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NOISE CONTROL FOR QUALITY OF LIFE

Inverse optimization of noise barriers

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ABSTRACT

In most cases planning of noise barriers should limit the sound level at defined locations (e.g. windows) below certain thresholds, but also keep the total building costs as low as possible. Currently the height and length of noise barrier segments are determined by manual forward planning which tends to overestimate the barrier area needed and might not use the full potential of the invested budget.
We expand our previously developed inverse planning concept, which includes Simulated Annealing and gradient based optimization algorithms. Pareto fronts are used as a visualization tool helping the engineer and decision maker in noise barrier planning.
We defined an objective function allowing us to apply the concepts of multiobjective optimization. Using a weighted sum approach we can reliably generate well distributed pareto fronts. We show that our optimization procedure generates more cost efficient barriers than current forward planning methods. With our pareto front visualization we offer a decision making tool to the planning engineer, allowing much more detailed, precise and transparent noise barrier planning.
Keywords: barriers, inverse optimization, pareto front

1. INTRODUCTION

Planning of noise barriers is always a compromise between reducing and limiting sound levels to certain thresholds from one side and the economic factors from the other. For example in Austria guidelines published by the Federal Ministry for Transport, Innovation and Technology [1, 2] define certain constraints for

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noise barrier constructions. Thresholds are defined for L_{DEN} and L_{night} in front of sleeping and living rooms. The construction of noise barriers is preferred over passive measures (e.g. noise protective windows) whenever possible. Noise barriers also protect open space around buildings, not only sleeping and living rooms. However, the costs of the total noise barrier installation should not exceed a certain amount that is N times the costs of alternative protective windows. Each receiver point in front of a window reduced below the threshold by the noise barrier, is not requiring passive measures and justifies higher noise barrier building costs. Such a point is considered compensated and the costs of its noise protective windows are added to the compensated passive costs.

The decision to build a particular barrier geometry is mainly based on forward planning performed by an engineer. Using manual forward planning different barrier geometries are simulated and the barrier costs are calculated in conjunction with the number of compensated receivers and their related compensated passive costs. If the economy factor, defined as barrier costs divided by compensated passive costs, is below a chosen threshold the optimization stops (e.g. in Austria this economy factor is currently 3 in case of traffic noise of already existing highways). This method causes problems: the barrier design might not be optimal, as the same barrier surface area could be distributed in different ways, improving total noise level attenuation at the receiver points. Neither do we gain any information on the gradient of the number of compensated receivers as a function of barrier costs.

Situations can occur where the economy factor threshold is reached, but with limited additional costs for an increase in barrier heights a substantial amount of receivers could achieve noise levels below the limit. Barrier design involves the two basic competing objectives sound level attenuation and costs, allowing us to formulate a multiobjective optimization (also called pareto optimization) problem. In this paper we show the feasibility of pareto front approximation by solving this multiobjective barrier design problem and present pareto charts as a useful tool in decision making.

2. METHODS

2.1. Objective Function

We model our problem and define an objective function based on the rule for noise barrier design specified in the Austrian guidelines:

- Strict noise immission limits. *($L_{limit,night} = 50dB$ and $L_{limit,DEN} = 60dB$ for the Austrian examples presented in section 3)*
- General maximum barrier height. *(2 m, 4 m or 5.5 m, depending on the scenario)*
- For economic evaluations, barrier cost is determined by a cost per surface area factor. *(200 €/m^2 for motorways and 180 €/m^2 for railways)*

The weighted sum method is an intuitive and often used approach for defining an aggregate objective function. For two objectives J_1 and J_2 the aggregate objective $\tilde{J}$ generally takes the form:

$$\tilde{J} = sJ_1 + (1-s)J_2, \qquad 0 \le s \le 1 \tag{1}$$

The optimization algorithm runs for a range of values of parameter s, approximating the pareto front with a number of pareto optimal points. For our multiobjective optimization problem this is a point with the best possible total noise level attenuation at a given barrier cost.

