Sound Quality–Based Acoustic Optimisation for Construction Machine Operators

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Abstract

Numerical simulation is widely used in product design for different purposes ranging from structural modelling, FEM analysis, vibroacoustics to multi-objective design optimisation. Unfortunately, its application to Sound Quality is still extremely limited. This paper describes the use of a multi-objective optimisation code aimed at identifying noise control solutions which can improve the sound quality at the operator station of earth moving machinery during real working conditions. In a previous study the case of stationary noise signals was analysed and a multi-objective genetic algorithm was used to find the modifications in the input spectrum which led to the minimization of the time-averaged values of loudness and sharpness. In this paper the optimisation algorithm was modified to be applied to time-variant noise signals, characteristic of real working conditions. New input variables were identified to describe the time variant characteristics of the input signals and a numerical code was developed according to the DIN-45631/A1 procedure in order to properly calculate the loudness parameter of time-variant sounds. The new multi-objective genetic algorithm was finally applied to different noise signals recorded at the operator position of loaders in working conditions, with the purpose to find the modifications in the input system which minimised the percentile values of loudness and sharpness parameters. The results confirm the significant link between sound quality condition and frequency content of the noise signals, making it possible to evaluate the spectral variations needed to obtain psychoacoustic improvements.

INTRODUCTION

As in many other fields of application, besides the mandatory provisions, the construction machine industry is now oriented towards the sound quality approach [1]. Hence, at least in the last decade, research has been dealing with the identification of a set of acoustic and psychoacoustic metrics able to describe people's auditory perception of noise signals with respect to the annoyance sensation. Results from previous studies on these noise sources showed that Zwicker's loudness and sharpness are the parameters most related to the subjective perception of annoyance [2,3].

In the meantime, numerical optimisation has extensively been used in many fields of structural design to analytically foresee which modifications of a system best satisfy a desired target [4]. When applied to stationary noise signals recorded at the operator station of a compact loader in idle condition, the acoustical optimisation permitted to analytically identify which variation in the frequency content led to the simultaneous reduction of loudness and sharpness values. As a consequence, noise spectrum modifications able to simultaneously reduce these parameters seemed to be a promising approach for improving the acoustic comfort at the operator position [5].

The validation of this numerical approach was mainly based on subjective listening tests, specifically designed to verify whether the optimisation process led to noise signals subjectively considered less annoying than the original one. The subjective validation provided clear evidence regarding the relevance of the simultaneous reduction of sharpness and loudness in improving the Sound Quality with respect to the annoyance attribute.

This paper presents the adaptation of this optimisation code to the case of time-varying noise signals, which are typical of real working conditions. New input variables, appropriate to describe the time variant characteristics of the system, were identified and a numerical module for the correct calculation of loudness for time-varying sounds was developed according to the DIN-45631/A1 procedure. This new procedure was applied to some noise signals recorded at the operator position of two different compact loaders while these machines were performing the same work cycle with the use of material.

The optimisation process led to noise signals less annoying than the original ones by means of changes in the frequency content of the input signals. Then all these solutions were further analysed in order to choose, if possible, only those satisfying two main features.

First, the optimised signals had to comply with the expectations of the operators who should use the noise emitted by the machine as a feedback of its good state of operation. Second, the spectral changes resulting from the optimisation process had to affect frequency intervals characteristics of specific machine components (engine, cooling system, hydraulic system, ...). The purpose of these investigations was to identify potential noise control solutions to improve the Sound Quality at the operator position at the design stage, with great saving of time and costs.

THE NOISE SIGNALS

The optimisation process was applied to noise signals binaurally recorded at the operator position of two compact loaders (A and B), with different dimensions and mechanical power. Recordings were performed by means of a very lightweight device consisting of two miniature pre-polarised condenser microphones

Table 1. Acoustic/Psychoacoustic parameters of the signals used in the optimisation process

