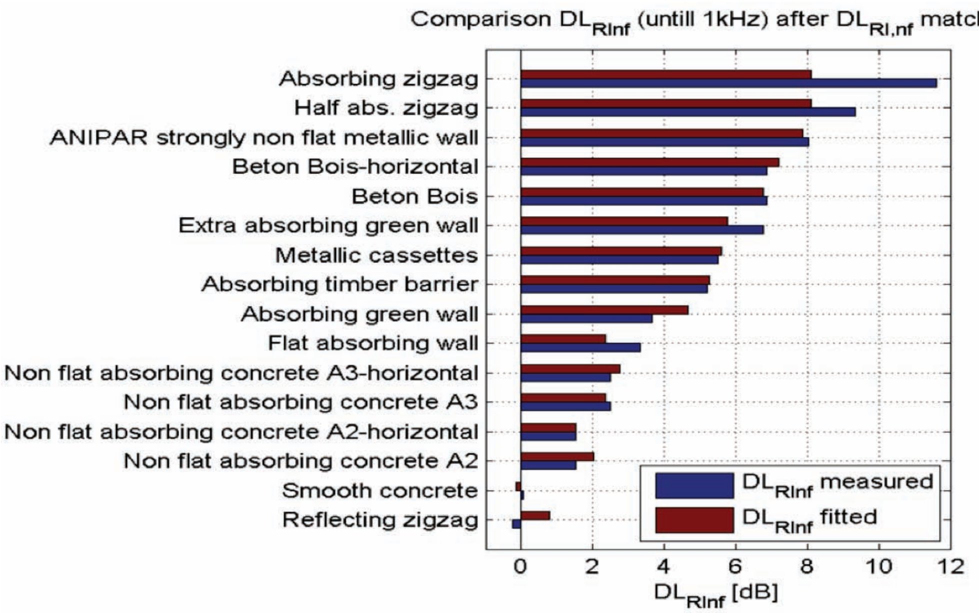
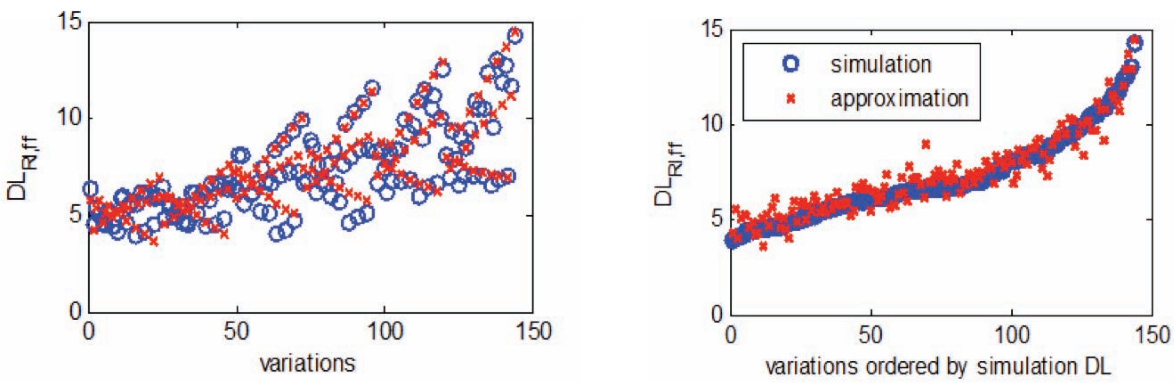


Figure 17: Comparison between Round Robin Test results and best fitting simulated variants (based on near field single number rating $DL_{RI,nf}$ in the frequency range 125 - 1000 Hz)

The second step estimates the far field reflection contribution for the best fitting simulated variant. It uses the material parameters of this best fitting variant and the barrier type and geometrical shape data. The basis of this estimation is a polynomial approximation of the far field simulation results that were computed with the BEM model. The estimated values have been compared with the original simulated values for all 1196 barrier variants and the 5 receiver positions. Figure 18 shows a graph of the comparison for one of the barrier types.



Results of polynomial approximation sorted in order of geometric variation

Results of polynomial approximation sorted in order of $DL_{RI,ff}$

Figure 18: Example of fitting performance - porous concrete ZZ type, at 5m receiver height

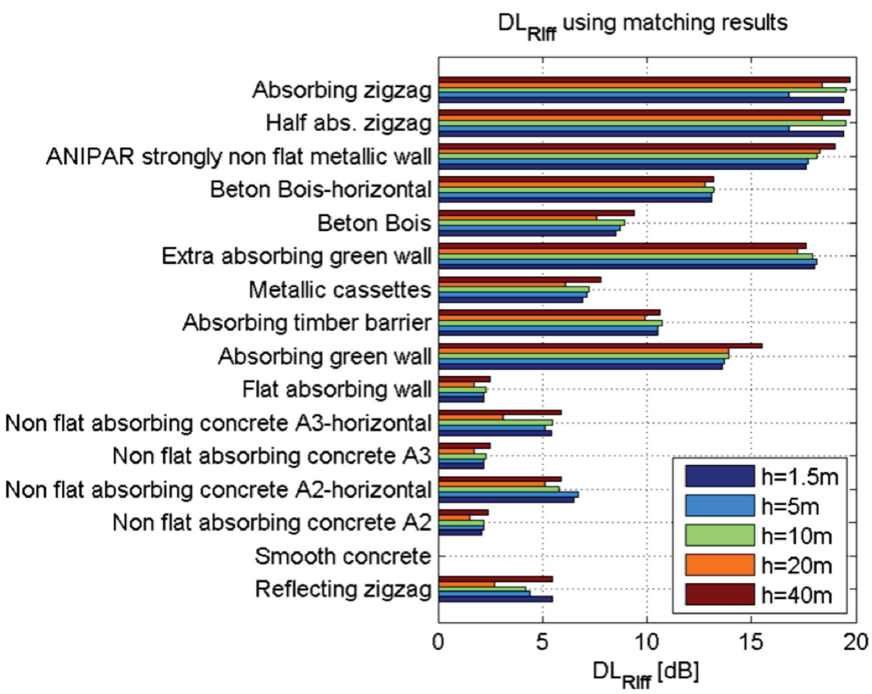
88 % of all the approximated data were within 1 dB of the original simulated values and 99 % were within 2 dB: it may be concluded that both steps of the method have an uncertainty margin of approximately ±1 dB compared to the measured / simulated values. The combined uncertainty of the extrapolation method may then be estimated at ±1,4 dB.
In this assessment of the estimation uncertainty the far field effects simulated with the BEM model are considered to be the “true” values: based on experiences in other studies there is a well-founded confidence in the reliability of the BEM simulation method, if it is used for modelling of sound propagation over relatively short distances.

Therefore **the engineering extrapolation method derived from the BEM simulation results is presented with confidence and the uncertainty values specified above are seen as realistic estimates**.

2.5 Examples of far field reflection effects computed with the engineering method

As an example of the results of the engineering extrapolation method, the data of the samples used for the WP 3 Round Robin Test have been used here as input to the engineering method. Both steps of the method (near field matching and far field extrapolation) were applied.

In Figure 19, the extrapolated results for each of the receiving heights are shown as a far field single number rating $DL_{RI,\,ff}$, the table beside the Figure shows the corresponding near field single number ratings $DL_{RI,\,nf}$ from the reflection tests.



Near field
$DL_{RI,\,nf}$
14,5
9,3
8,2
7,9
7,9
7,0
6,4
5,2
3,3
3,8
3,5
3,5
2,5
2,5
0
-0,7

Figure 19: Example of the results of the engineering extrapolation method

From those results, it can be seen that the far field effect does not always follow closely the near field reflection index values. This is logic and expected: if the barrier sample has a surface shape with large dimensions in vertical and horizontal directions, the far field effects of this surface design may be substantial and can enhance the reduction of reflections due to the absorption characteristics of the material.

In many cases the surface shape effects are also dependent of the receiver height.

2.6 Scope and availability of the engineering extrapolation method

The goal of the method is to give an *indication of the far field reflection effects* that can be achieved with a specific NRD design.

The scope of the method is *limited to the NRD types and geometries considered in the database*: if a specific design does not fall within that range, it cannot be assessed with the engineering method and new BEM simulations have to be carried out in order to obtain a reliable estimate of its reflectivity effects. The execution of a dedicated BEM simulation is also advisable if an assessment of the far field effects of a specific barrier design with less uncertainty is targeted.

The complete extrapolation method is described in a separate document in the format of a draft for an informative annex to the future revised standard for in situ testing of the reflectivity of noise barriers (EN 1793-5).

For an easy use of the method, it is also implemented in a pre-programmed Excel spread sheet (Fig. 20) that is available to public through the QUIESST website (www.quiesst.eu).

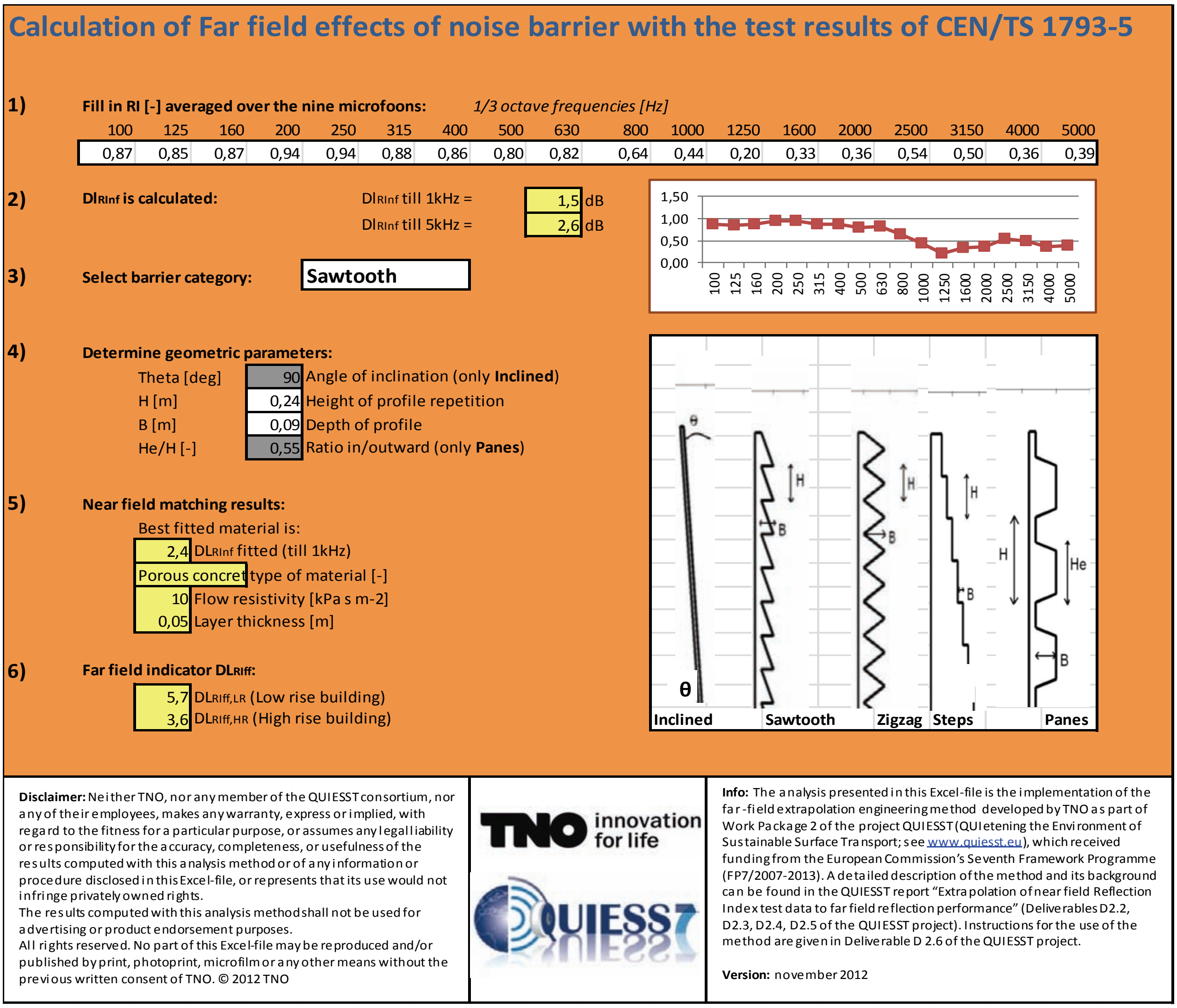


Figure 20: the QUIESST spread sheet for an easy use of the engineering extrapolation method

3 Work Package 3 (WP3) Improvement of the in-situ method for sound absorption and insulation measurement

3.1 Introduction and background information

The NRD European market offers many products with different shapes and materials, and new ones are appearing. It is essential to qualify their performance in terms of sound absorption and airborne sound insulation when placed alongside roadways or railways.

As already stated in 2.1, the acoustic performances of NRD are mainly tested under "diffuse sound field" conditions in laboratories: those conditions are not representative of the vast majority of practical applications, better represented by "open sound field" conditions.

Figure 21 shows such tests made according to the European standard EN 1793-1 [1].

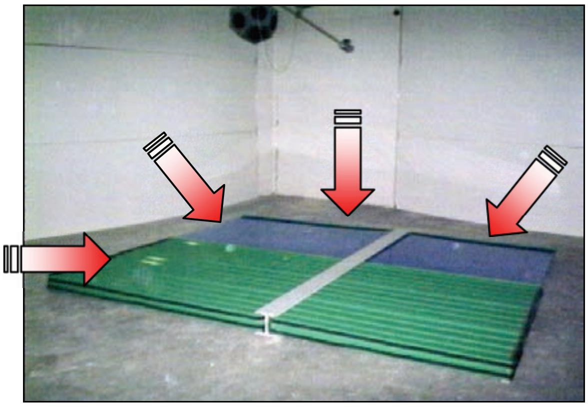


Figure 21: Sound absorption measurement in a reverberant room: sound field is "diffuse", i.e. it arrives from all directions

Laboratory methods imply diffuse sound field conditions (see 2.1) that are not representative of real installation conditions and workmanship. Moreover, those methods do not allow an easy control of the NRD long term acoustic performances years after years, as is needed in order to assess NRD sustainability. There was thus a real need to develop a method able to characterize NRD **in situ,** i.e. where they are installed and used.

For in situ measurements, the tentative CEN/TS 1793-5 [4], based on the results of the former ADRIENNE project [3], is currently used by several Member States, but it is still limited in low-frequency resolution and physical representativity.

Figure 22: a noise barrier alongside a road (courtesy CIR Ambiente): the sound field (represented by the arrow) is not diffuse

3.2 Objectives of the new method

Given the above outlined situation, the objectives were:

1. to develop a new robust in situ measurement method in order to assess the sound absorption/reflection and airborne sound insulation characteristics of NRD,
2. to assess the accuracy of this new method.

The first objective implies that the new method must be applicable on the site where the NRD are installed, without removing or altering them in any way and in presence of an unpredictable background noise, variations of meteorological conditions, traffic flows, etc. It should be kept in mind that the new method is not intended to qualify NRD to be installed in almost "diffuse sound field" conditions, e.g. inside tunnels or deep trenches: in those cases, the traditional laboratory methods supply the necessary information.

The second objective may be achieved by assessing the so called "uncertainty" of the measurements by means of an inter-laboratory test (or Round Robin Test, RRT). In this context, the word "uncertainty" means a quantitative evaluation of the reliability of the results; it should be noted that it doesn't mean "error" or "wrong result": on the contrary, the declaration of the uncertainty is the best way, according to the recommendations of all international standard organizations (ISO, CEN, OIML, etc.), to assess the accuracy of a measurement [8].

3.3 Benefits for the stakeholders

The new measurement method provides the different stakeholders with a reliable tool to assess the acoustic performance of NRD as installed in practice.

NRD manufacturers, road and rail administrations, laboratories and research centres will be able to benefit from this method for:

- the determination of the intrinsic characteristics of noise reducing devices to be installed along roads or railways, to be measured either on typical installations alongside roads or railways or on a relevant sample section;
- the determination of the in situ intrinsic characteristics of noise reducing devices in actual use;
- the comparison of design specifications with actual performance data after the completion of the construction work and on the construction site;
- the verification of the long term performance of noise reducing devices (with a repeated application of the method).

3.4 Outcomes of WP3

The two objectives of WP3 have been achieved.

Objective 1:

a new robust method for measuring on site the intrinsic characteristics of NRD have been established.
Figures 23 and 24 show examples of the method, a technical outline is given in 3.5.1 and 3.5.2; the full description is given in the QUIESST deliverables D3.3 [5] and D3.4 [6].

