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Holistic optimisation of noise reducing devices

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The work presented in this paper is part of the QUIESST European project, in which one of the objectives is to perform multi-objective holistic optimizations of noise reducing devices. We present here optimization results concerning the extrinsic performances of noise barriers. The performances under interest are acoustical, economical and environmental. The variety of noise barriers considered is very wide, ranging from straight and flat barriers, to rough or capped barriers. A total number of four noise reducing device families are optimized. Acoustical performances are obtained from numerical calculations: the Boundary Element Method (in 2D) is used to obtain relative sound pressure levels at a set of receivers in different situations. These situations include road and rail sources; rural and urban cases; flat, embanked and depressed topographies. The economical performance is calculated according to the maintenance cost of the different materials in use in the barrier. Four environmental performances indicators are considered; their calculation is based on a life-cycle assessment analysis. All performances are expressed as a gain (or loss) relative to a reference screen. It is shown that the optimization procedure allows one to obtain a wide variety of optimized noise reducing devices, and hence provides a helpful design tool by allowing one to focus on specific parameters.

1 Introduction

We focus in this work on extrinsic performances of Noise Reducing Devices (NRDs). We consider acoustic performances as well as non-acoustical ones. Environmental impact is assessed trough life-cycle analysis and costs of noise reducing devices are also considered. The aim is to optimise the NRD performances simultaneously using numerical simulations. Note that the objective of this research is not to deliver optimised noise barriers. These solutions would depend on too many parameters that could possibly be accounted for in numerical simulations. The main objectives of the present work are a) to determine whether or not it is worth performing any optimisation on the noise reducing device performances and b) to assess the potential gain that can be achieved through these optimisations.

In this paper a first section presents the different environmental situations that are addressed. Section 3 presents the evaluation method of non-acoustical parameters while section 4 explains the execution of optimisations and provides an analysis of optimisation results. Conclusions are finally given.

2 Definition of environmental situations to assess

The aim of this work is to optimize, using numerical simulations, the acoustical performance of noise reducing devices in different environmental situation. In order to assess the barriers efficiency, virtual receivers are placed on each side of the barrier. Hence two groups of 6 receivers are placed on the left and on the right side of the barrier. Within each group, three receivers are placed at a height of 2 m and three are at a height of 4 m. The distance between two consecutive receivers is 2 meters. The distance from the barrier to the groups of receivers depends on the environmental situation under study; these situations are detailed below.

2.1 Types of environments

Two different types of environments are considered in this paper: rural and urban environments. Those two cases differ by the distance at which receivers are placed. In the case of an urban environment, receivers are at about 30 m away from the noise reducing device, and placed along buildings facades. The distance between the building facade and the nearest receiver is 0.5 m. In the case of rural environments, receivers are at a distance of about 100 m from the barrier.

For each type of environment, three types of topography are considered: flat, embanked and depressed topographies. Embankment and depression consist in steps of 5 m with a slope of 30°.

2.2 Types of noise sources

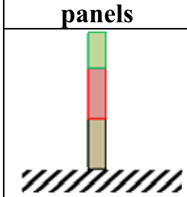
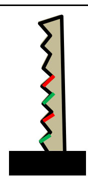
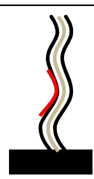
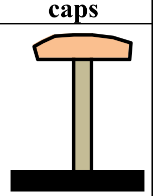
Two different noise sources are accounted for in this work: road and railway sources. The railway source is composed of a single point source above a ballast platform. The source is placed 5 cm above the height of the rail, at the centre of the right-most lane. The source spectrum used corresponds to the spectrum of the French TGV (at a speed of 300 km/h). Only rural environment is considered with railway sources.

The road source is 5 cm above an asphalt road. Depending on the type of environment (urban or rural) we consider a 2-lane road without shoulders (urban environment), or a 2x2 lane road with shoulders (rural environment). The spectra corresponds to cars at 50 km/h and 110 km/h, for urban and rural cases, respectively.