	Machines			***Machines***	
Parameter	***A***	***B***	***Parameter***	***A***	***B***
Leq (dB)	77.9	75.9	N_5 (sone)	28.1	31.0
LAeq (dBA)	68.0	70.4	N_{10} (sone)	27.3	29.9
Mean Loudness (sone)	23.0	25.1	N_{50} (sone)	22.1	25.9
Mean Sharpness (acum)	1.20	1.37	N_{90} (sone)	20.4	23.1
			N_{95} (sone)	20.0	20.9
Lp_5 (dB)	81.1	78.7	S_5 (acum)	1.35	1.56
Lp_{10} (dB)	80.1	77.8	S_{10} (acum)	1.30	1.52
Lp_{50} (dB)	77.2	75.3	S_{50} (acum)	1.19	1.42
Lp_{90} (dB)	74.4	72.9	S_{90} (acum)	1.10	1.31
Lp_{95} (dB)	73.6	72.1	S_{95} (acum)	1.08	1.28

positioned at the entrance of the operator's ear canals (binaural microphones B&K 4101). The noise acquisitions were carried out while the machines were performing the same work cycle which included two main operations: the loading of the material from a stockpile and the unloading of it in a specific position. Besides the noise signals, also the tachometer signal was recorded in order to relate at each time the frequencies of the noise spectrum to the rotational frequencies of the different components of the machine. In normal working conditions, the main periodic noise contributions by the machine components are all strictly related to the engine rotational speed. These noise contributions are primarily due to the engine injection cycles, to the engine cooling system and to the hydraulic system.

Previous investigations showed that the use of materials like gravel generates noise contributions which greatly affect the annoyance sensation but they are completely unrelated to the machine components [3]. For this reason, only the noise signals recorded when the machine was working with loam were considered for numerical optimisation. Figure 1 shows the measurement setup for binaural recordings.

The recordings had a duration of 7-8 seconds and included both the loading phase and the movement of the machine. Two different recordings were made, one for each type of compact loader (A and B). As left and right tracks were fairly similar for both the recorded signals, only the right ones were used as input signals in the optimisation process.

Figure 2 shows the sonograms of the sound pressure level of the two noise signals chosen for the acoustic optimisation. Table 1 summarises the results of the objective analyses performed on these signals in terms of acoustic and psycho-acoustic parameters.

Taking into account that during the execution of the work cycle the engine rotational speed of these machines ranged from 2000 to 2500 rpm, the above sonograms highlight a significant difference between the two machines:

- At the engine characteristic frequencies (40-400 Hz frequency range) the noise levels are higher for signal A than for signal B;
- At the characteristic frequencies of the cooling and hydraulic systems (500-3150 Hz frequency range) the noise levels are higher for signal B than for signal A.

ACOUSTIC OPTIMISATION PROCEDURE

Numerical optimisation is widely used to analytically foresee which modifications of a defined system would lead to configurations that best meet the desired target. It is a powerful analytical tool but it requires an accurate definition of the best set of variables describing the system, as well as the identification of the objectives to be achieved.

As in the case of stationary signals, the target of this optimisation process was the simultaneous minimisation of the objective parameters best related to the annoyance sensation. The time dependency of these signals, however, made it necessary to choose new variables describing the system and new objective functions so that they could both reflect the same variability

Figure 1. Binaural recordings at the operator position in working conditions.