Objective 2:

the accuracy of the method has been assessed by means of an inter-laboratory test.
Some more technical data are given in 3.5.3; the full description of the inter-laboratory test and its outcomes are given in the QUIESST deliverable D3.5 [7].

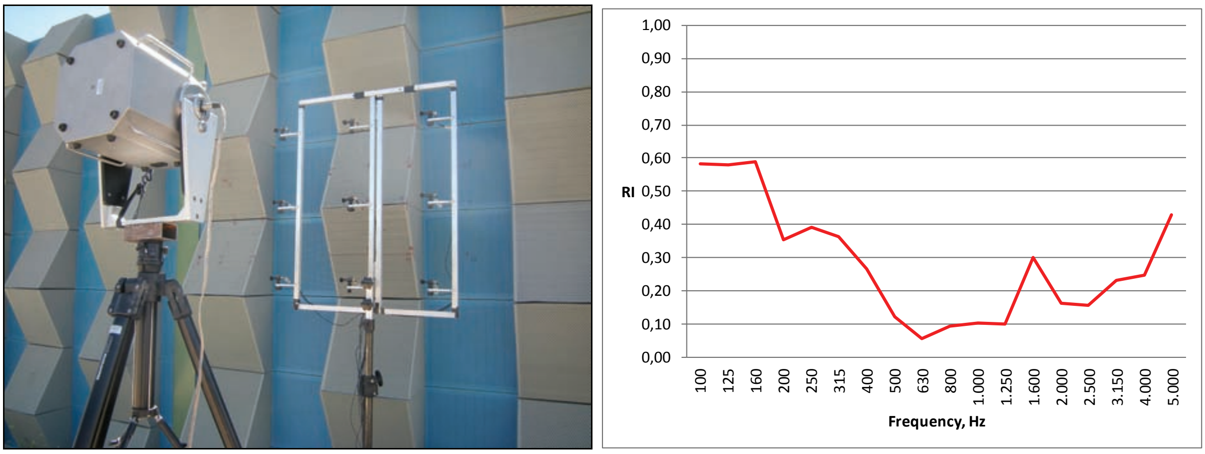


Figure 23: Left: sound reflection measurement in situ
Right: measurement results in ⅓rd octave bands. DL_{RI} = 8 dB

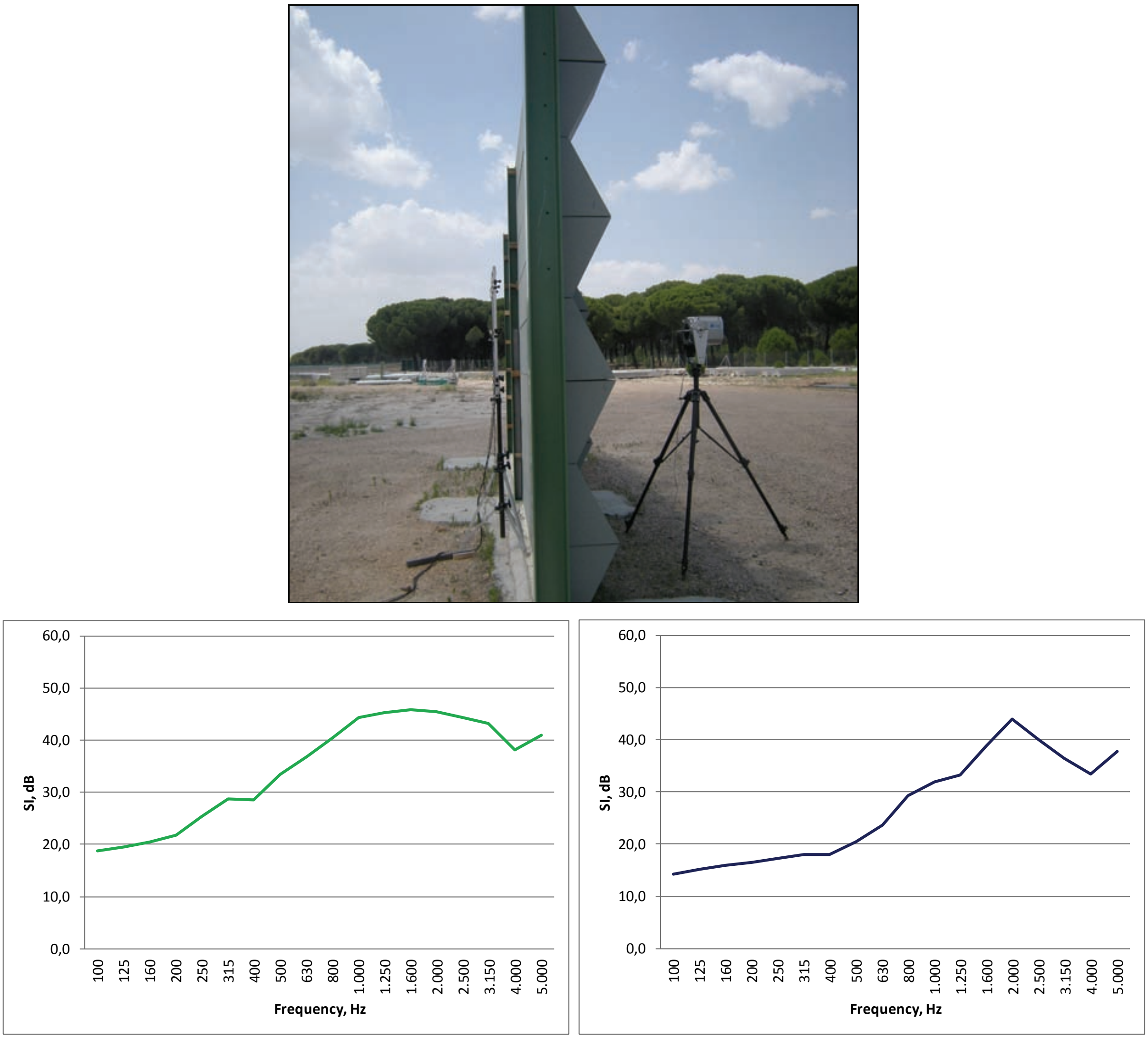


Figure 24: Top: airborne sound insulation measurement in situ
Left: measurement results for the acoustic elements in ⅓rd octave bands $DL_{SI,EL}$ = 33 dB
Right: measurement results across posts in ⅓rd octave bands $DL_{SI,P}$ = 24 dB

3.5 Outline of the new in situ measurement method

3.5.1 In situ sound reflection measurement

An artificial sound source (loudspeaker) and a square array of nine microphones (0,80 x 0,80 m) are used (Figures 23 and 25). Multichannel acquisition can be exploited. The array is placed between the loudspeaker and the device under test. The sound source emits transient sound waves that travel through the microphone array to the device under test and then reflects on it.

The microphones receive both the direct sound travelling from the sound source to the device under test and the reflected sound (including scattering).

A free-field measurement, taken for each microphone with the same source and microphone configuration but far away from any reflecting object, is then subtracted from the previous one in order to isolate the reflected component.

Several technical improvements (specifications for analysis windows application, a new algorithm for signal subtraction, a quantitative criterion for measuring the quality of the subtraction, etc.) have been developed in order to assure accurate results, even in difficult conditions (Figure 26).

From the ratio of the acoustic power of the direct and the reflected components, averaged on the nine microphones, a characteristic quantity is calculated: **the sound reflection index RI**. It is a dimensionless quantity, presented as a function of frequency in the ⅓rd octave bands between 100 Hz and 5 kHz. From those frequency dependent values, a single-number rating can be calculated, called DL_{RI} and expressed in decibels.

In this formulation three newly defined *"corrective factors"* are included to master all the details of the measurement: a geometrical *divergence correction factor* taking into account the path length difference between the direct and reflected waves, a *directivity correction factor* taking into account the sound source directivity, and a *gain correction factor* used to compensate any gain mismatch (if any) of the amplification settings between the "free-field" and "barrier" measurements.

All this gives *RI* values physically meaningful and independent of the sound source used.

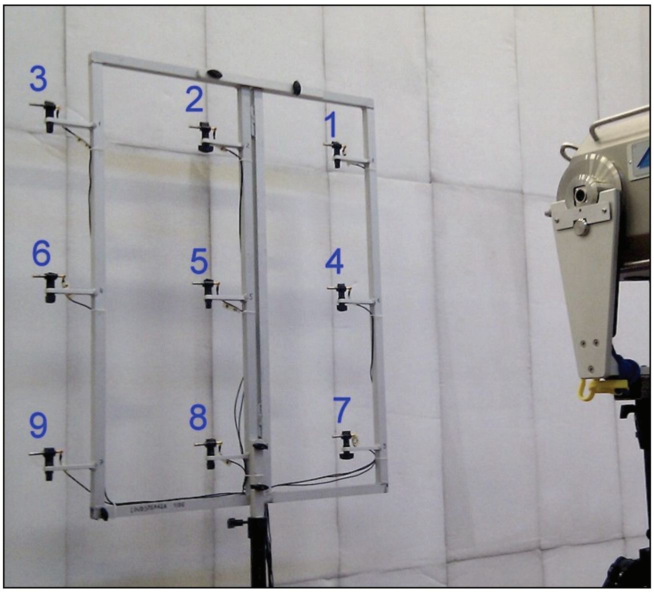


Figure 25: Sound reflection index measurements:
sound source and microphone array in front of a sample noise barrier

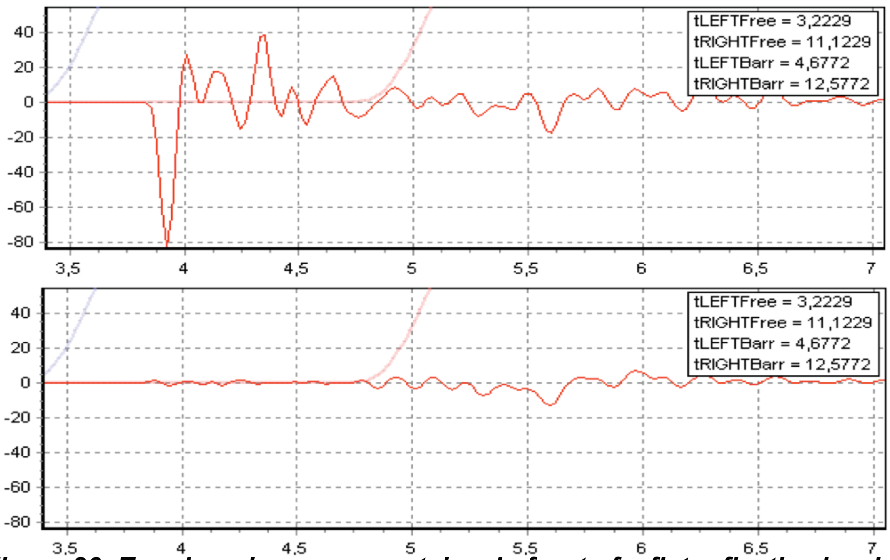


Figure 26: Top: impulse response taken in front of a flat reflective barrier
Bottom: the same impulse response after the signal subtraction
(X axis: signal strength in dB, Y axis: time in ms)

3.5.2 In situ airborne sound insulation measurement

The sound source emits a transient sound wave that travels toward the device under test and is: partly reflected, partly transmitted and partly diffracted by it. The microphone array placed on the other side of the device under test receives both the transmitted sound pressure wave travelling from the sound source through the device under test, and the sound pressure wave diffracted by the top edge of the device under test (Figure 27).

If the measurement is repeated without the device under test between the loudspeaker and the microphone, the direct free-field wave can be acquired.

From the ratio of the acoustic power of the direct and the transmitted components, energetically averaged on the nine microphones, a characteristic quantity is calculated: **the sound insulation index *SI***. It is a dimensionless quantity, expressed in dB and presented as a function of frequency in the ⅓rd octave bands between 100 Hz and 5 kHz. From the frequency dependent values a single-number rating can be calculated, called DL_{SI} and expressed in decibels.

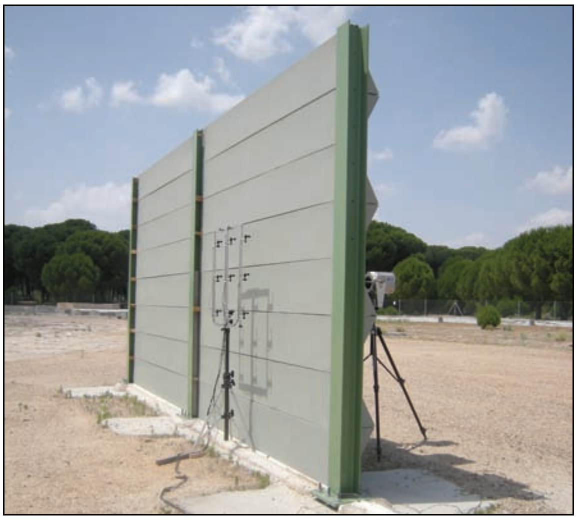


Figure 27: Sound insulation index measurements: sound source and microphone array near a sample noise barrier, in front of the acoustic elements

3.5.3 Repeatability and reproducibility

The above outlined methods have been verified by 8 independent laboratories on 13 samples installed on 2 test sites in Grenoble (France, Fig.28) and Valladolid (Spain, Fig.29).

Overall, the test has been carried out following the procedure for an inter-laboratory test (also called Round Robin Test, or RRT) in order to be able to get both the repeatability and the reproducibility of the method.

Figure 28: the Grenoble test site (France)

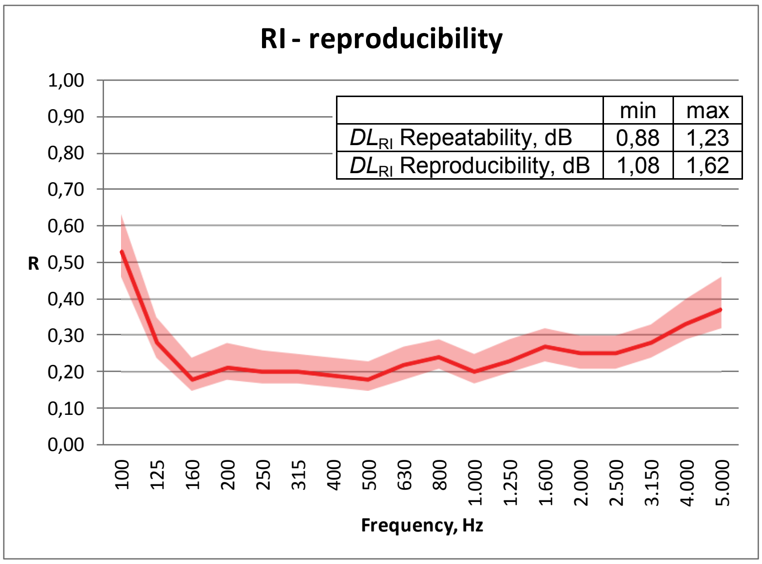
Figure 29: the Valladolid test site (Spain)

The **repeatability** is the random variation of the measurement result under constant measurement conditions, while the reproducibility is the random variation of the measurement result under changed conditions of measurement.

The **reproducibility** is directly used to declare the reliability of the method according to the ISO guide on uncertainty in measurement [8]. In other words, if *M* is the value of a single measurement and *R* is its reproducibility, there is a probability of 95% that the true value of a single measurement lies in the interval [*M* – *R*; *M* + *R*].

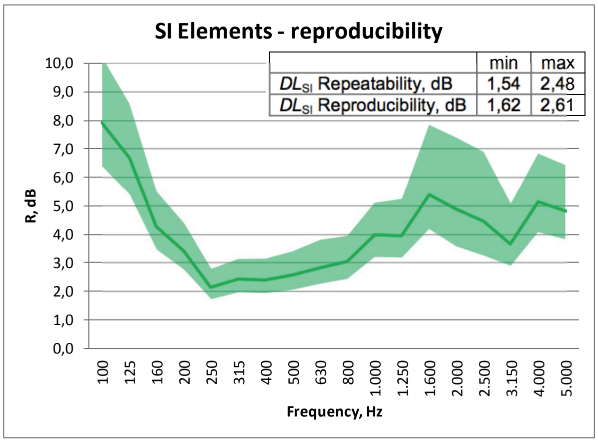
Both the repeatability and the reproducibility are different for each ⅓ rd frequency band; their trend as a function of frequency is shown in Figures 30 and 31 that summarize the results of the Round Robin Test.
It is worth noting that **these results have been achieved on real-life samples**, built as in practice with irregularities and sound leaks due to average workmanship; in other words, these samples were not fully homogenous "laboratory samples". Thus, the final repeatability and reproducibility values do include the effect of sample irregularities.

In this regard, the final values obtained, already satisfying as they are, may be considered a worst-case estimate.