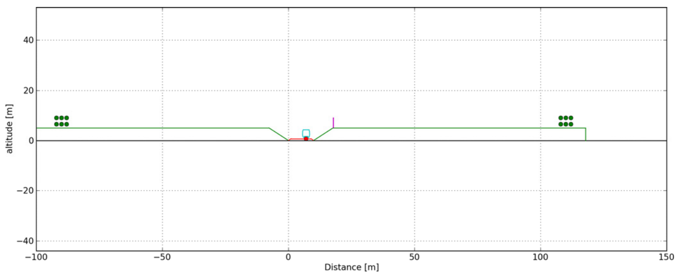
2.3 Types of noise reducing devices

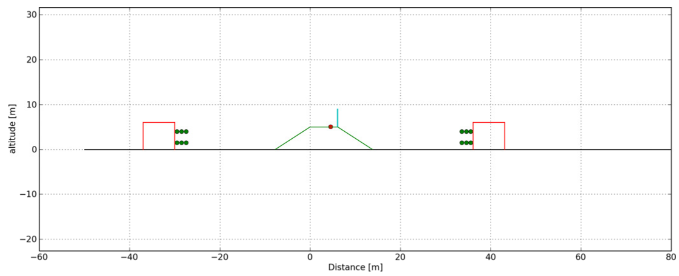
In a previous work, noise reducing devices were classified within 9 different families. In order to limit the computational times, we restrict the analysis to a group of 4 noise reducing device families. The studied barriers are shown in Table 1 below. Flat homogeneous noise reducing devices were also considered so as to obtain a reference.

Table 1: noise reducing device families considered

Multiple panels	Roughness	Curvatures	Smooth caps
			

Figures at the top of the next page show two examples: road source/urban/embanked case on the right and railway source/rural/depressed case on the left. On each figure the receivers are denoted by green dots, the source with a red dot.





3 Non-acoustical parameters

In this research we consider not only acoustical performances, but also performances relative to the environmental impact of the barrier and performance relative to its cost.

3.1 Cost evaluation

Economical parameters considered are:

- construction costs
- maintenance costs
- demolition costs

Demolition costs include transportation but do not consider material reuse. Construction and demolition costs (see Table 2) are taken from a document from the “Ministerie van Infrastructuur en Milieu” of Nederland. These figures relate the construction and demolition costs to the NRDs heights. Note that the hypothesis that the construction and demolition costs are independent of the main NRD material is made. This can be explained by the fact that the most important part of the costs do not come from materials, but manpower. On the contrary, maintenance costs depend on the main material used in the construction of the NRD (see Table 6). Note that the maintenance costs do not include repair costs from potential accidental damages.

Table 2: construction and demolition cost of noise reducing devices

NRD height [m]	Construction cost [€/m]	Demolition cost [€/m]
2	1449	312
4	2678	379
6	3884	446

Table 3: NRD maintenance costs depending on the main NRD material, per m² and per year

NRD height [m]	Construction cost [€/m²/year]
Concretes and bricks	2,93
Timber	1,46
PMMA	1,48

3.2 Environmental impact evaluation

In this paper, Life Cycle Assessment methodology has been automated to evaluate the environmental performances of many NRD solutions. In this particular case of study, some hypothesis had to be made about methods, indicators, functional unit, materials and life cycle steps involved.

Some of the main non-acoustical parameters considered in the extrinsic and holistic optimization are environmental parameters. Indeed environmental parameters are used to support environmental decision-making, such as industrial process optimization or the choice of environmentally friendly products. It has been decided to use LCA (Life Cycle Assessment) to perform the environmental assessment of the NRDs.

LCA is defined by the International Standards Organization (ISO). At national level, that LCA methods have been standardised in France through the **NF P 01 010 standard**: Environmental quality of construction products — Environmental and health declaration of construction products [1]. At European level, a harmonized standard is under development in the CEN/ TC 350: **prEN 15804** Sustainability of construction works – Environmental product declarations – core rules for the product category of construction products [2].

The results of a LCA are expressed as a set of environmental indicators. Based on the indicators interdependence and environmental relevance, the environmental parameters proposed for the holistic optimization are:

- Energy, expressed in MJ/Functional Unit,
- Global Warming Potential (GWP), expressed in kg CO_2 equivalent /Functional Unit,
- Waste (non hazardous and inert), expressed in kg/Functional Unit,
- Water consumption, expressed in liter/Functional Unit.