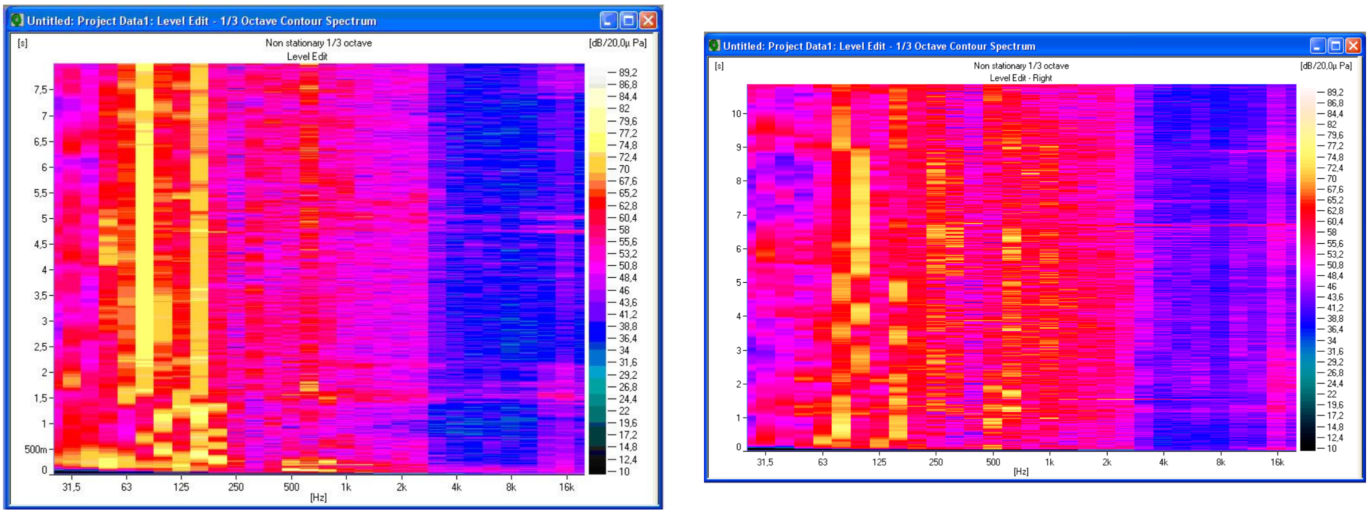

Figure 2. Sonograms of the sound pressure levels: machine A (left) and machine B (right).

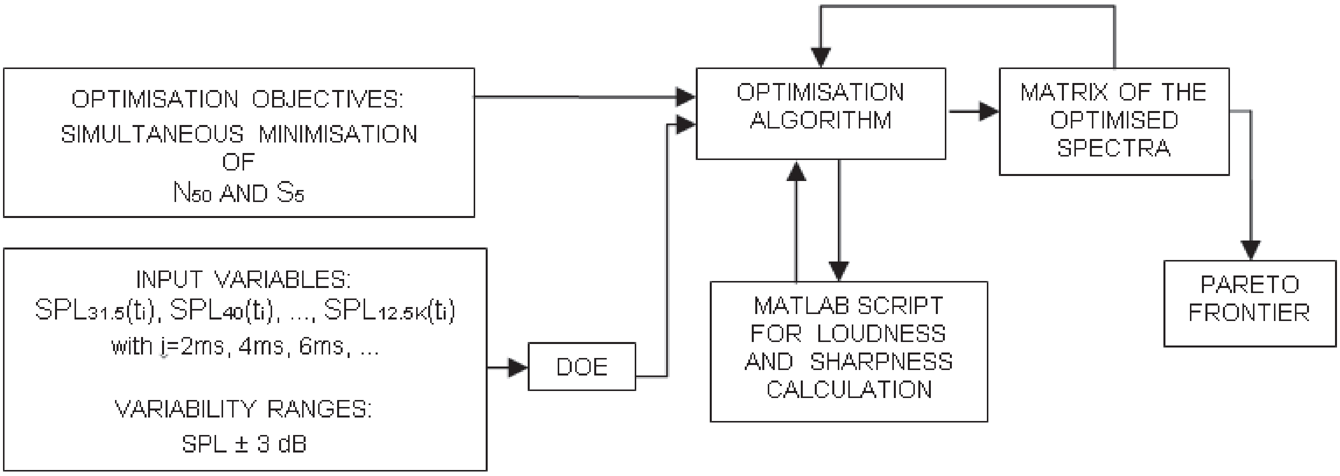

Figure 3. Flowchart of the optimisation procedure.

over time.

For an accurate description of the input system, two aspects of the noise signal had to be simultaneously considered: its time dependency and its frequency dependency. Starting from the 1/3 octave band spectrum of the input signal (from 31.5 Hz to 12.5 kHz), a complete description of this signal was obtained by a matrix of twenty seven variables; each of them being a vector containing the time history of the sound pressure level of a specific frequency band: $SPL_{31.5}(t)$, $SPL_{40}(t)$, …., $SPL_{12.5k}(t)$. In such a way, the twenty seven sound pressure levels in the frequency range 31.5-12500 Hz, calculated every 2 ms, were identified as the most suitable set of variables to describe the input system. This specific temporal resolution was chosen as it was consistent with the characteristics of the human hearing system.