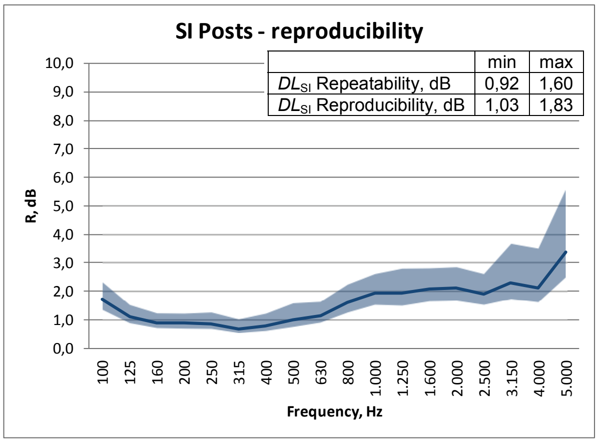


	min	max
DL_{RI} Repeatability, dB	0,88	1,23
DL_{RI} Reproducibility, dB	1,08	1,62

Figure 30: Reproducibility of the sound Reflection Index measurement method in ⅓rd octave
Thick red line: median value, Light red area: range between min. and max. values
Table of the 95% credible intervals for reproducibility and repeatability
of the single-number rating of the sound reflection index DL_{RI} in dB



	min	max
DL_{SI} Repeatability, dB	1,54	2,48
DL_{SI} Reproducibility, dB	1,62	2,61



	min	max
DL_{SI} Repeatability, dB	0,92	1,60
DL_{SI} Reproducibility, dB	1,03	1,83

Figure 31: Reproducibility of the Sound insulation Index measurement method for the acoustic elements and at post in ⅓rd octave
Thick green/blue lines: median value, Light green/blue areas: range between min. and max.
Tables of the 95% credible intervals for reproducibility and repeatability of the single-number rating of the sound insulation index for the acoustic elements and at posts DL_{SI} in dB

4 Work Package 4 (WP4) Database of Acoustic performance of the European NRD

4.1 Introduction and background information

The European Noise Reducing Device market offers many already approved products, while many new ones are appearing. However, even if the European product standard EN 14388 is published since 2005, no *comprehensive database* of the NRD acoustic performance did exist so far. Such a database would allow a fair comparison between products referring to common standards, giving an overview of the current products and providing the stakeholders with relevant data.

At the same time, the **relationship between laboratory and in-situ methods** was also interesting to survey: QUIESST aims to provide more detailed information on the correlation between all the test methods, and to achieve a better overview of the different products present on the market.

The main objective was thus the creation of a **comprehensive database of acoustic NRD performance for the European NRD market**.

4.2 Benefits for Stakeholders

This database provides the different stakeholders with comprehensive data on the acoustic performance of European NRD and with information and guidance on the practical use of those data. NRD manufacturers, laboratories and research centres and road and rail administrations will be able to benefit from this information in the following ways:

- The database gives an overview of past and currently available solutions for noise reducing devices and their acoustic performance according to the current European measurement methods for in-situ and laboratory sound absorption and sound insulation.
- It allows them to interpret, compare and relate the acoustic performance data generated by the different methods.
- It enables them to expertly use relevant acoustic NRD performance specifications (e.g. for tenders).
- It promotes the development of novel and improved NRD.
- It allows them to assess the potential acoustic performance of new products in comparison to the existing market.
- It assists them in selecting the most suitable and cost-effective NRD type for their applications.

4.3 Overview of the Database Content

The NRD database contains data obtained with the different methods presenting single number rating and ⅓rd octave band spectra and acoustic NRD families.

The database contains 414 different NRD manufactured by 40 noise barrier manufacturers, and more than 1421 different measurement results, from tests performed by 25 different laboratories from 9 European countries.

Concerning the composition of the collected data, more than 400 test results are on in-situ sound reflection, around 120 are on sound absorption measured in the laboratory, while 250 test results are concerning in-situ sound insulation and 100 sound insulation measured in the laboratory.

Figure 32 shows an overview of the current content of the NRD database, while Figure 33 shows the amount of data collected grouped by the measurement method.

The measurement methods currently covered in the database are the following:

- Laboratory measurements for sound absorption and sound insulation according to EN 1793-1 and EN 1793-2,
- The so-called "Adrienne" in-situ method for sound absorption and airborne sound insulation according to CEN/TS 1793-5, and prEN 1793-6
- The newly developed QUIESST method for measurements of sound reflection,
- French in-situ method for sound absorption and airborne sound insulation NFS 31089.

Entry type	Number of entries
NRD	414
Tests	1421
Manufacturers	40
Laboratories	25
Countries	9

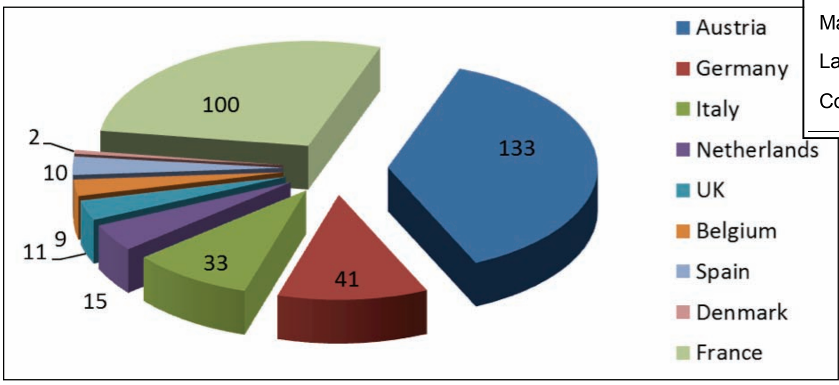


Figure 32: Geographical distribution of the Noise Reducing Devices present in the database and European countries represented

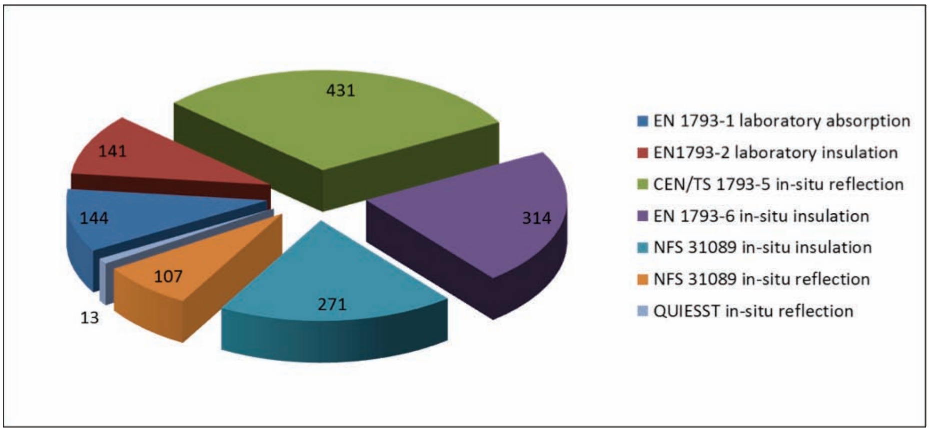


Figure 33: Amount of data collected following the test method

Considering the different material composition of the NRD, the majority of the collected data represents the European market distribution fairly well. Currently, most of the available data come from wood-fibre concrete, metallic cassettes and timber barriers, while transparent materials, photovoltaic barriers, added devices and green walls are less represented in the database: Figure 34 shows the different materials types of NRD current present in the database, while the table 1 presented hereafter lists the different categories of NRD that have been considered.

A detailed view of the database content including all the performed analyses are presented in the QUIESST deliverable D4.3.

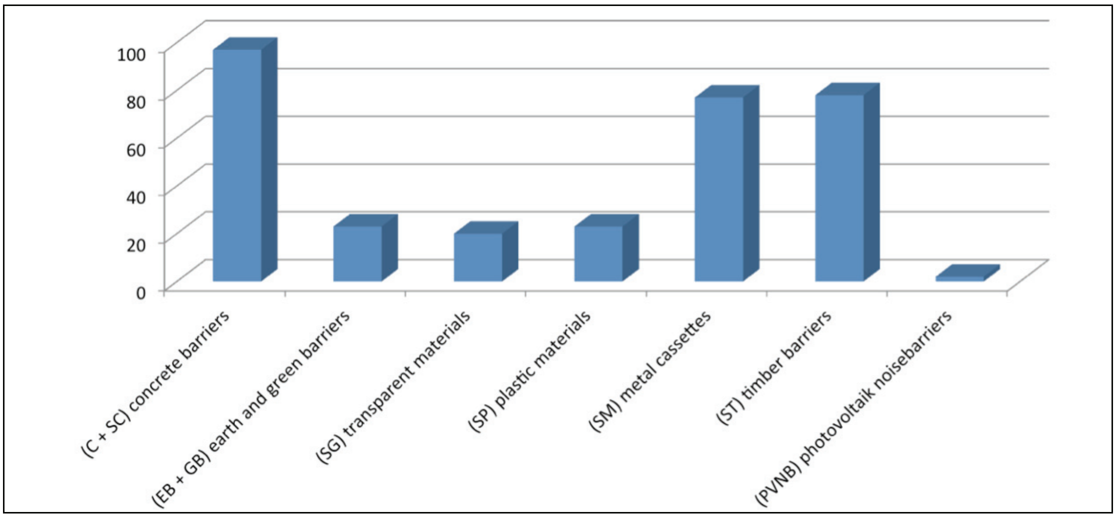


Figure 34: NRD material types contained in the database

Table 1 - Definition of the different NRD categories in the database

Barrier Type	Description
SM – Steel supporting structure + Metallic panels	Most steel supporting structures have a H-shaped appearance. At least the surface layer consists of metallic material
SC – Steel supporting structure + concrete panels	Structure of posts like in SM. At least the surface layer consists of concrete. Wood-fiber concrete barriers can also be assigned to this family.
ST – Steel supporting structure + Timber panels	Structure of posts like in SM. At least the surface layer consists of timber.
SG – Steel supporting structure + Transparent panels	Structure of posts like in SM. It is very highly probably that the noise barrier consists of only one transparent layer (e.g. acrylic glass)
C – Self-supporting concrete or brick system	NRD made of self-supporting construction. An example would be brick wall.
SP – Steel supporting structure + plastic panels	Structure of posts like in SM. At least the surface layer consists of plastic material
CT – Tunnel-concrete structure	Tunnel-structure, which surrounds the entire road to provide full noise screening. May be constructed self-supporting or with concrete beams supported by concrete pillars.
Stu – Tunnel steel structure	Tunnel-structure, which surrounds the entire road to provide full noise screening. Consists of steel supporting structure and metallic cassettes.
GT – Tunnel with transparent panels	Tunnel-structure, which surrounds the entire road to provide full noise screening. Consists of steel supporting structure and transparent panels
GB – Green barrier	NRD type, which obtains its acoustic properties of soil with vegetation. A classic example would be a concrete structure with containers, filled with earth and plantings.
GA – Gabion with stones	NRD made of a gabion framework (solid metallic grid) filled with stones.
EB – Earth barrier	Artificial or natural earth wall – can be planted or unplanted
PVNB – Photovoltaic noise barrier	Usually a conventional noise barrier with added photovoltaic elements.

4.4 Structure of the internal database

The database serves two different objectives: the first one is to perform an *in depth* statistical analysis of the current and historic data, the second one is to provide information about NRD for the general public, and especially for road and railways administrations. However, this leads to major issues of confidentiality. On the one hand, there was a need to collect for as many data from the manufacturers as possible to perform the analysis, while not all manufacturers and research institutions want to share this detailed information with the public and especially their competitors. For this reason, the detailed content of the so-called *internal database* will not be accessible to the public. Because of this, a second version of the database has been developed using only anonymous data and statistical information about the different NRD classes. Infrastructure administrations can check the currently possible performance of different classes while the manufacturers test reports and confidential information will not be publically available.

Concerning the structure of the internal database Figure 35 shows the UML diagram of the database design and its classes. The database is split into two main parts: the NRD part and the test part:

- In **the NRD part**, general information about the NRD and its manufacturer are contained. The relevant information for the database are: name or designation, manufacturer, and the physical properties (e.g. shape, roughness, inclination).
- The second part of the database is dealing with **the test results**, the goal of the database being to compile the results of laboratory measurements (EN 1793-1 and -2), the ADRIENNE method (CEN/TS 1793-5) and the new QUIESST method for comparison. The common properties of all measurements are date, test-site, testing organization, and the NRD on which the measurement was performed. For in-situ tests several additional parameters concerning the meteorological conditions during the measurement are recorded. These are surface dryness and temperature, wind speed and direction and air temperature. For laboratory tests, the additional parameters are item configuration (width, height, surface), air temperature and humidity.

The object and attachment classes are used to add metadata about the document management process (e.g. creator, creation and modification time) and links to additional files and pictures. Because a lot of data is only available in unstructured documents of differing quality, these attachments are important additional sources of information.

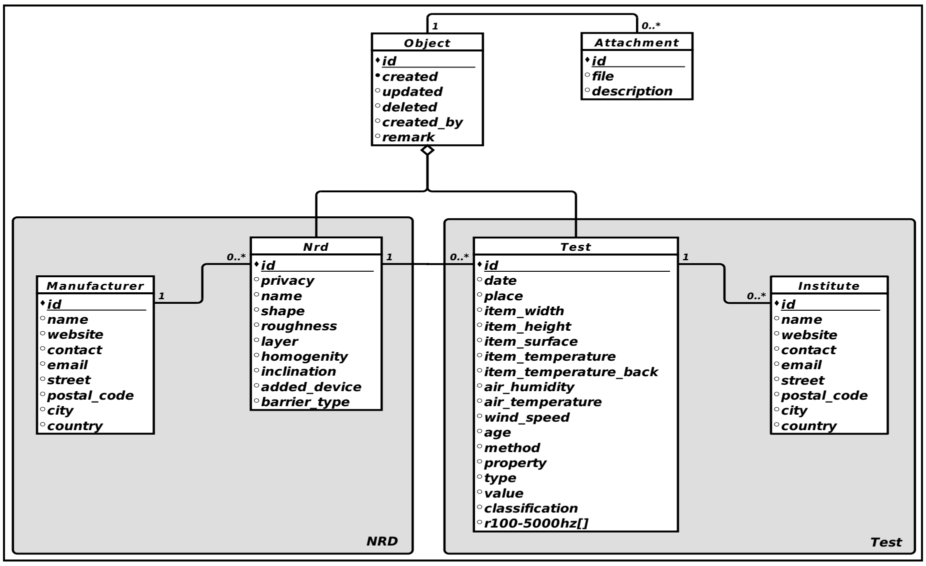


Figure 35: Structural overview of the internal database

As shown in Figure 36, an NRD entry can link to several tests. These test-entries may represent an overall result (from different institutes) or a partial result, for instance only one vertical rotation according to the standard CEN/TS 1793-5. Furthermore, an NRD-entry must be assigned to a manufacturer. The same applies for test-entries, except that they are linked to a test institute.

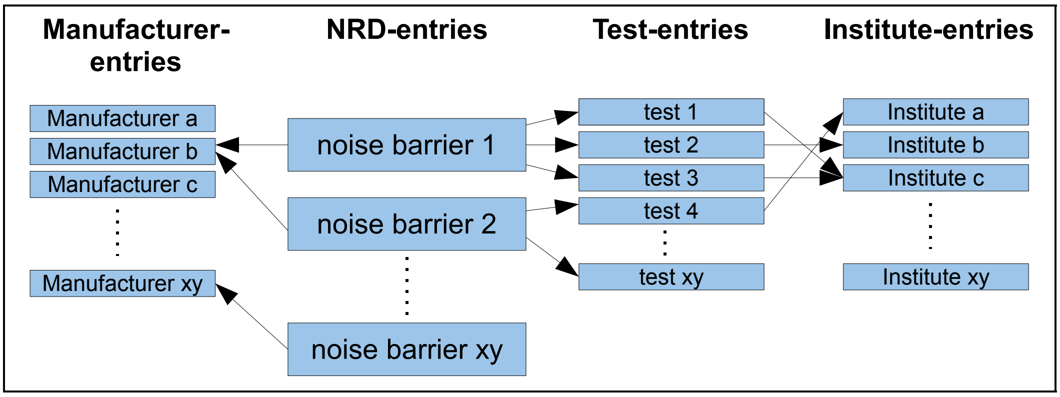


Figure 36: Structural design of the database from the user's perspective

4.5 Case Studies from the internal database

Based on the data contained in the internal database, some relevant case studies can be shown in the following paragraphs.

Metallic barrier

As a representative NRD example, a metallic barrier consisting of aluminium cassettes filled with sound-absorbing material has been chosen. Beneath a surface layer made of perforated aluminium sheet, the cavity in the cassette is filled with rock wool. In addition to this, the acoustic elements are supported by a massive steel structure.