3.2.1 Functional unit

The functional unit provides a reference to which the inputs and outputs can be related. This enables comparison of two essential different systems. For this optimization phase of noise barriers, the functional unit chosen for the performed LCA is:

To ensure the function of noise reduction device during one year along one linear meter

The height of the noise barrier can vary in function of the studied NRD.

3.2.2 Service life

NRD’s environmental impacts are calculated for a year of service. Thus it is necessary to define the service life of each NRD. This is a complex task as it can depend of environmental conditions and material’s quality.

Thus it has been decided to consider the Reference Service Life of the NRD equal to the shortest lifetime of the different materials of the device. In order to define each material’s lifetime, we have assumed that all materials used in the NRD conception are very good quality materials. They are all supposed to last at least 20 years (timber’s considered lifetime). The Reference Service Life chosen, as well as material density, are given in Table 4. The calculated impacts of a NRD are then divided by this shortest lifetime of its components so as to obtain impacts per years of service life.

Table 4: material density and reference service life

Material	Material informations	
	Mass density [kg/m^3]	Reference Service Life [year]
Reinforced concrete	2400	50
Wood concrete	600	50
Pouzzolane concrete	1500	50
Brick	1000	50
PMMA	1190	25
Mineral wool	70	25
Timber	472	20

3.2.3 Considered materials

After carrying out a review of the literature about NRD's conception, and exchanges with acoustic engineers from CSTB, a list of the 7 most used materials for NRDs construction has been established and is: reinforced concrete, wood concrete, pozzolanic concrete, brick, PMMA, mineral wool, timber.

3.2.4 Hypothesis on NRDs lifecycle

In this LCA automation task, a partial assessment of the impacts of the NRD's life cycle is performed; it is only a part of a 'cradle-to-grave' assessment. Indeed, only the production of each material needed for the NRD assembly and its transportation to the implantation site are assessed here. Thus, the results of the LCA only correspond to the sum of the environmental indicators corresponding to production stage of the amount (i.e. the mass) of materials used for the construction of each type of NRD, plus a standard transportation mode.

It is well known that around 80 to 90% of the environmental impacts are usually attributable to the production phase. Although the processes to manufacture the NRD and to assemble the materials together are not considered, it can be stated that the most part of the impacts are assessed here.

The construction stage, the use stage and the end of life stage of the product are omitted in this optimization. Nevertheless, some hypothesis can be made on the following steps of the life cycle:

Transportation is not neglected here because previous environmental studies on noise barriers had already shown [5] that transportation can significantly affect the overall impacts of a NRD. The transport phase is mainly dependant to the travelled distance and weight of the NRD. Thus we decided to take into account a mean transport distance of 100 km for all NRDs. The added environmental impacts were calculated from the Ecoinvent 2.0 dataset untitled "*transport, lorry 20-28t, fleet average*", and are presented in Table 5 below.

Posts and fixating processes are neglected in this LCA automation, because it appeared too case-dependant and complex to automate.

Lastly, the end of life stage was not considered here. The waste indicator just shows the amount of inert and non dangerous waste due to the production of materials and transportation).

Table 5: Environmental indicators, for the transport of 1000 kg of material over 100 km

	Energy [MJ]	Global warming potential [kg CO2 eq]	Waste [kg]	Water consumption [l]
Transport, lorry 20-28 t, fleet average 100 T.km	299	19.3	2.82	77.6

3.3 Environmental indicators values for selected materials

According to the previous hypothesis, the table below presents the values of each four environmental indicators for the 7 main NRD's constituent materials. The calculated indicators values correspond to the production of one ton of each material, and its transportation over 100 km. Mass density and Reference Service Life are also informed for each material. The values presented here are carried out from the ECOINVENT LCA database, and modelled with the Life Cycle Analysis software SIMAPRO 2.4.7.