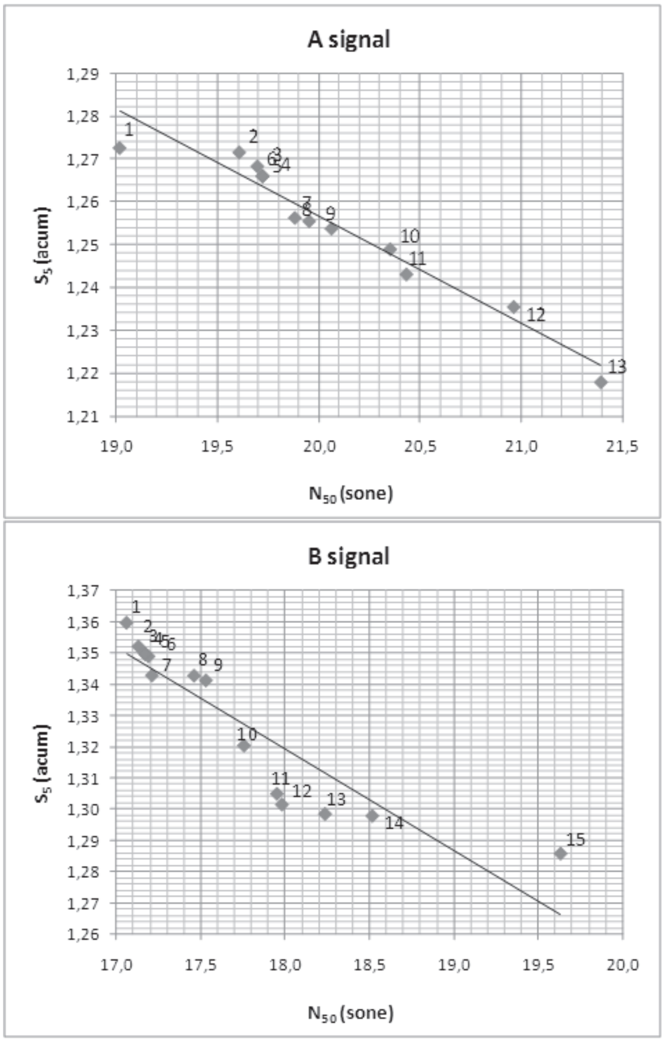

Figure 4. Pareto Frontier solutions: A (top), B (bottom).

Referring to the identification of the objective functions, the results of a previous investigation performed on time-varying noise signals were very valuable for this choice [6]. In that study we found a very high correlation between the subjective sensation of annoyance and the loudness and sharpness percentile values N_{50} and S_5. For this reason, the simultaneous reduction of the above percentile parameters was chosen as target of this optimisation process.

A second set of objective functions (N_5 and S_5) was also tested, following the suggestions made by Fastl and Zwicker [7] that the use of the fifth percentile of loudness for physical measurement of noise emission would be recommended. However, the simultaneous reduction of the percentile values N_5 and S_5 did not lead to any significant difference in the results and so it was no longer taken into consideration.

The numerical analyses were performed using the multi-objective genetic algorithm (MOGA) governed by the ModeFrontier optimisation procedure [8,9]. This procedure has the great advantage of allowing the input in the process of results from other external codes. The calculation of loudness and sharpness values was therefore performed by a MATLAB script developed for this purpose. This script read the values of the time-frequency matrix as input and gave the array of the values of loudness and sharpness as output.

The loudness values were calculated according to the procedure described in the DIN 45631/A1 standard in order to take into account the time variability of these noise signals. In fact, the simple rule to distinguish time varying from stationary sounds, based on the ratio N_5/N_{95} [10], gave values that were well above 1.1 (1.4 and 1.48, respectively), confirming the variability over time of these signals.

As with every genetic algorithm, also MOGA requires the definition of a set of reference configurations (Design of experiment, DOE) in order to be trained on the characteristics

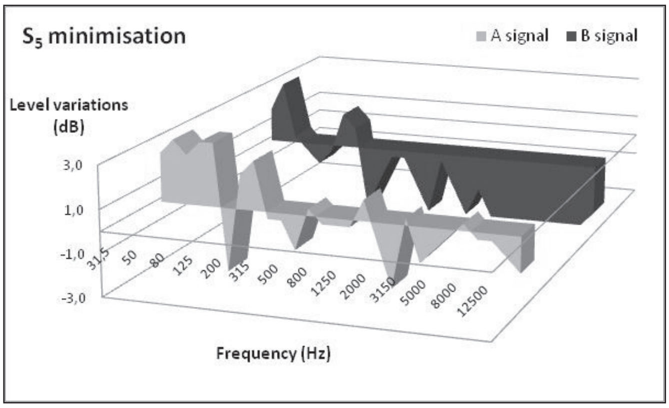

Figure 5. Spectral changes suggested for minimising S_5.