We introduce the noise penalty factor P to define our aggregate objective function $F(x_i)$:

Minimize

$$F(x_i) = \underbrace{\sum_i c_i a_i x_i}_{\text{total barrier cost}} + \underbrace{P \sum_j \Delta L_j(x_i)}_{\text{excess noise}} \tag{2}$$

subject to boundary conditions

$$l_i \le x_i \le u_i \tag{3}$$

with

$$\Delta L = max(L_i - L_{limit}, 0) \tag{4}$$

i: barrier segment
j: receiver

x_i: height of barrier segment i
a_i: length of barrier segment i
c_i: cost per square meter of barrier segment i

P: noise penalty factor [$\frac{€}{\mathrm{dB}}$]
ΔL_j: sound level exceeding noise immission limit at receiver j [dB]
L_i: sound level at receiver j [dB]
L_{limit}: noise immission limit [dB]

l_i: lower boundary condition of barrier segment i
u_i: upper boundary condition of barrier segment i

P takes the function of parameter s introduced above, for realistic problems it is of order of magnitude of 10^2 to 10^4.

2.2. L-BFGS-B Algorithm

L-BFGS-B is a gradient based quasi-Newton method using a limited memory variation of the Broyden-Fletcher-Goldfarb-Shanno (BFGS) update to approximate the inverse Hession matrix, developed and expanded by Nocedal et al. [3–5] to include boundary conditions (-B).

We justify the choice of L-BFGS-B as our main algorithm with previous successful implementations of the L-BFGS variation [6]. It is suited for large problems, exhibits relatively quick convergence rates and is freely available. The recent update to L-BFGS-B version 3.0 shows significantly improved performance.

L-BFGS-B may get trapped in local minima. Careful starting value choice is paramount to finding pareto optimal points.

2.3. Pareto Charts

Pareto charts are our primary visualization means to show the optimization results to the decision maker in a comprehensible manner. While the pareto front, by definition is a plot of total barrier cost (first term of the objective function) vs. total excess noise (second term of the objective), we instead use either the noise penalty factor P or the barrier cost as a constant axis to compare various measures of noise barrier efficiency, such as average noise level attenuation or number of receivers below noise limit.

Each pareto optimal point corresponds to an optimal noise barrier shape at a given noise penalty factor P.

2.4. Sound Propagation

For our proof of concept application a simplified sound propagation model is used. It calculates only one octaveband according to *ISO 9613-2* [7].

The optimization algorithm exchanges sound and geometric data with a planning and sound propagation calculation programm. Simulating the point to point based sound propagation model consumes the most computation time during the optimization process. We decided to use a precalulation approach, commonly used in engineering and avoiding interaction between sound propagation engine and algorithm engine at every iteration.

Sound pressure levels are calculated for a range of minimum to maximum barrier height at previously defined height intervals and a 3D-Matrix is built with one dimension each for wall segment IDs, receiver IDs and wall segment heights respectively. To deliver sound pressure levels at continuous barrier heights, linear interpolation is used, thereby doing the essential step in gradient calculation. Basically a lookup table for the algorithm is created.

The wall baseline is segmented after receiver projection, allowing the algorithm user to control the wall segment lengths and thereby the number of variables. This is acceptable as long as point source spacing is small compared to the wall segment length.

With this precalculation approach, sound propagation calculations are part of the initial preparations done only once, improving the speed of the actual optimization algorithm by a factor of ten or more, depending on scenario complexity. The user experience is improved greatly and quick experimentation with different settings is possible.

3. RESULTS

3.1. Starting Value Calculation

We use an iterative process to calculate a starting value close to the pareto optimal barrier (see Figures 1 and 5):

- Step 1: Search for a receiver above the noise l imit and identify which sound propagation path contributes most to the total sound level. Identify the wall segment related to that sound propagation path. barrier height, which affects the receiver the most.
- Step 2: Increase the height of the segment chosen in step 1 by a fraction of the maximum barrier height (e.g. 2%).
- Step 3: Continue with step 1 for a different receiver. When cycled through every receiver, choose the first one again.

The process stops when every receiver is below the noise limit or a user-defined maximum barrier cost is reached. The latter condition is important, otherwise the process fails to retain a correct barrier shape for problems with high noise immission levels. In this manner we arrive at a fairly good first guess for problems where the maximum barrier height is easily reached.

Table 1 – Example "A": noise immission levels of all 18 receivers at $P = 10200$. L_0 values are the noise immission levels without any wall present, $\Delta L_{opt} = L_0 - L_{opt}$.