Table 6: Environmental indicators, for the production and transport of 1000 kg of material

	Energy [MJ]	Global warming potential [kg CO2 eq]	Waste [kg]	Water [l]
Reinforced concrete	1,14E+03	1,43E+02	2,42E+01	1,82E+03
Wood concrete	7,87E+03	3,67E+02	4,03E+01	1,69E+03
Pouzzolane concrete	5,46E+03	6,18E+01	5,35E+00	2,02E+02
Brick	3,02E+03	2,51E+02	7,17E+00	4,89E+02
PMMA	1,45E+05	8,40E+03	1,07E+02	2,03E+04
Mineral wool	1,92E+04	1,05E+03	3,39E+02	1,00E+04
Timber	2,22E+04	1,49E+02	2,47E+01	1,27E+03

4 Execution of optimizations and results analysis

To simulate acoustic propagation we use a 2D implementation of the Boundary Element Method (BEM, see [6], [7]), an efficient calculation method that allows us performing the simulations in a reasonable amount of time.

The optimisation model used is based on Evolution Strategy (ES) and Non-Dominated Sorting. Evolution strategy (ES) draws on the same principles as Genetic Algorithms (GA). There are however significant differences between GA and ES. First GA goes deeper in the analogy with living beings and distinguishes phenotype and genotype while ES operate on the phenotype only. GA operates on binary strings. So the search space is bounded and the variables are discrete. The different data type processed leads to a different mutation operator. The first algorithm of this kind was proposed by Holland [8]. More up to date presentations are available in [9]. The Non-dominated sorting genetic algorithm (NSGA) was proposed by Srivinas and Deb [10]. It is based on several layers of classification of the individuals. All non dominated individuals are classified into one category (they are then given an artificial fitness value), then this group is ignored and the process continues until all individuals have been classified (giving artificial fitness values always smaller than the smallest of the group creating before). There are the several Pareto borders. Any number of objectives can be considered with this method and the diversity of individuals in the research space is well kept; but the use of artificial values makes the implementation more complicated than for other.

The optimization procedure uses an Evolution Strategy algorithm which consists in populations of 50 individuals which evolve during (at max.) 10 generations for each of the four noise reducing device families. It resulted in about 2 000 function evaluations. Calculations were performed on two computers which sum up 20 processing units and 16 GB of RAM. Optimizations took several days to complete.

4.1 Representation of optimization results

The main objectives of the present work are:

- to determine whether or not it is worth performing any optimization on the extrinsic acoustical NRD performances and
- to assess the potential gain that can be achieved through these optimizations

In any cases the objective of this research of to deliver optimised "optimal sound barriers". Optimised performances as expressed as a ratio (or difference for acoustical quantities in decibels) to a reference noise reducing device. This reference noise reducing device is a straight, 10 cm thick concrete barrier.

4.1.1 Performances aggregation

Performances are aggregated according to their type:

- acoustical performances: insertion losses on both receiver groups
- environmental performances: energy consumption, global warming potential, waste production and water consumption
- cost performances: construction, maintenance and demolition costs

There is no weighting associated to these aggregations, i.e., the aggregated values are simply the arithmetic means of the concerned values.

4.1.2 Grading system

One hence obtains for each of the individual in the final generation 3 performance indicators:

- one acoustical indicator expressed as a gain (or loss for negative values) in dB compared to the reference noise reducing device
- one indicator relative to the environmental impact of the NRD, expressed as a ratio to the reference NRD
- one indicator relative to the cost of the NRD, expressed as a ratio to the reference NRD

The most efficient way of representing and comparing these three indicators for each individual is by using radar plots. Radar plots easily allow comparing several barrier performances together.

Hence a grading system is applied to the aggregated indicators. Concerning acoustical performances, the following grading system is used (ΔL is the improvement compared to the reference):

- ΔL > 12 dB => grade = 10
- 12 dB > ΔL > 9 dB => grade = 8
- 9 dB > ΔL > 6 dB => grade = 6
- 6 dB > ΔL > 3 dB => grade = 4
- 3 dB > ΔL > 1 dB => grade = 2
- 1 dB > ΔL => grade = 0

Concerning the environmental and cost performances, the following grading system is used (X is the ratio of the indicator value to the indicator value of the reference barrier):

- X < 0.1 => grade = 10
- 0.1 > X > 0.25 => grade = 8
- 0.25 > X > 0.5 => grade = 6
- 0.5 > X > 1 => grade = 4
- 1 > X > 2 => grade = 2
- X > 2 => grade = 0

4.2 An example: flat homogeneous barriers

In this section we present the optimisation results that concern the family of flat homogeneous noise reducing devices.