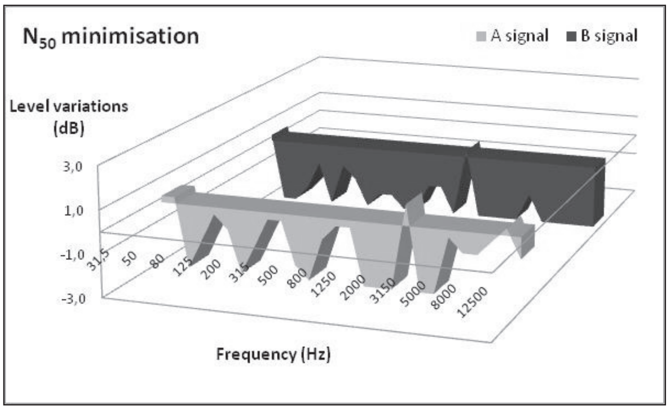

Figure 6. Spectral changes suggested for minimising N_{50}.

of the system under investigation [11]. In the ModeFrontier application, the required DOE is created according to a random approach (Sobol methodology), while the user has to specify only the range of the variations admitted for each of the 27 variables describing the system. Figure 3 shows the flowchart of the optimisation procedure applied to the two noise signals.

RESULTS

The optimisation procedure was applied to both noise signals A and B, separately. In each run the range of admitted variations for each of the 27 variables describing the system was set at ±3 dB.

The output of the optimisation process included a set of several solutions (Pareto Frontier). Each solution consisted of twenty seven dB-values representing the level variations, frequency by frequency, suggested by the optimisation algorithm in order to minimise N_{50} and S_5 parameters. All the Pareto Frontier solutions had loudness and sharpness percentile values N_{50} and S_5 significantly lower than those of the original signal. In this group, however, there were some solutions that were better than others with respect to the minimisation of the loudness percentile N_{50} but worse in relation to the minimisation of the sharpness percentile S_5 and vice versa. The identification of further constraints to the specific problem would be necessary in order to select the best solution among the many mathematically possible.

Fig. 4 shows the Pareto Frontier solutions of both signals A (top) and B (bottom) as a function of N_{50} and S_5 (objective functions). The solutions are numbered sequentially starting from the one with minimum value of N_{50}. For signal A, N_{50} ranges from 19.0 sone to 21.4 sone and S_5 from 1.22 acum to 1.27 acum. Regarding signal B, N_{50} ranges from 17.1 sone to 19.6 sone and S_5 from 1.29 acum to 1.36 acum.

Despite the fact that the two noise signals had a different distribution in frequency of the noise levels, some general conclusions about the effects of the optimisation process on the shape of the noise spectrum can be drawn. When looking at the two extreme Pareto Frontier solutions, for example, the following information can be obtained.

The best solutions with respect to the minimisation of sharpness (no.13 for signal A and no.15 for signal B) suggest significant noise reductions at medium-high frequencies, but, unfortunately, an increase of noise levels was found at low frequencies (40-630 Hz) for both signals, as shown in Figure 5.

Despite the high correlation of the S_5 parameter with the annoyance sensation caused by these kinds of signals, this solution clearly shows that noise modifications aimed at S_5 minimisation are worthless in practice due to the increase of levels at low frequency.

In addition, when applied to noise signals which have significant contributions at low frequency (for example signal A, see Fig. 2), the modifications do not lead to any significant reduction either in the overall level or in the N_{50} value. Referring to signal A, the optimisation process led to the same sound pressure overall level and to a N_{50} value about 0.7 sone below the original value. This difference, however, is lower than the value of "just noticeable difference" in loudness [12] and therefore meaningless.

The best solutions with respect to the minimisation of loudness (no.1 for both signals) suggest significant noise reductions all through the frequency range, as shown in Figure 6. This mainly derives from the fact that loudness strongly depends on sound level.

Noise modifications aimed at N_{50} minimisation are extremely effective. The overall sound pressure levels of the optimised signals are significantly lower than the original ones, with differences of about 2.5 dB for signal A and 4.8 dB for signal B. Even if these solutions are better with respect to minimisation of loudness than of sharpness, they still lead to modified signals with values of S_5 significantly lower than the original values. The differences (0.08 acum for signal A and 0.14 acum for signal B) are significant since they are higher than the "just noticeable difference" in sharpness [12].