According to the classification criteria the NRD is homogeneous and has a multiple layer structure with a flat surface layer. This particular NRD-entry has been selected due to the presence of linked test-entries for all relevant measuring methods. Figure 37 shows the ⅓rd octave band measurement results according to the standards EN 1793-1, EN 1793-2, CEN/TS 1793-5 and prEN 1793-6.

Figure 37: Test results of the metallic barrier according to the different standards

The lower right plot contains sound insulations results of a post measurement as well as for the acoustic element. For privacy reasons, the name of the manufacturer of the noise barriers and the one of the laboratory have been concealed.

Timber barrier

This example of a barrier is made of multiple layers of wooden laths supported by H-shaped steel posts. In the database the NRD is classified with a flat shape, a vertical inclination and has only one horizontal layer (equates to “homogeneous”). After a short look at the pictures of the devices available in the database one would expect the property “small roughness” – but since the roughness of the surface is smaller than 8 cm, the NRD is classified with “no roughness”.

The attached test-entries include in-situ sound insulation measurements with a very careful description of the measurement conditions, like the location in form of GPS coordinates. Moreover, the notes of every entry contain the exact measuring point at the acoustic element or post. Combined with the available photos of the tested NRD, a very good reconstruction of the measurement conditions as well as an accurate interpretation of the measurement results is possible. Exemplary results and the measurements notes are shown in Figure 38. This case study presents a very accurate entered NRD with its corresponding test-entries.

Due to the absence of laboratory measurements for comparison, the present NRD-entry does not contribute any relevant information for the relationship between laboratory and in-situ methods. Nevertheless, it shows how easy a detailed NRD record can provide the same information as a test report, but in a much more practical way, especially for data analysis.

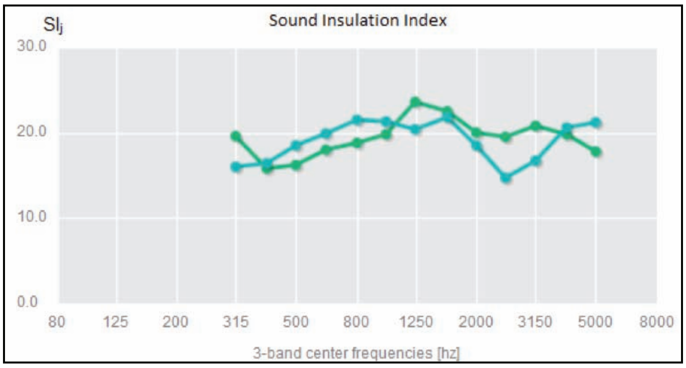
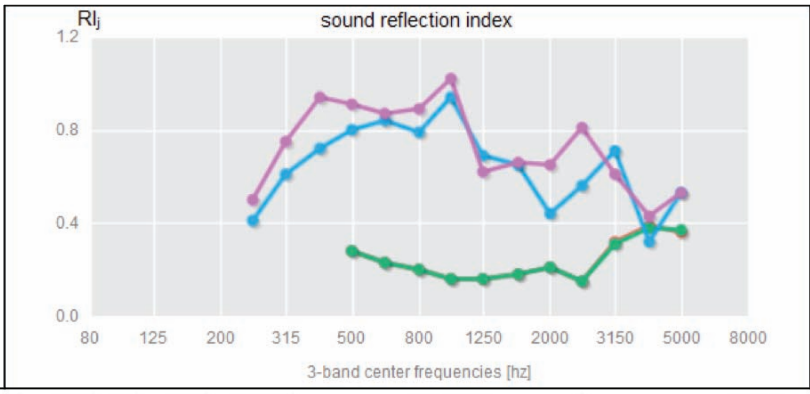


Figure 38: ⅓rd octave band results of element and post

Wood-fibre concrete barrier

This case study deals with a barrier made of wood-fibre concrete with a steel supporting structure. In addition to a concrete basement, the NRD is also equipped with a T-shaped barrier top device. For improving the sound absorption, the noise barrier has a rough surface on the side facing the traffic. It should be noted at this point, that there very few NRD with added devices in the database – this representative example is an exception. For classification, the NRD has the properties “multiple layer structure” and a “homogeneous” surface. The added device and the different basement are not taken into account for the latter, but are noted in the remark-field of the NRD-entry. The small roughness (less than 8 cm) leads to the classification “no roughness” with an additional note. Since this noise barrier has been tested by different laboratories, a variety of sound reflection measurement results is available. In addition, a selection of results with different lower cut-off frequencies is displayed in Figure 39. The graph illustrates a big discrepancy in single-number ratings between the tests with different cut-off frequencies due to the small height of the tested barrier. Of course it is not the objective of this report to investigate this fact – but the present case study demonstrates how easily results from different test reports can be compared for analysis with the NRD database.



		Method	Property	Type	Class	Value	Measured	Organisation	Remark	Actions
☑	(green)	Adrienne	Reflection	AVERAGE		DLRI: 7.0	2005-05-23		(3/AV/500Hz); Meas.location on highway A9 at km 154.2 at a parking area; DLRI is average value of meas.points located on the acoustic element; cutoff-frequency at 500Hz	
☑	(blue)	Adrienne	Reflection	AVERAGE		DLRI: 1.5	2005-06-22		(1/AV/250Hz); Meas.location on highway A9 at km 154.2 at a parking area; DLRI is average value of meas.points located on the acoustic element; cutoff-frequency at 250Hz	
☑	(pink)	Adrienne	Reflection	AVERAGE		DLRI: 1.1	2005-06-22		(2/AV/250Hz); Meas.location on highway A9 at km 154.2 at a parking area; DLRI is average value of meas.points located on the post; cutoff-frequency at 250Hz	

Figure 39: ⅓rd octave band results of sound reflection index according to CEN/TS 1793-5 The frequency in the remark field indicates the used lower cut-off frequency for the test

4.6 Structure and Use of the Public Database

The public database is the main output of WP4. The database has been developed as a website in order to be directly accessible for all the stakeholders from the QUIESST website. The public database is based on the analyses performed with all the data collected during the project. For confidentiality reasons only an overview of the data and the results of the analyses can be presented to the public and not the data itself, which are present only in the internal database.

Figure 40 shows the main page with a short introduction on the QUIESST project and the QUIESST database. The database sections can be found on the top right part of the page.


QUIESST database of European NRD

Overview | Single-number ratings | 1/3 octave band | Detailed analyses

QUIESST project

QUIESST - QUIetening the Environment for a Sustainable Surface Transport - is a project co-funded by the European Community's Seventh Framework Programme (FP7/2007-2013) that began on the 1st of November 2009. The QUIESST project addresses surface transport noise abatement (road and rail), considers cost benefit analysis and addresses the END objectives, covers true holistic noise abatement solutions through wave propagation and systems for passive compensation. Its team, made of 13 partners from 8 countries integrates the relevant stakeholders: Infrastructures, Industry, Universities, Research Institutes and SME. It addresses important environmental and economic concerns and will contribute to promote EU Noise Reducing Devices industry.

QUIESST database of European Noise Reducing Devices (NRD)

The database of European NRD has been developed in work package 4 of the QUIESST project. This database provides the different stakeholders with comprehensive data on the acoustic performance of European NRD and information on the practical use of those data. NRD manufacturers, laboratories and research centres as well as road and rail administrations will benefit from this information in the following ways:

- The database gives an overview of past and currently available solutions for noise reducing devices and their acoustic performance according to the current European measurement methods for in-situ and laboratory sound absorption and sound insulation
- It allows them to interpret, compare and relate the acoustic performance data generated by the different methods
- It enables them to expertly use acoustic NRD performance specifications (e.g. for tenders)
- It promotes the development of novel and improved NRDs
- It allows them to assess the potential acoustic performance of new products in comparison to the existing market
- It assists them in choosing the most suitable and cost-effective NRD type for their applications

SEVENTH FRAMEWORK PROGRAMME

Co-funded by
the European Commission -
7th Framework Programme

Figure 40: Main page of the QUIESST database with sections

Menu "overview"

In this section an overview of the general content of the database is presented. Diagrams and Figures on the overall data present in the database can be seen as in Figures 33 and 34.

Menu "single-number ratings"

The section "single values" contains separate diagrams for each measurement method taken into account. After having performed different types of analysis and consistency proof, four main categories have been defined in order to have enough statistical relevance for the chosen NRD types. The Figures present in this section show the distribution of the single number rating grouped by the measurement methods, for the main types of noise barriers present in the database. Figure 41 shows the distribution of the single number rating according to the in-situ method for sound reflection for the main types of NRD present in the database.

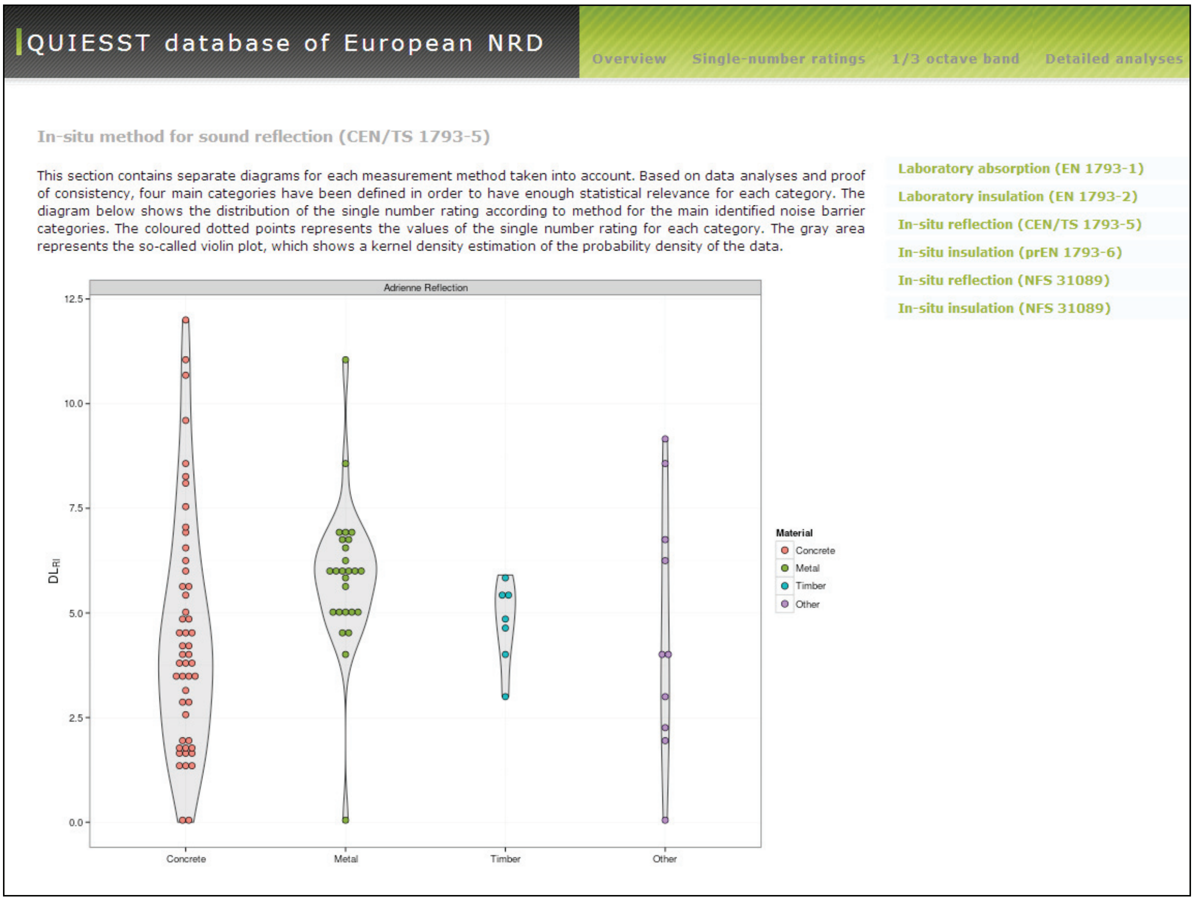
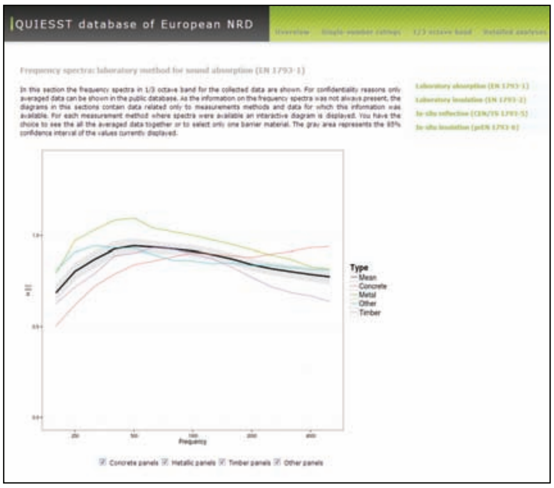


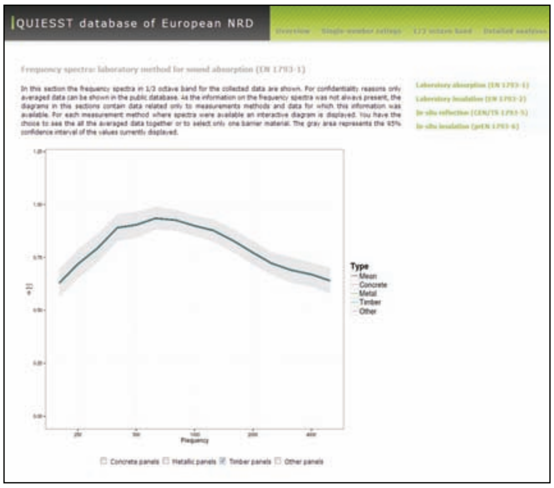
Figure 41: Overall values according to the different measurement methods: distribution of all the NRD single number ratings according to the in-situ method

Menu "1/3 octave band"

In this section the 1/3 octave band spectra-of the collected data can be seen. For each measurement method and barrier type interactive diagrams can be displayed, giving the choice to see the whole dataset or to select only one material type.

For example, Figure 42 shows the measurement results according to the laboratory method for sound absorption (EN 1793-1) for the four main NRD types and the average of all results with the 95% confidence interval, while Figure 43 shows the measurement results for timber barriers only. In this case the 95% confidence interval is also restricted to this barrier type only (and not to the whole dataset).





Measurement according to the laboratory method for sound absorption (EN 1793-1): measurements results and averages of all results with 95 % confidence intervals

(left) Figure 42: for the 4 main NRD types
(right) Figure 43: timber NRD only

<u>Menu "Detailed analysis"</u>

In addition to the overview of the single number ratings and the frequency spectra, more detailed analyses and comparisons between the different methods have been performed. In this section, the following analyses and comparisons are presented:

- Correlation between laboratory and in-situ method for sound insulation over all barrier types (EN 1793-2 & prEN 1793-6)
- Correlation between laboratory and in-situ method for sound insulation for each material where sufficient data were available (EN 1793-2 & prEN 1793-6)
- Correlation between laboratory and in-situ method for sound absorption/reflection over all barrier types (EN 1793-1 & CEN/TS 1793-5)
- Correlation between laboratory and in-situ method for sound absorption/reflection for each material where sufficient data were available (EN 1793-1 & CEN/TS 1793-5)
- Comparison between in-situ sound insulation measurements performed in front of a post and measurements performed in front of a noise barrier element over all barrier types (prEN 1793-6)
- Comparison between in-situ sound insulation measurements performed in front of a post and measurements performed in front of a noise barrier element for each material where sufficient data were available (prEN 1793-6)
- Comparison between different methods for in-situ sound reflection, where sufficient data were available (CEN/TS 1793-5 and NFS 31089)
- Comparison between different methods for in-situ sound insulation, where sufficient data were available (prEN 1793-6 and NFS 31089)
- Cluster analysis of the collected results for each measurement method separately in order to identify NRD families based on the frequency spectra

Figures 44 and 45 show some examples of the analysis that can be found under the database section "Detailed analysis".

In the last example, one can see that the coefficient of the linear regression shows a very good accordance between the two methods (laboratory (EN 1793-2) and in-situ (prEN 1793-6). The correlation is based only on the cases where both methods have been used for testing the same barrier.

Based on the huge amount of data collected, it will be possible to perform many other analyses in follow-up research.