The last generation (generation #10) contains optimised individuals; optimisations are applied on acoustical performance of both sides of the screen, environmental performances (energy consumption, global warming potential, water consumption and waste production) and cost performances. These performances are then aggregated, and lead to three performance indicators: acoustical, environmental and cost indicator, as explained above.

Figure 1 to Figure 3 below show the radar plots obtained after post-processing. The figures show, for each performance indicator, the grade obtained, which is between 0 and 10.

One can see that the last optimized generation contains a wide variety of individuals. The individual shown in Figure 1 is quite good acoustically; the individual in Figure 2 has good environmental performances, while the individual shown in Figure 3 has mean performances.

Hence the developed optimization procedure and tools allow one to obtain a wide variety of optimized individual, in which one can choose, depending on the specific goal of the its application, the corresponding optimized barrier.

5 Conclusions

We developed in this research an optimisation process applied to noise reducing devices. These optimisations not only concern acoustical performances but also environmental performances as well as construction, maintenance and demolition costs. It was shown that the multi-objective optimisations lead to a wide variety of optimised barriers, and hence provide a helpful tool for NRD design.

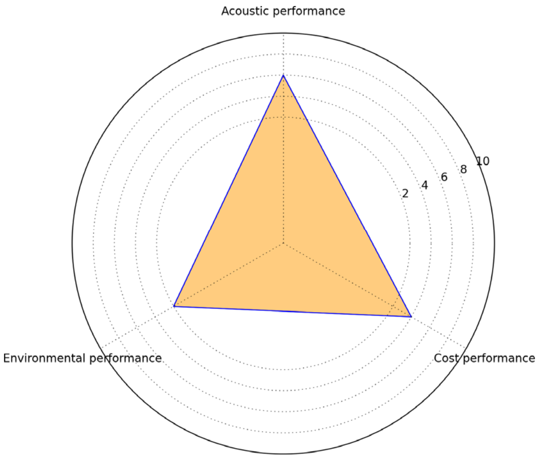


Figure 1: an optimized individual at the last generation

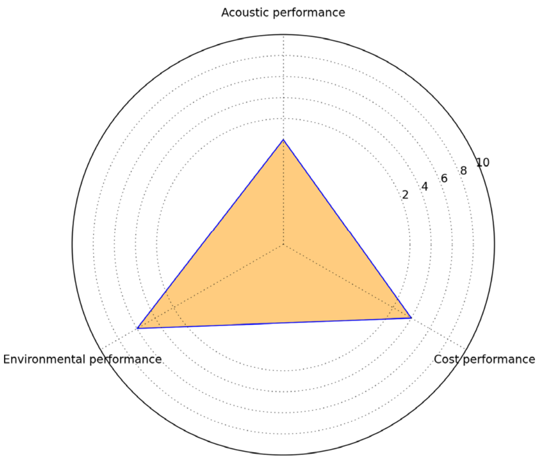


Figure 2: an optimized individual at the last generation

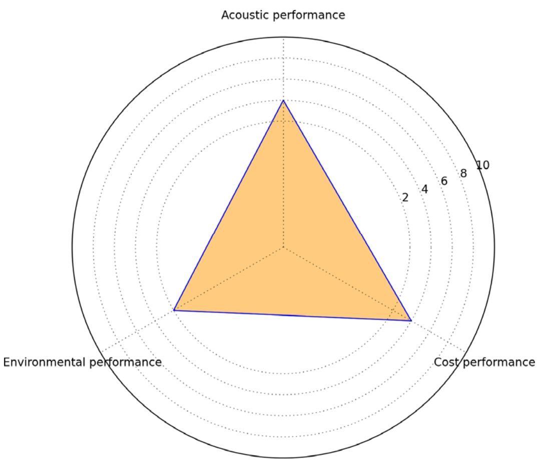


Figure 3: an optimized individual at the last generation

Acknowledgments

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