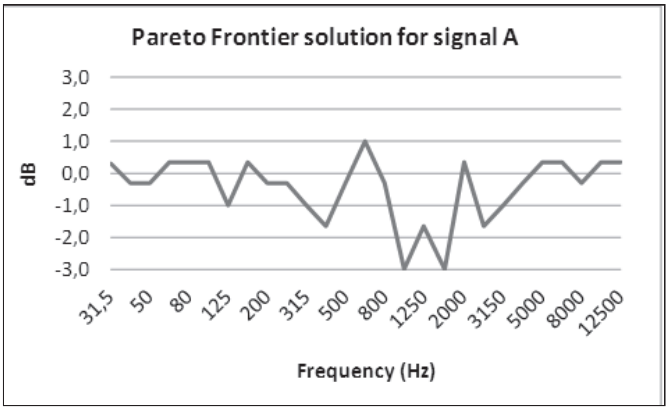

Figure 7. Pareto Frontier solution no.3 for signal A: N_{50} = 19.7 sone and S_5=1.27 acum.

Although noise modifications aimed at the N_{50} minimisation could potentially have high relevance for improving the comfort conditions, their implementation, however, turns out to be almost unfeasible in practice. Based on the above considerations, the sharpness minimisation leads to solutions with meaningless reductions both of the overall sound pressure level and of the loudness N_{50} value. On the other hand, the loudness minimisation leads to solutions with significant reductions both in the overall sound pressure level and in the sharpness S_5 value, but unfeasible in practice. Consequently, the solution to be implemented in the machine should not be chosen from these extreme solutions.

Looking for a compromise between sound quality improvement and practical constraints, the right approach could be to start from the solution with the minimum value of loudness and proceeding to solutions with progressively higher loudness values until a feasible solution is found, if it exists. As an example, Figure 7 shows the case of signal A. Solution no.3 leads to optimised values of loudness and sharpness equal to N_{50}= 19.7 sone and S_5 = 1.27 acum.

These modifications lead to a significant reduction of the overall sound pressure levels (L_{eq} is reduced by 3.3 dB and L_{Aeq} by 4.8 dBA) and they ensure a reduction of both psycho-acoustic parameters well above their corresponding just noticeable differences. In addition, the most relevant modifications mainly refer to the noise in the frequency range 800-2000 Hz which is closely related to a specific part of this machine (hydraulic system). Then the practical implementation of these suggestions seems to be feasible.

Regarding signal B, all the Pareto Frontier solutions were similar and concerned a wide frequency range. Therefore, it was impossible to find a solution which suggested modifications closely related to a specific part of this machine. In such a case all the solutions highlighted the need for more drastic modifications, not excluding a complete acoustical redesign of the machine.

CONCLUSIONS

The optimisation process applied to time-varying noise signals was aimed at minimising the loudness and sharpness percentile values N_{50} and S_5 in order to improve the Sound Quality at the operator station of earth moving machinery during real working conditions. The numerical optimisations were performed using the multi-objective genetic algorithm (MOGA) governed by the ModeFrontier optimisation procedure while the calculation of loudness and sharpness percentile values was performed by MATLAB scripts specifically developed in order to take into account the time variability of the noise signals.

The output of the optimisation process included several solutions (Pareto Frontier), all with loudness and sharpness percentile values N_{50} and S_5 significantly lower than those of the original signals. When looking at the two extreme Pareto Frontier solutions, the following information was obtained. The best solutions with respect to the minimisation of sharpness percentile value S_5 suggested significant noise reductions at medium-high frequencies, but unfortunately, an increase in noise levels at low frequencies (40-630 Hz). Despite the high correlation of the S_5 parameter with the annoyance sensation caused by these kinds of signals, this solution clearly shows that noise modifications aimed at S_5 minimisation are worthless in practice because of the increase of levels at low frequency.

The best solutions with respect to the minimisation of loudness percentile value N_{50} suggested significant noise reductions all through the frequency range. This mainly derives from the fact that loudness strongly depends on sound level. Although noise modifications aimed at the N_{50} minimisation could potentially have high relevance for improving the comfort conditions, their implementation turns out to be almost unfeasible in practice. Looking for a compromise between sound quality improvement and practical constraints, the right approach could be to start from the solution with the minimum value of loudness and proceeding to solutions with progressively higher loudness values until a feasible solution is found, if it exists.

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