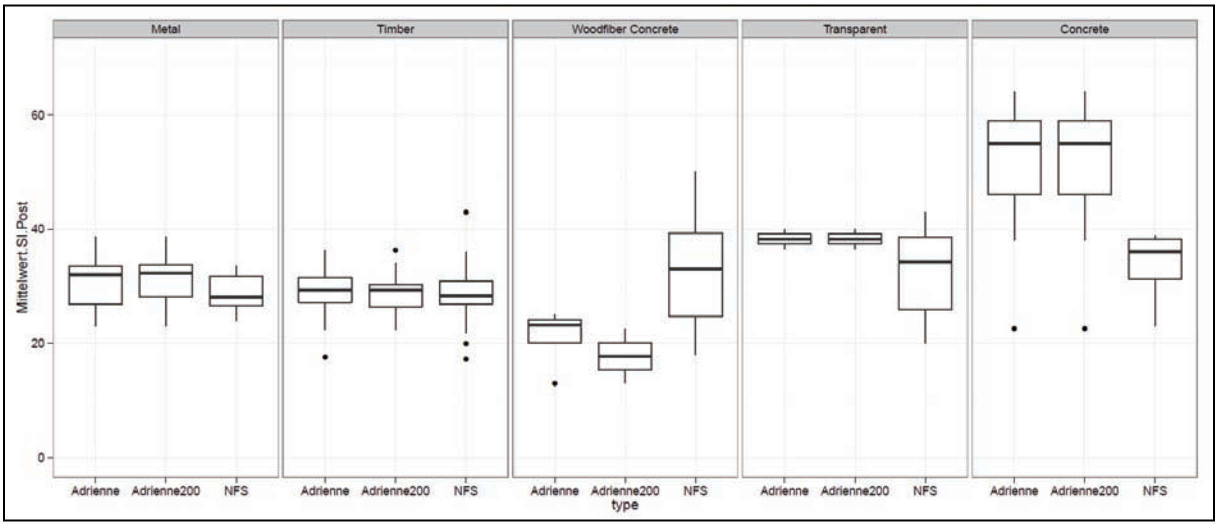


Figure 44: in-situ measurements of sound insulation at post: Comparison between French NFS method, CEN/TS 1793-5 (Adrienne) and CEN/TS 1793-5 (Adrienne) restricted to the 200Hz to 5 kHz frequency range

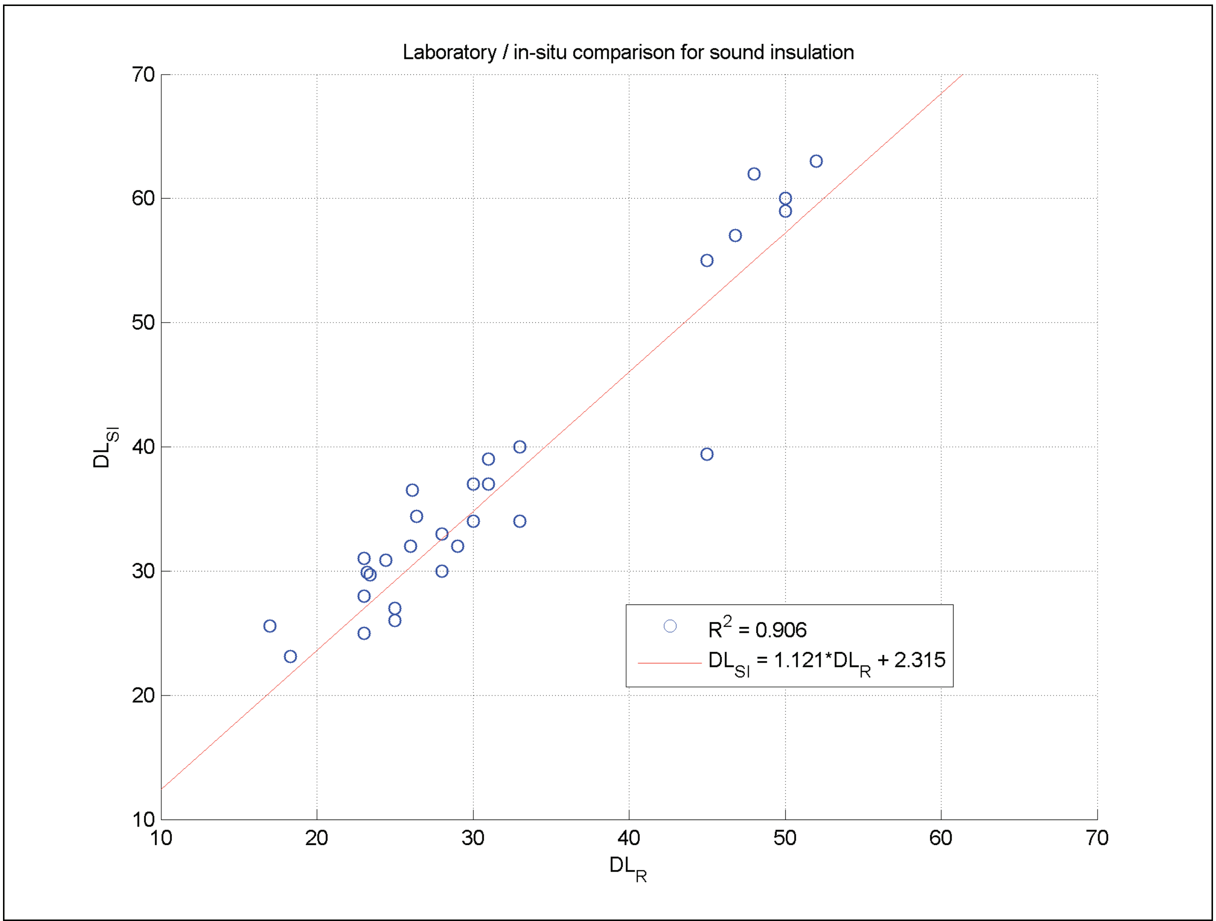


Figure 45: Correlation between laboratory (EN 1793-2) and in-situ (prEN 1793-6) method for sound insulation measurements over all NRD types available in the database

5 Work Package 5 (WP5) Holistic optimisation of NRD

5.1 Introduction

The main challenge of this Work Package was to develop an original optimisation methodology dedicated to complex shape NRD, taking into account acoustic and non-acoustic parameters simultaneously through global performance indicators.

The goal was not to produce the "best optimised NRD", but instead to give the opportunity to engineers as well as manufacturers to re-use this approach for their own research.

We established a comprehensive database of optimised solutions that could be queried through a simple, complete reference tool, in order to help relevant stakeholders at the upstream phase of urban planning projects.

5.2 Choice of best practice models

In order to accurately predict the acoustic losses during reflection, diffraction and transmission through a barrier of complex shapes with non-homogeneous absorbent material distribution, a critical state of the art was carried out in an attempt to choose the most appropriate sound prediction methods as well as optimisation models [9].

5.2.1 Sound propagation models

Four main 2D sound prediction models were selected to be the most pertinent for the purpose of accurately predicting complex shape NRD performances:

- The **BEM** (Boundary Element Method) that is very flexible to model noise barriers of complex shape including impedance jumps and curved surfaces. On the other hand, BEM ignores the effects of atmospheric gradients due to meteorological effects and should be used for predictions not too far from the NRD (100 m propagation max);
- The **FDTD** (Finite-Difference Time-Domain) model that takes into account atmospheric refraction and therefore can be used to include meteorological conditions in the optimisation of barrier shapes. On the other hand, FDTD is a bit less flexible than BEM for modelling complex shapes;
- The **TLM** (Transfer Line Matrix) that offers flexibility in the description of the geometry of the boundaries with atmospheric refraction taken into account;
- The **TMM** (Transfer Matrix Method) that is dedicated to the prediction of sound transmission and absorption through a multi-layered noise barrier.

We also suggest using hybrid models such as the FDTD-PE and BEM-PE (PE for Parabolic Equation model) for NRD effects at long ranges taking into account meteorological effects.

A 3D asymptotic model such as the **Ray method** is recommended when studying the global impact of NRD on realistic large built areas, as described hereafter in this section. Then the model should be adapted to complex situations by including results from BEM, FDTD, TLM and TMM.

5.2.2 Optimisation models

As regards with selection of best optimisation models, our recommendations are:

- Concerning mono-objective optimisations the **evolutionary strategy** is the most relevant, since many parameters have to be simultaneously optimized;
- Concerning multiple-objective optimisation, both approaches by **aggregated methods** and **Pareto methods** are advised;
- The construction feasibility of the optimised NRD should be taken into account in order to avoid unfeasible noise abatement solutions.

5.3 Acoustic and non-acoustic optimisation indicators

We developed a new methodology for holistic optimizations of NRD [10]. One challenge was to achieve a multi-criteria optimisation from acoustic but also non-acoustic parameters. Thus three families of indicators that we recommend to use were selected: acoustic, environmental and economic indicators.

5.3.1 Acoustic indicators

Two types of NRD optimisation may be achieved: intrinsic and extrinsic.

Intrinsic optimisation means that one evaluates any acoustic performance in the vicinity of the noise barrier, ignoring its own environment and considering a point noise source [11]. The performance indicators we used were those calculated in the relevant EN 1793 standards: the reflection index DL_{RI}, the transmission index DL_{SI} and the diffraction index DL_{DI}.

Extrinsic optimisations are achieved considering the NRD in its environment [12]: real sound sources, infrastructure heights, topography and, eventually, buildings. We calculated the sound level difference ***IL*** as the acoustic indicator, for receivers located on both sides of the infrastructure. *IL* represents the acoustic gain obtained with an optimised NRD compared to the reference concrete barrier.

5.3.2 Environmental indicators

As a result of a specific Life-Cycle Assessment (**LCA**), a set of environmental indicators was proposed [10]. Among them we recommend to utilize the four ones used in QUIESST: **Energy**, **GWP** (Global Warming Potential), **Waste** (non-hazardous and inert) and **Water consumption**. These environmental indicators were evaluated for a set of 8 common materials used in NRD engineering (wood concrete, timber…) on a basis of a common functional unit, chosen here to be the production of 1000 kg of material and its transport over 100 km. We also took into account the reference service life of each material exploited. Recommended values are available in [10]. We finally used the ratio of the indicator value to the one of the reference barrier.

5.3.3 Cost indicators

In our approach, the cost indicator was the sum of three parameters: **construction**, **maintenance** and **demolition costs**. Demolition costs included transportation but did not consider material re-use. Applicable values are proposed in [10]. As previously, we used the ratio of the indicator value to the one of the reference barrier.

5.4 Holistic optimisation methodology

5.4.1 Description of the methodology

The different steps of this new holistic optimisation methodology [10-12] are shown in Figure 46.

The starting stage is the random creation of a set of 50 different NRD within fixed NRD family and environmental situation (source/area/topography). Then an evaluation of the acoustic, environmental and cost indicators is achieved, and a linear averaging is done to obtain 3 *aggregated indicators*: ***ACOU***, ***ENV*** and ***COST***. All these indicators are compared to those obtained for the reference NRD: a straight, rigid concrete barrier. Then 12 new NRD (25% of 50) are created with limited changes (in shape and material) from the 12 "best" NRD they finally replace. Hence a new set of 50 NRD is revaluated. This optimisation process ends when the highest values of all indicators vary by less than 5% from an evaluation step to another.

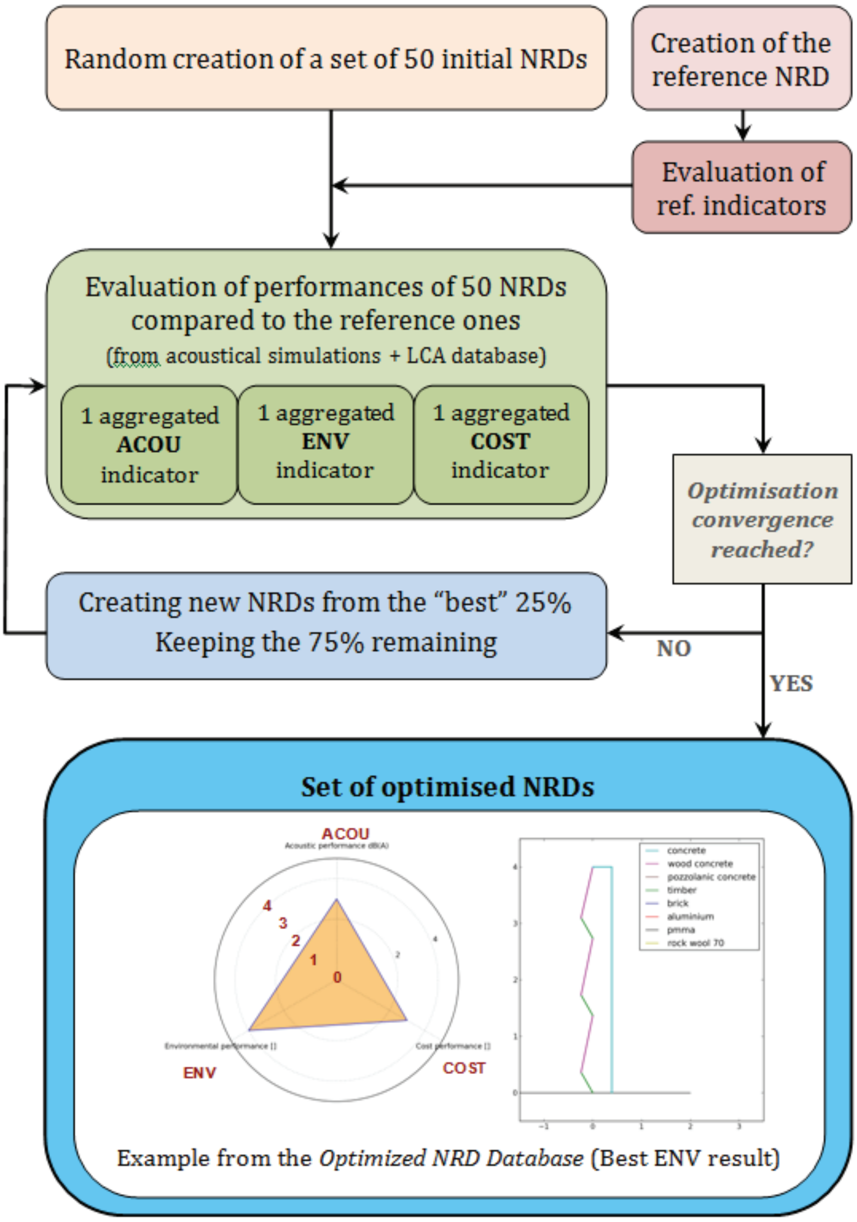


Figure 46: General flowchart of the holistic optimisation methodology

5.4.2 *Application to typical NRD families*

This holistic optimisation methodology has been applied to acoustic and non-acoustic performances of 4 generic NRD families (Fig.47) in different environmental situations including road and railway sources, rural (absorbing ground) and urban (rigid ground) areas, as well as flat, embanked (+5 m) and depressed (-5 m) topographies [12].

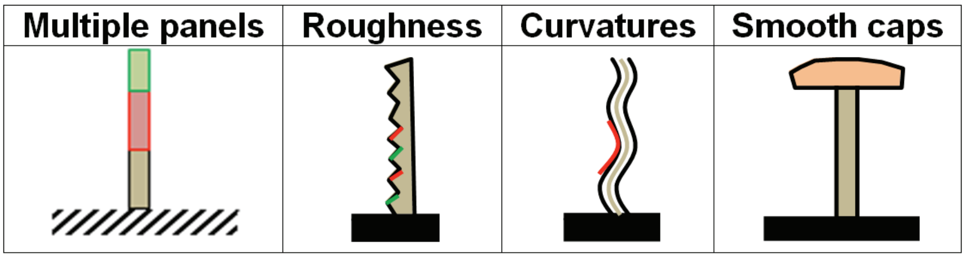


Figure 47: generic NRD families considered for the holistic approach

A grading system [12] has been applied to the 3 aggregated indicators in order to express them on a dimensionless scale ranging from 0 (bad) to 4 (very good). A radar plot display is recommended to present these 3 global NRD performance indicators.

5.4.3 *Optimized NRD database*

All extrinsic NRD optimisation results were recorded in a **database** that can be queried through a simple, complete reference tool. A first step consists in selecting the type of source as well as the environmental configuration, the infrastructure topography and the NRD family tested (Fig.48).

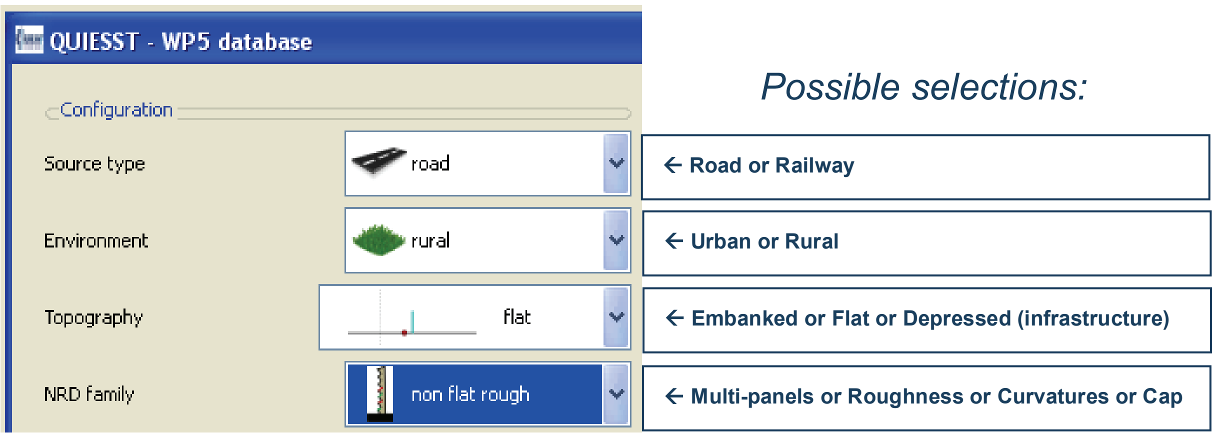


Figure 48: Query parameters of the Optimized NRD database

One also may select one of three following configurations for calculation of the *ACOU* indicator: receiver at the source side only (sound reflection), receiver at the receiver side only (sound diffraction), or receivers on both sides.

Then, in a second step, the user has to select one optimised solution among the set of final optimised NRD obtained at the end of the optimization process described in Figure 46.

To do so, the user should tune the three aggregated indicators *ACOU*, *ENV* and *COST* to the desired weights (in percentage), 0%, 50% and 100% meaning minimum, medium and highest importance, respectively (Fig.49).

For instance, in order to select the solution corresponding to the best *ACOU* aggregated indicator (whatever the *ENV* and *COST* indicators), one has to tune as follows: *ACOU*=100, *ENV*=0, *COST*=0.

One can also display all results one by one using the function “individuals”.

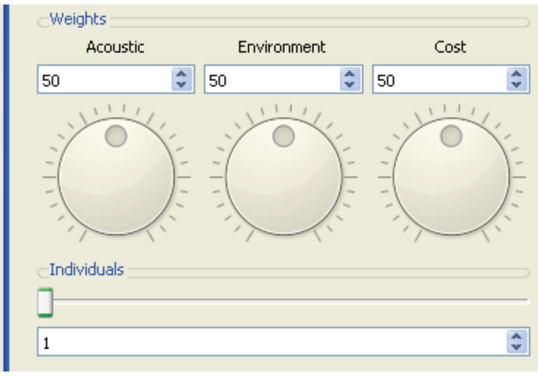


Figure 49: Weighting the 3 aggregated indicators ACOU, ENV and COST

Finally, the selected optimised solution is displayed, as shown in Figure 50, giving the following information:

- The *general* shape of the optimised NRD in a vertical section,
- Materials used and their location on the NRD surface,
- The NRD optimisation shape parameters (width, tilting, roughness size, etc.)
- The corresponding values of *ACOU*, *ENV* and *COST*

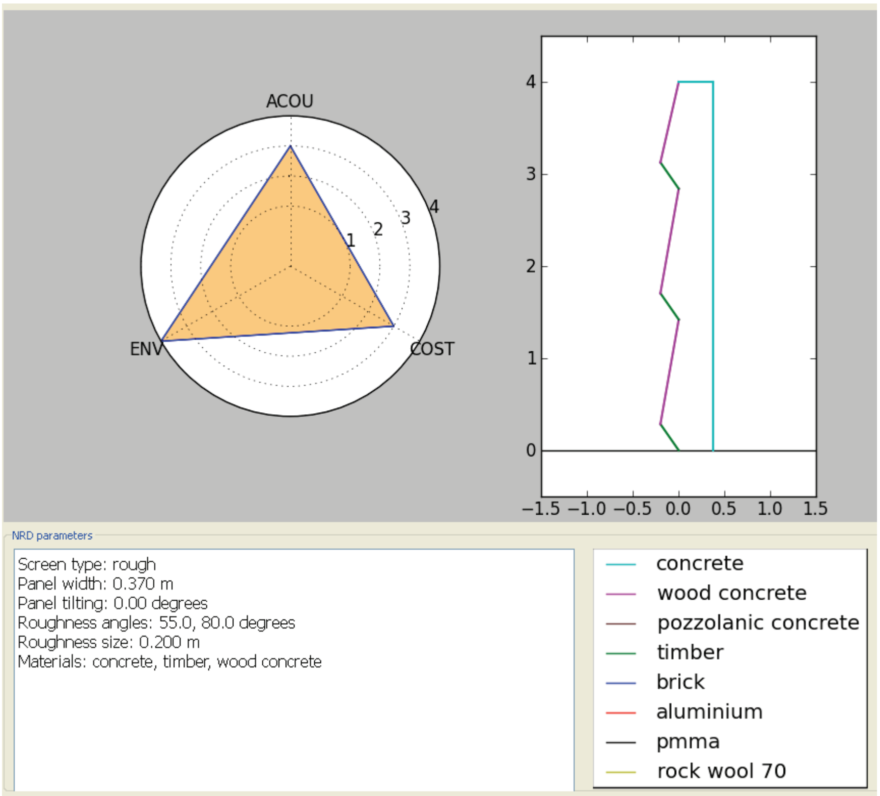


Figure 50: Example of result displayed by the Optimized NRD database tool

5.4.4 *Example of use of the Optimized NRD database*

An example of typical results one can get from the database is presented hereafter.

Considering the case of a strongly non-flat barrier along a motorway on a flat, rural terrain with the receiver at the source side only (sound reflection), we extracted three solutions optimised in priority for ACOU (Fig.51), ENV and COST (Fig.52), whatever the values of the two other aggregated indicators: one may note the great diversity in shapes and materials used depending of the choice of the indicators' weightings.

This database could be re-used and adapted at the upstream phase of future traffic noise impact projects in order to globally assess the potential acoustic gain that may be obtained by optimising (in shape and in material type) a conventional noise barrier taking also into account both the environmental impacts and the cost efficiency.

This database, as well as the whole process that was developed to create it, may be thus considered as a first step toward a comprehensive decision support tool dedicated to NRD.

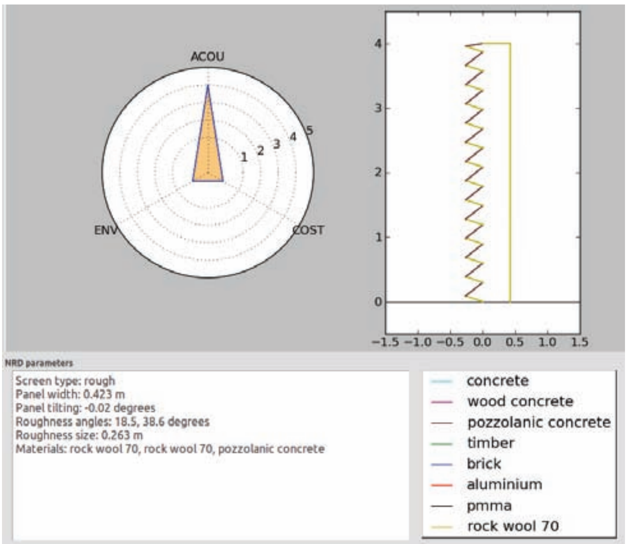


Figure 51: Results from the Optimized NRD database obtained for a high ACOU value

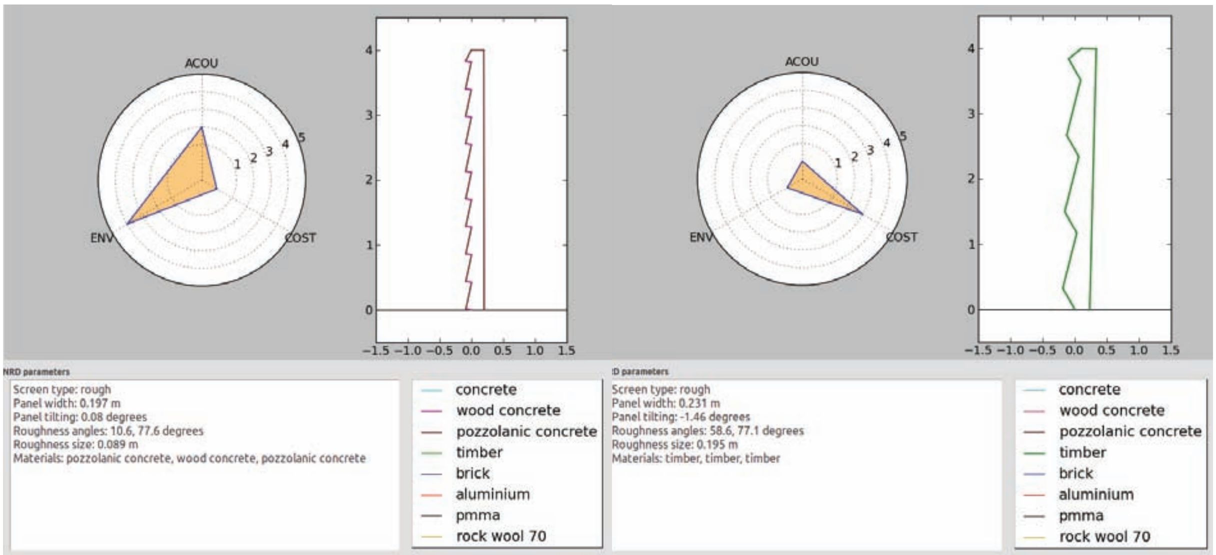


Figure 52: Results from the Optimized NRD database obtained for a high ENV value (left) or a high COST value (right)

5.5 Global impact

We also aimed at using the previously optimised NRD and placing them in a realistic 3D built environments [13]. With the use of a sophisticated multidimensional interpolation model developed in [14] and a ray tracing method OASIS developed at CSTB (Fig.53), we showed the ability to determine how much these optimised NRD allowed reducing the amount of people exposed to high noise levels.

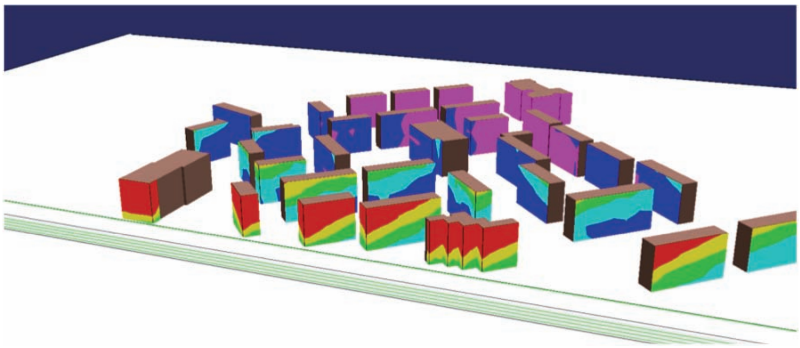


Figure 53: View of OASIS software integrating optimized NRD with facades noise maps

5.5.1 *Application*

Three different types of dwellings along a motorway were considered: collective (21 mH), semi-collective (9 mH) and individual housings. Different optimised NRD were tested. Final results were given through **histograms** showing for each of the studied cases (depending on type of optimised barrier, type of dwelling, road infrastructure) the proportion of inhabitants subject to a sound level abatement (L) by step of 1 dB(A) (Fig.54).

In this approach, we distinguished people living at lower, intermediate and upper floors.

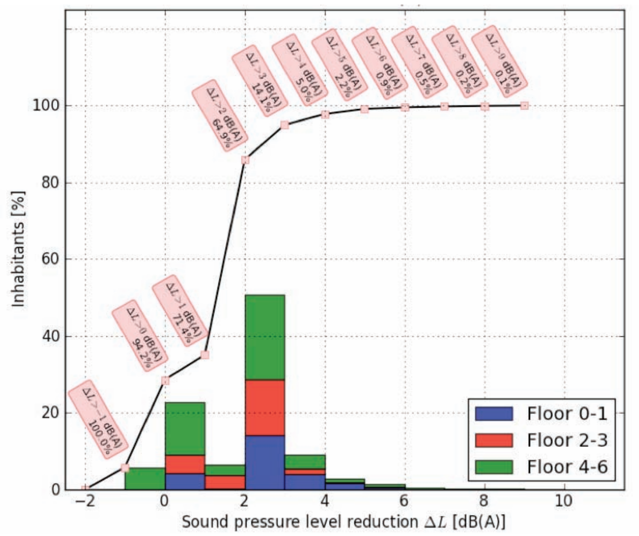


Figure 54: Example of sound level reduction histogram

We also calculated the *population exposure indicator* difference $L_{den,pop}$ [15] that represents the difference between the $L_{den,pop}$ obtained with the reference NRD and the $L_{den,pop}$ obtained with the optimised NRD in terms of global sum of noise level of all residents on the most exposed facades: values of L ranged from 0 to 8 dB(A), when average values on all receivers $L_{den,pop}$ were from 0 to 5 dB. The highest values of L were obtained for:

- the lower (ground and first) floors of the semi-collective housing,
- the 2nd and 3rd floors of the individual housing,
- the upper floors of the collective housing.

Another way of presenting global results is to give for a specific case the proportion of population benefiting from a noise abatement of at least 3 dB(A).

In this research, depending upon the type of optimised barrier and type of dwellings considered, the proportion varied from 1% to 70%, pointing out that:

NRD optimisation should be realised for very specific noise situations (sources/environment/receivers location).

6 Work Package 6 (WP6) Sustainability

6.1 The Importance of Sustainability for NRD

NRD are a growing part of Europe's transport infrastructure: a key objective of the Commission of the European Communities' White Paper on European transport policy (COM(2001)370) 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 NRD options. As such there is an urgent need for **more sustainable noise reduction devices (NRD)**, as there is a current worldwide lack of support for practitioners in this area.

The problem is not a minor one when one considers the size of typical projects which have to incorporate the complexities of the designing task, the enormity of construction work, as well as the resources required to maintain and eventually remove NRD once they have reached the end of their life cycle.

In fact, NRD can use as much resources and have as much of an impact on the built environment as many other large built structures. For example, typical installations of noise barriers may be 2 km, or 4 km if both sides of the carriageway are treated. A typical height is 4m which means that the total area of the erected noise barrier is 16,000 m^2. At an average installed cost of approximately 120 euro/m^2 for a timber option this amounts to a total resource cost of nearly 2m Euro. 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 (see Fig.1 for an example of a transparent NRD near Lugano in Switzerland designed by Sir Norman Foster).

The expenditure of this scale of public funds underlines **the need for the sustainability of NRD to be considered at *all* stages and, in particularly, in the design and procurement process where often lowest installation cost has greatest weight in the decision process**. It also implies that policy makers and industry professionals/designers be aware of the growing sustainable agenda for surface transport systems including the supporting infrastructure and the need for action to address current inadequacies.

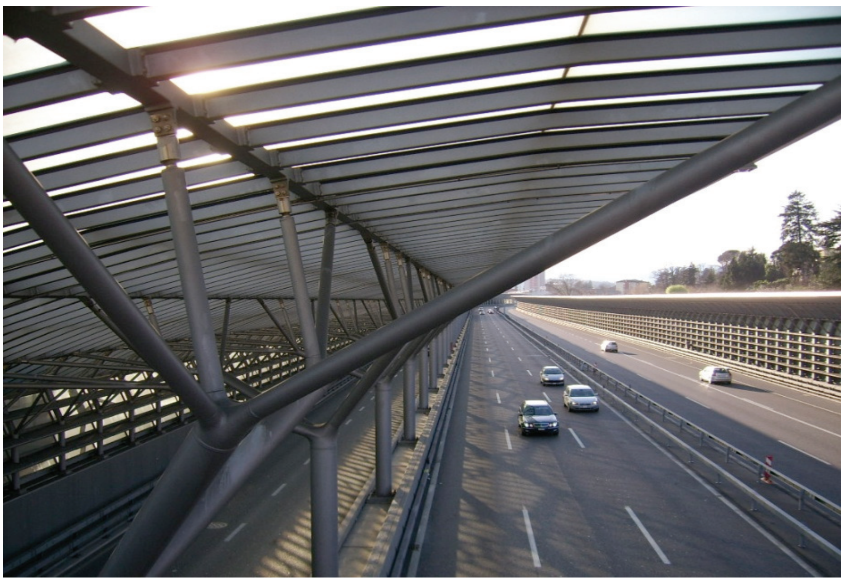


Figure 55: View of a transparent barrier / road cover near Lugano, Switzerland

To be fully compliant, all aspects of sustainability (technical, social, environmental and economics) of NRD *must be assessed at each stage* of the NRD lifecycle, namely: design, construction, usage, maintenance and repair, and demolition / removal (Fig.56).

Figure 56: Principles of Sustainability for NRD

Assessing sustainability involves measuring and evaluating many and conflicting attributes in an unbiased way. In order to assist the relevant stakeholders to assess the sustainability of NRD projects with the view to complying with and supporting the transport and overall global sustainability agenda, the following key novel QUIESST outcomes are presented herein for the industry:

1. **Definition of NRD Sustainability:** a relevant definition of sustainable NRD, which the relevant stakeholders could utilise for purposes such as designing, managing, and procuring more sustainable NRD, is given.
2. **Sustainability Key Performance Indicators for NRD projects:** a set of relevant sustainability key performance indicators for measuring, monitoring, benchmarking, and reporting aspects critical to the sustainability of NRD projects is presented and discussed.
3. **The relevant generic set of sustainability assessment criteria and indicators for assessing the whole life sustainability of NRD projects:** the primary set of systematically researched and industry validated set of criteria that represents assessing the whole life sustainability of NRD projects is presented and discussed.
4. **Generic database of sustainability criteria values per main NRD type:** Table 2 lists the 13 main NRD types considered for sustainability. From using the relevant generic set of sustainability assessment criteria established, the indicative database of sustainability criteria values for the 13 main NRD types, i.e. their sustainability performance, across their whole life has been produced.
5. **The Decision Making Process for Assessing the Sustainability of NRD via a Multi Criteria Analysis Approach:** the overall approach for assessing the sustainability of NRD options using selected sustainability criteria is presented and discussed.
6. **An example analysis for Assessing the Sustainability of Noise Barriers** using three different MCA methods and generic sustainability data is presented and recommendations on how to use these methods are also given.

Table 2 - Main NRD Types considered for sustainability

No.	Key	Noise Barrier
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
11	GA	Gabion with stones
12	EB	Earth barrier(earth berm)
13	PVNB	PVNB (photovoltaic noise barrier)

As a result of the research work, the above will assist the relevant stakeholders, such as transport/noise policy makers and national road and rail authorities - and consultants, contractors, asset managers, and the relevant manufacturers - to prepare tenders and bids in their procurement related activities that can show a demonstrable commitment to achieving sustainability related objectives with respect to NRD.

6.2 Defining 'Sustainability' for NRD

It is important to first define sustainability in order to understand what we are trying to measure and assess within the context of NRD projects.

There are many definition of sustainability, but in order to provide a practical and contextual definition the relevant stakeholders could utilise, NRD sustainability has been broadly defined as the following: ***'The optimal consideration of technical, environmental, economic and social factors during the design, construction, maintenance and repair, and removal/demolition stages of NRD projects'.***

Figure 57 illustrates how sustainability factors should be incorporated throughout the lifecycle of NRD.

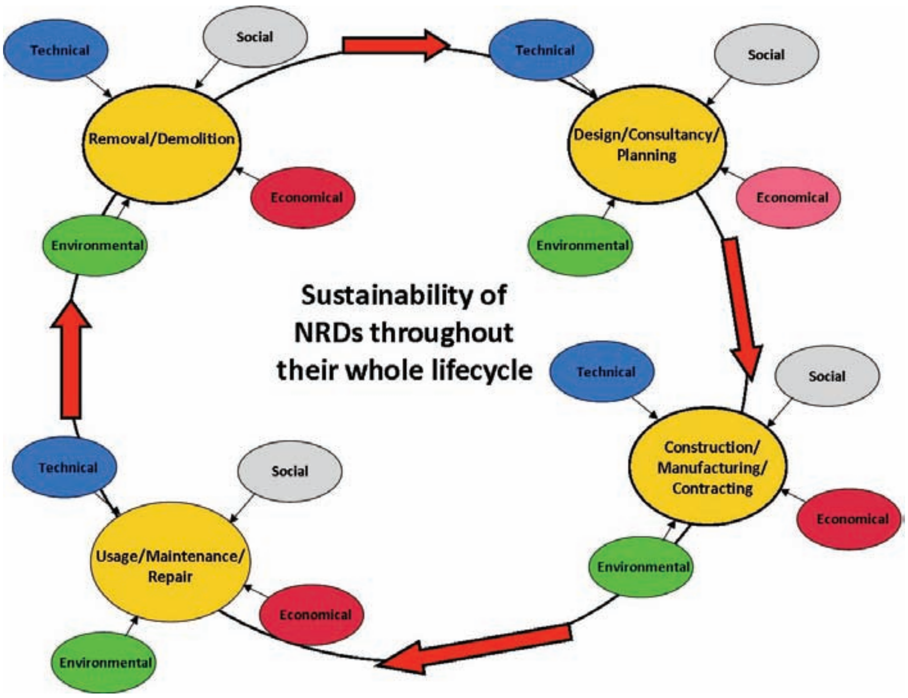


Figure 57: Sustainability factors to consider throughout the whole lifecycle of NRD

Additionally, the state of the art review and sustainability gap analysis on NRD sustainability confirmed that the above factors were not being fully considered across the whole life cycle of NRD, and considerations such as: the whole life cycle cost, calculating the carbon footprint, engaging with impacted communities, or designing solutions to prevent the effects of climate change, were not common practices in the procurement and management of NRD.

This in turn provided the basis to develop an appropriate assessment method using relevant to generic sustainability criteria to support the aforementioned.

6.3 Sustainability Key Performance Indicators for NRD projects

Various commentators have described the use of Sustainability **Key Performance Indicators (KPIs)** as essential components in the overall assessment of progress towards sustainable development. They are useful for monitoring and measuring the state of the environment by considering a manageable number of variables considered critical to sustainability. Table 3 shows the subsequent generic set of sustainability KPIs for NRD projects.

Table 3 - Generic set of sustainability KPIs for NRD projects

KPI n° per Sustainability Factor	NRD Sustainability Assessment Criteria	Key Performance Indicator (possible way of measurement)	Benchmark to Improve Sustainability Performance
Social	**Acoustic comfort**	No. of complaints from residents	Reduce
	Work related sicknesses and Injuries	No. of reported health incidents/work related injuries due to working conditions	Reduce
	Vulnerability of the barrier to vandalism	No. of reported acts of vandalism to the NRD (includes graffiti)	Reduce
	Glare control for road users	No. of reported road accidents due to the glare from the noise barrier to the emergency services	Reduce
	Crossing facilities such as footbridges/ underpasses	No. of complaints from the impacted community due to the lack of adequate crossing facilities	Reduce
	Acceptance of the architectural design of the NRD	No. of complaints due to the architectural design of the NRD	Reduce
	Loss of view for residents and road users	No. of complaints from residents and road users due to loss of views	Reduce
	Barrier design/type via public consultation	No. of projects that included (and implemented) a stakeholder engagement plan	Increase
	Use of local companies and labour	No. of local companies employed/No. of local labour opportunities realised	Increase
	Social acceptability of the NRD	No. of complaints from residents	Reduce
Technical	**Use of new materials**	% new(virgin)material content/m3 or m² or m	Reduce
	Use of recycled materials	% recycled material content/m3 or m² or m	Increase
	Local materials	% local material content/m3 or m² or m	Increase
	Whole barrier service life	Years	Increase or maintain
	Acoustic durability in-situ	years (yrs) until acoustic performance drops below the accepted level	Increase or maintain
	Buildability/constructability of the noise barrier	square meter/day to build the noise barrier system	Increase
	Durability	No. of years the NRD system can be used in comparison to its design life	Increase
Environmental	**Loss of land**	'Footprint' (m²) of the NRD/m or total length	Reduce
	Overall waste production	kg/m²	Reduce
	Materials used for energy recovery at the end of its life	% material recoverable for energy/m²	Increase
	Recyclability potential	% recyclable /m²	Increase
	Re-use potential	% re-usable/m²	Increase
	Carbon footprint (global warning potential)	kg CO2equivalent/m²	Reduce
	Water footprint	litre/m²	Reduce
	Embodied energy content (Use of primary energy resources/consumption)	MJ/m²	Reduce
	Renewable energy production (Photovoltaic/small scale wind turbines)	MJ/m²	Increase
Economic	**Capital costs**	Euro/ m²	Reduce
	Maintenance and repair costs	Euro/ m²	Reduce
	Removal/replacement costs	Euro/ m²	Reduce
	Income generation	Euro/ m²	Increase

Hitherto, no research informed set of sustainability key performances indicators specifically for NRD projects existed for the relevant stakeholders. The use of a set of industry and project specific sustainability KPIs will allow the relevant stakeholders to measure, monitor, benchmark, and report on key sustainability related issues for NRD. Using these sustainability KPIs could aid meeting compliance with developing and established legislations/standards related to: sustainability reporting, procurement, sustainability monitoring, and decision making.

6.4 Relevant Generic Sustainability Criteria for Assessing the Sustainability of NRD

Sustainability criteria highlight issues that are important for sustainability assessment: primary criteria are not usually measurable, and will typically have a set of secondary criteria below them which define the primary criteria. Secondary criteria underpin the primary criteria and are specific to the primary criteria under consideration. They are measured through the use of indicators. Indicators are the 'Unit of measurement' for secondary criteria which may be either quantitative or qualitative. In some cases, secondary criteria may have further attributes/tertiary criteria that define them further and are measured through the use indicators, too. This hierarchy of criteria levels can carry on as much as necessary; however, typically there are no more than 3 levels. Figure 58 shows the sustainability assessment framework for NRD and its cascading structure for ordering criteria and indicator sets.

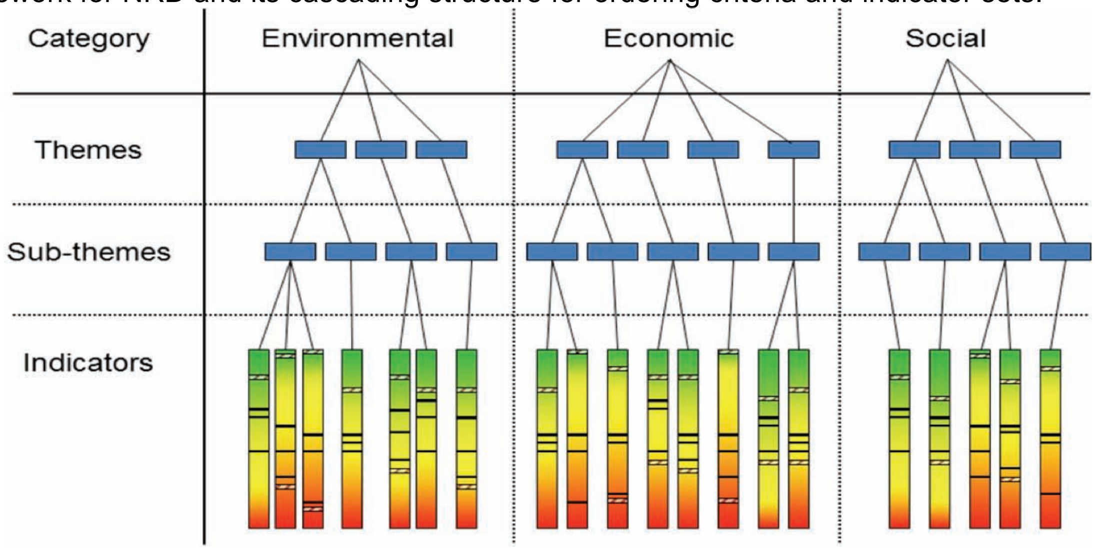


Figure 58: Sustainability framework for NRD and the structure for ordering their criteria and indicators

A 'Top-Down-Bottom-Up (TDBU)' research strategy was developed and implemented to create and validate the relevant generic set of sustainability criteria for NRD projects. This mainly involved gathering expert opinion from the relevant stakeholders involved with NRD through a series of workshops, questionnaires and interviews. Table 4 shows the resulting 22 sustainability primary criteria defined for NRD. These '22 primary criteria' respectively highlight all the major issues to consider, and so assess, across each sustainability factor. In total, 141 criteria form the complete sustainability hierarchy for NRD, of which, 92 are directly measurable. The TDBU research results highlighted a general consensus amongst the stakeholders in supporting the initial set of sustainability criteria, whereby 93% of the total proposed criteria were rated as 'moderately important-very important' by the stakeholders.

Table 4 - Summary of sustainability factors and primary criteria ranked in order of importance

Sustainability Factor	Primary Criteria
Technical	-Material selection -Buildability/constructability -Flexibility and adaptability
Environmental	-Energy -Land use -Air quality and climate change -Flora and fauna -Water -Waste
Economic	-Life cycle cost -Green value - Financial sources -Compensation cost -Affect on local residential/commercial property prices -Contractual and procurement type
Social	-Safety and security -Health and well-being -Severance/separation -Social acceptance -Architectural design and local context -Community engagement -Local employment and engagement with local business

However, it should be noted that **optimising a particular criterion in isolation, e.g. cost and technical performance, does not necessary increase the sustainability of NRD projects**. Indeed, it is the combination of the outcome of *all* measured criteria in relation to each other in an equitable way within the defined sustainability framework which shows the relative sustainability of the project as a whole. Multi Criteria Decision Making (MCDM) tools offer one viable approach to assessing multiple NRD sustainability criteria in conjunction with each other in an unbiased way to generate an index value to denote overall sustainability performance.

6.5 Generic database of sustainability criteria values per main NRD type

Using the generic set of NRD sustainability criteria previously established, research was carried out to generate and collect indicative sustainability criteria values for the 13 main NRD types across their whole life. The research results were tabulated into a database and as a result the sustainability performances of the 13 main NRD types can be viewed and compared. However, the database is too large to be practically presented within this guidebook. As such, Figure 59 below provides a description and overview of the database of sustainability criteria values per main NRD type.

The generic database of sustainability criteria values per main NRD type can be used to either:

1. benchmark the sustainability performance of a given NRD type with respect to the average/generic data provided in the database for the NRD type in question, or
2. use the generic data in place of collecting site/system specific data when it is considered impractical (or in some cases not necessary) to conduct the sustainability assessment, and so reduce significant analysis time and costs.

Such transparency in the performance of sustainability related issues per main NRD type can in turn drive competitiveness and innovation to develop and design more sustainable NRD solutions, as the presented data can be used for the creation of scenarios and for conducting quickly ‘what if’ projections.

Overall, the developed database of generic sustainability criteria values per main NRD type will assist the relevant stakeholders to conduct tentative analyses using generic data and thus determine the sustainability of NRD options.

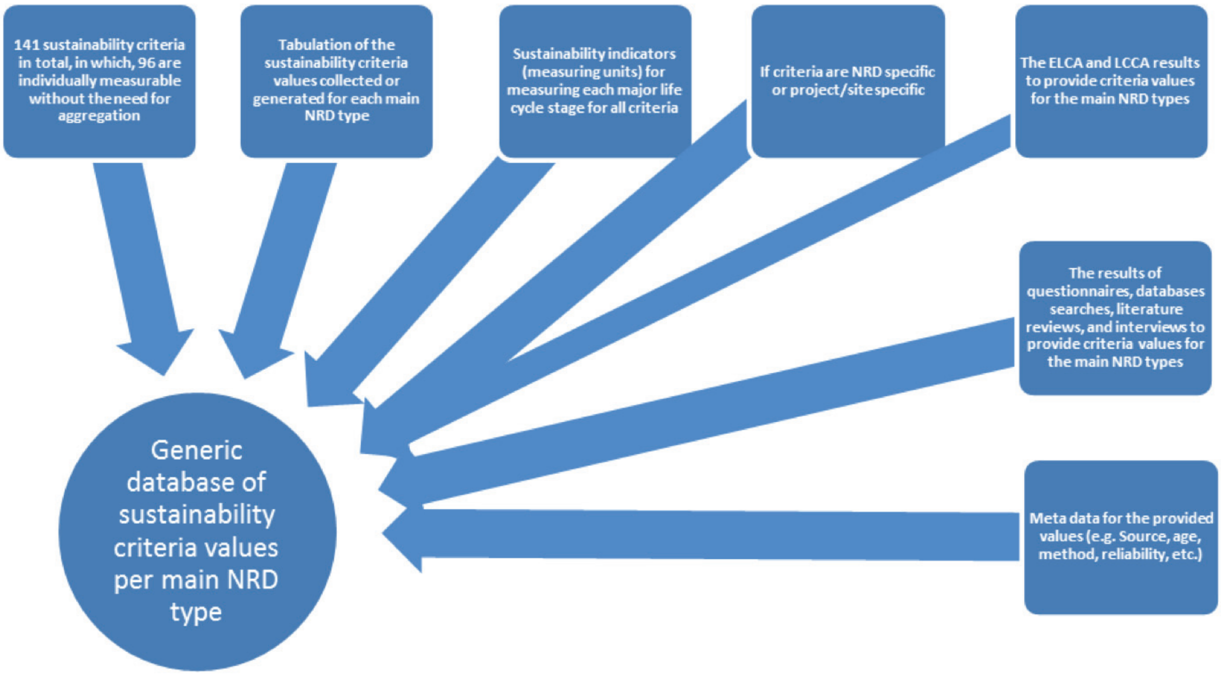


Figure 59: Key highlights of the generic database of sustainability criteria values per main NRD type

6.6 The Stages for Assessing the Sustainability of NRD via Multi Criteria Analysis Approaches (MCA)

The assessment of the sustainability of NRD is a multi-criteria analysis (MCA) problem as it involves selecting and assessing multiple conflicting NRD sustainability criteria. Figure 60 shows the main stages for assessing the sustainability of NRD via MCA approaches.

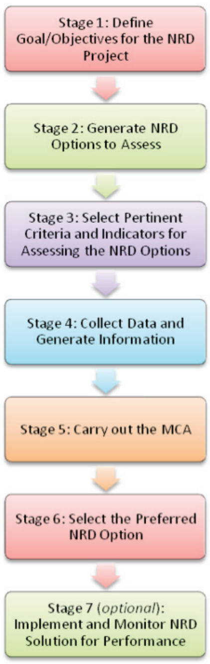


Figure 60: Stages for assessing the sustainability of NRD projects

Figure 60 highlights the logical order and key stages to follow in assessing the sustainability of NRD. Of importance, Table 5 below lists recommended analytical/data generating tools for efficiently generating criteria information for completing Stage 4, and so data for the MCA, whilst Table 6 lists recommended MCDM tools ranging from simple-to-complex for carrying out the MCA to assess the sustainability of NRD by scoring or ranking them from the point of view of their overall sustainability.

Table 5 - Recommended analytical/data generating tools for generating criteria information for carrying out the MCA

Environmental	Economic	Social	Technical
E-LCA (Environmental Life Cycle Analysis)	LCCA (Life Cycle Cost Analysis)	S-LCA (Social Life Cycle Assessment)	Relevant NRD EN Standards
EIA (Environmental Impact Assessment)	CBA (Cost Benefit Analysis)	SIA (Social Impact Assessment)	-

Table 6 - Recommended MCDM tools for carrying out the multi criteria analysis (MCA) to assess the sustainability of NRD

MCDM Tool/Technique for Carrying out the MCA	Pros	Cons
SAW/WSM (Simple Additive Weighting/ Weighted Sum Method)	-Easy to follow -No complicated calculations -Results are easy to understand -Audit trail easy to follow -Internal consistency and logical soundness -Non expert friendly -Realistic time and manpower resource requirements for the analysis process -Can be easily set up in MS Excel -High likelihood of being adopted by industry	-Limited scope to modelling criteria -Criteria must be independent of each other to avoid double counting -Is a 'trade-off' method
AHP (The Analytical Hierarchy Process)-	-Simple model to build -Logical process -Efficiently handles qualitative and quantitative attribute values -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. -Is a 'trade-off' method
SMART/SMARTS/SMARTER (Simple Multiple Attribute Rating Technique)	-True tree structure independent of alternatives -Results not affected by the introduction of new alternatives -Software not required	-Similar cons to SAW
TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)	-Internal consistency and logical soundness -Easy to follow -Intuitively appealing -No complicated calculations -Can be easily set up in MS Excel -Results are easy to understand -Simple index value given -Results can be easily shown graphically	-Large number of procedures -Large number of computations -Provides an overall result -Is a 'trade-off' method
Dominance Method	-Little to no mathematical calculations required -Low time and manpower resources requirements for the analysis process -Easy to follow -No need for software -Results can be shown graphically	-Criteria are not weighted -Audit trail may be difficult to follow -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 - can be used to choose, rank, and sort alternatives -is a 'non-trade-off' method	-High cognitive strain -Not transparent -Most likely will require an MCA expert to aid/carry out the analysis, or specialist software
PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluations)	- Encourages more interaction between the decision maker and the model in seeking out good options -Proponents argue that its outranking concept is more relevant to practical situations than the restrictive dominance concept -is a 'non-trade-off' method	-Similar to ELECTRE -High cognitive strain -Requires the use of specialist software to practically implement

Any one of the above recommended MCDM tools are able to generate a sustainability assessment index score in the range 0 to 1 or -1 to 1 for potential design and build NRD solutions, or built and operating NRD projects, relative to either the set of alternatives considered, or to a user defined baseline. Each MCDM tool is relatively easy to follow and time efficient to conduct analyses with once one is fully trained in using the selected MCDM tool(s) and, where applicable, relevant software packages. As each method is able to solve MCA problems and offer an index value, it is ultimately up to the stakeholder which approach they prefer and how detailed they wish to make the conclusions from their assessments.

Indeed, the generation of index values to denote the overall sustainability in the range 0 to 1 or -1 to 1 (depending on the MCDM tool selected) is a useful feature as it will allow the relevant stakeholders to test solutions and conduct 'what-if' analyses for: design and build NRD projects, built and operating NRD, and construction products related to NRD projects in the aim of improving the overall score. This effectively allows one to test integrating issues of designing and implementing low carbon strategies to mitigate against the effects of climate change in parallel to considering social, economic, and technical related issues and select the 'best solution'. Conversely, solutions which aim to be technically proficient, such as having a high service life, low maintenance requirement, durable against extreme weathering, etc., can be compared against achieving low carbon and energy related objectives in a fair and unbiased way based on how criteria are selected. As such, many decision priority contexts could be generated using the generic set of sustainability criteria established for NRD.

Overall, the work completed here will allow for a universal approach to assessing the sustainability of NRD projects that will be consistent with the overall global transport sustainability agenda.

6.7 An Example Analysis of Assessing the Sustainability of NRD

An example of assessing the sustainability of a given NRD type (a steel noise barrier) using a small set of selected criteria and generic NRD sustainability performance data is given below. Table 7 shows the three Multi Criteria Analysis (MCA) tools selected and the respective modelling requirements thereto for assessing the sustainability of the NRD.

Table 7 - MCDM tools selected to assess the multiple sustainability criteria selected for the example analysis

	MCDM Tool		
	SAW	**PROMETHEE**	**ELECTRE 3**
Complexity (Simple, medium, complex)	Simple	Complex	Complex
MCDM tool classification	Compensatory/trade-off method	Non-compensatory/Non-trade off	Non-compensatory/Non-trade off
Produces a score to denote preference? (Yes/No)	Yes, [0,1] Index	Yes, [-1,1] Phi Net Flow	Yes, [0,1] Concordance Index
Software essential?	No	Yes	Yes
Criteria modelling requirements	OHIS raw criteria values	OHIS raw criteria values, indifference, and preference thresholds for the selected criteria	OHIS raw criteria values, indifference, preference, and veto thresholds for the selected criteria

It should be noted that the assessment of sustainability is always a relative concept.

There are principally two relative assessment approaches:

1. the sustainability assessment is relative to the set of alternatives (or options) being considered, or
2. the sustainability assessment is relative to an absolute state/user defined baseline.

Approach 1 is well-suited for design/planning/procuring selection problems, and approach 2 is well-suited for determining the absolute sustainability of a single existing built NRD project, i.e. the assessment is not relative to any other built project.

As the absolute sustainability assessment of a single built steel noise barrier project is required in this example, approach two is applicable. As such, it is necessary to define an Optimal Hypothetical Ideal Solution (OHIS) as the user defined baseline for conducting the sustainability assessment. The OHIS represents the best performing/best solution. Thereby, the steel noise barrier type in this example will be assessed relative to the OHIS in order to assess its sustainability in absolute terms.

Table 8 shows the performance matrix of the steel noise barrier type with respect to the sustainability criteria selected, and the modelled/defined raw OHIS criteria values, indifference, preference, and veto thresholds used for assessing the sustainability of the steel noise barrier example.

Table 8 - Performance matrix and modelled criteria parameters for assessing the sustainability of the example steel noise barrier type

		MCA Modelling Requirements			
		SAW	PROMETHEE/ELECTRE 3		ELECTRE 3
Sustainability Assessment Criteria (C)	Measured Criteria Values (Steel Noise Barrier)	Final Raw OHIS Criteria Values	Indifference Threshold	Preference Threshold	Veto Threshold
C1: Resistance of the barrier to vandalism (1-10 rating)	2	10	not required	not required	not required
C2: Social acceptability of the NRD (1-10 rating)	4	10	not required	not required	not required
C3: Recyclability potential (% recyclable/m²)	56.1	100	10	50	100
C4:Global warming potential at each life cycle stage (kg CO2equivalent/m²)	170.29	0.01	50	100	200
C5: Fabrication/manufacturing + installation cost (€/m²)	143.7	80	15	40	80
C6: Maintenance cost (€/m²)	85	40	7.5	20	60
C7: Removal/demolition cost (€/m²)	19.3	15	5	10	40
C8: Use of new materials (% new(virgin)material content/m3)	99	10	10	80	100
C9: Use of recycled materials (% recycled material content/m3)	1	100	10	40	100
C10: Whole barrier service life (Years)	30	50	5	10	80

The SAW, PROMETHEE, and ELECTRE 3 multi criteria analysis of the selected criteria and data shown in Table 9 have been carried out to assess the sustainability of the steel noise barrier example.

The OHIS was used to perform pairwise comparisons against (PROMETHEE and ELECTRE 3) and used to benchmark the steel noise barrier project's sustainability performance relative to it (SAW). Table 8 presents the relevant overall index values/preference scores generated by SAW, PROMETHEE, and ELECTRE 3 to denote the overall sustainability performance of the assessed noise barrier.

Table 9 - NRD sustainability preference index scores generated by the SAW, PROMETHEE, and ELECTRE 3 multi criteria sustainability analysis for the steel noise barrier type example

	NRD Sustainability Overall Preference/Index Scores for the Steel Noise Barrier Example	
	OHIS	**Steel Noise Barrier Type**
SAW	1	0.36
PROMETHEE	n/a	-1
ELECTRE 3	n/a	0.12

Each method has produced an absolute index/preference score in the range [0, 1] or [-1, 1] relative to the OHIS, whereby the higher the value, the more it is preferred. In each method, the OHIS has, as expected, scored considerably higher than the steel noise barrier type example used as this solution, based on OHIS raw criteria values defined, and thus represents the best performing/best solution. As such, the OHIS will always be ranked first or achieve scores close to being perfect. In practice, a concerted effort should be made to maximise the overall sustainability score or try to mirror the OHIS to achieve more sustainable NRD. Whilst a conclusion cannot be drawn based on ten sustainability criteria, only the results of the analysis for the Steel Noise Barrier presented in Table 8 show a relative low level of sustainability for all three MCA methods used.

While the complexity of the three MCA tools selected vary, the implementation of the PROMETHEE and ELECTRE 3 MCA methodology and use of the relevant software package(s) is relatively inexpensive and time efficient to conduct sustainability analyses for NRD projects once a member of staff is fully trained in using these. The capital cost to do this is very comparable to consulting a MCA expert, and so is considered by the researchers a worthwhile investment. Please note that the ELECTRE 3 software package is freely available and freeware packages also exist for the PROMETHEE MCA tool.

The relevant stakeholders can set up models like that described above to assess the sustainability of their own projects and conduct 'what-if' analysis for improving the overall sustainability score/index of the NRD project concerned. Such an approach will allow for a more objective, transparent, and unbiased approach in the procurement and management of NRD meeting sustainability related objectives, and justifying public expenditure.

6.8 Overall Benefits of the NRD Sustainability Research and Contribution to the State of the Art for the NRD Industry

NRD Industrial Associations have been directly involved in this research both at national and European level and relevant benefits are expected from a common approach in sustainability evaluation and assessment.

NRD manufacturers have always shown a great interest in sustainability assessment due to its construction products being developed due to the environmental need of reducing noise disturbance in residential areas. As a consequence a "green" approach is often present in procurement and installation of solutions and products to fit an environmental need.

Asking for sustainable products without a common and reliable method for sustainability assessment, may lead to confusion on the market and distortions in competition. A harmonised and reliable method in product sustainability evaluation is then the first benefit expected by NRD Industry.

The implementation of product and systems for noise reduction always implies a complex and long process involving all major aspects to be considered in sustainability MCA. Various social implications clearly emerge in the early stage of the design phase; technical aspects and the whole life cycle costs are to be considered during design, procurement and installation activities and environmental friendly materials are always preferred. Other products used for surface infrastructure currently require a simpler decision making approach.

Sustainability assessment method developed during this research for NRD may represent a valid ground to implement a similar approach in other sectors (i.e. safety barriers, lighting systems, etc.). A second important benefit for the market is represented by the possible enlargement of similar approach to the NRD related industrial sectors. The lack of a common assessment methodology has been the reason for a different concept of sustainability across Europe.

In northern European countries, social and environmental aspects are always dominating factors in NRD choice. NRD application may even been rejected if they do not properly address issues such as respect of the environment or acceptance from the residents. In the southern regions of the continent design and construction phases have often been driven by technical and economic matters.

The method(s) developed showed how all four factors will have to be considered throughout the whole lifecycle of NRD. It is to be remarked that common methods and approaches do not necessarily sacrifice needs emerging from different cultural and social backgrounds in various European countries. Criteria have been defined through a data collection performed in different counties. They are likely to cover the full range of criteria being used in decision making process. Weighting factors introduction when using MCDM tools allows for a flexible approach in sustainability evaluation.

At present, **industry training is required to not only promote the message of developing and implementing low carbon and sustainable strategies for NRD projects, but also for providing guidance on how to implement the main MCDM tools for assessing selected NRD sustainability criteria**. As such, there is scope to create jobs by providing this training to close this existing gap in the knowledge base for the NRD industry.

In the future, NRD Industry will be asked to face new challenges regarding product qualification and testing against legislation and standards. The new Construction Product Regulation (305/2011/EU -CPR) that will be in force in the second half of 2013 is promoting a new approach in products qualification based on the declaration of performance against seven essential requirements. With respect to the previous Construction Product Directive (89/106/EEC - CPD) some relevant new challenging requirements have been included.

Sustainability has been specifically addressed with the new 7th basic requirement (Table 10).

Table 10 - New requirements of the Construction Product Regulation (CPR) 305/2011/EU

CPD	CPR
1- Mechanical resistance and stability	1- Mechanical resistance and stability
2- Safety in case of fire	2- Safety in case of fire
3- Hygiene, health and the environment	3- Hygiene, health and the environment ***throughout the life cycle + safety of workers***
4- Safety in use	4- Safety and **accessibility** in use
5- Protection against noise	5- Protection against noise
6-Energy economy and heat retention	6-Energy economy and heat retention **Energy efficiency of construction work during construction and dismantling**
	7-Sustainable use of natural resources

A lot of work is needed to define common harmonised standards for all products in different fields of construction activities. Given that NRDs are considered “road equipments”, they are already covered by approved harmonised standards referring to EN 14388. Updating of the existing standard is then foreseen and **the method developed within this research project will be an essential aid to define evaluation procedures to meet sustainability as the 7th basic requirement**. The NRD industry can then benefit for coming first on the market with a full set of standards. A similar approach can then be propagated to other sectors of Road Equipment’s Industry with an evident advantage for the Surface Transport development agenda.

Various analytical tools have been applied within this research project to generate data for sustainability assessment; some MCDM tools have been recommended and applied. The approach has been considered to be flexible in order to meet the needs of various stakeholders. **Development of standards for the sustainability assessment of products introduced into the market will then help the NRD Industry but will also be a an essential tool for Public Authorities and Road Managers when implementing Public Procurement techniques**.

Guidelines have been presented for the first viable method for assessing the sustainability of NRD. The guidelines will assist the relevant stakeholders, such as transport/noise policy makers and national road and rail authorities - and consultants, contractors, asset managers, and the relevant manufacturers prepare tenders and bids in procurement related activities- show a demonstrable commitment to achieving sustainability related objectives with respect to NRD. **Further significant research outputs by the team concerned with NRD sustainability can be found within the main deliverable reports**.

Overall, the work completed here will allow for a universal approach to assessing the sustainability of NRD projects that will be consistent with the overall global transport sustainability agenda.

Within the targets and the scope of the Industrial Associations involved in the present research project the implementation and dissemination of sustainability assessment methods is a priority. The NRD market is expected to strongly increase in Eastern European Countries and outside Europe where transport infrastructures projects are being developed. In western part of the continent NRD will represent an important item in existing infrastructure refurbishment plans. **The MCDM for NRD sustainability has been designed and developed to fit both cases.**

7 References

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