L_{opt}	L_0	ΔL_{opt}
50.0	54.1	4.1
49.3	52.9	3.6
48.8	51.4	2.6
49.2	53.0	3.8
50.0	54.0	3.9
49.8	54.1	4.3
49.7	54.1	4.4
49.6	54.2	4.6
49.2	54.2	4.9
49.2	54.1	4.9
49.5	54.9	5.4
49.5	55.2	5.7
49.6	55.5	5.9
49.8	55.8	6.0
50.1	56.5	6.4
50.3	56.9	6.6
50.0	56.3	6.3
49.7	55.2	5.5

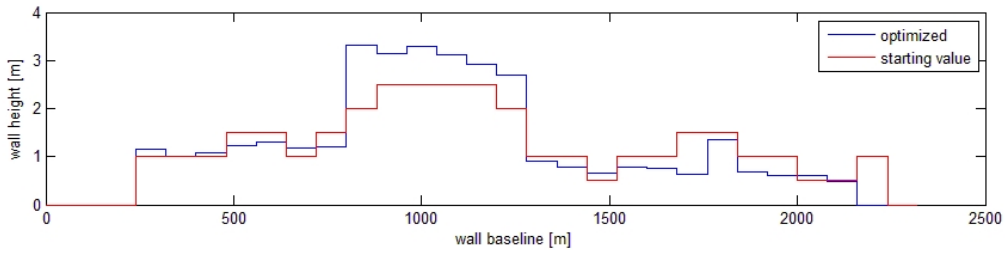

Figure 1 – Example "A": optimized noise barrier at $P = 10000$.

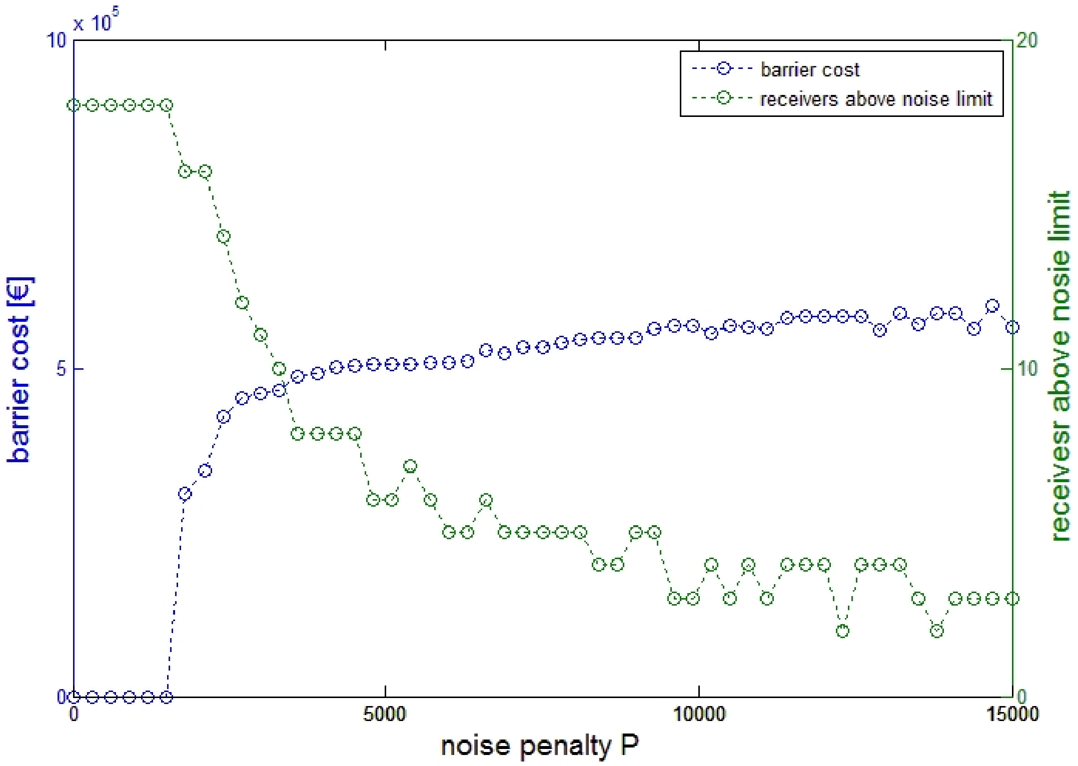

Figure 2 – Example “A”: noise penalty based plot of barrier cost vs. number of receivers above the noise limit. *P* was varied from 0 to 15000 in steps of 300.

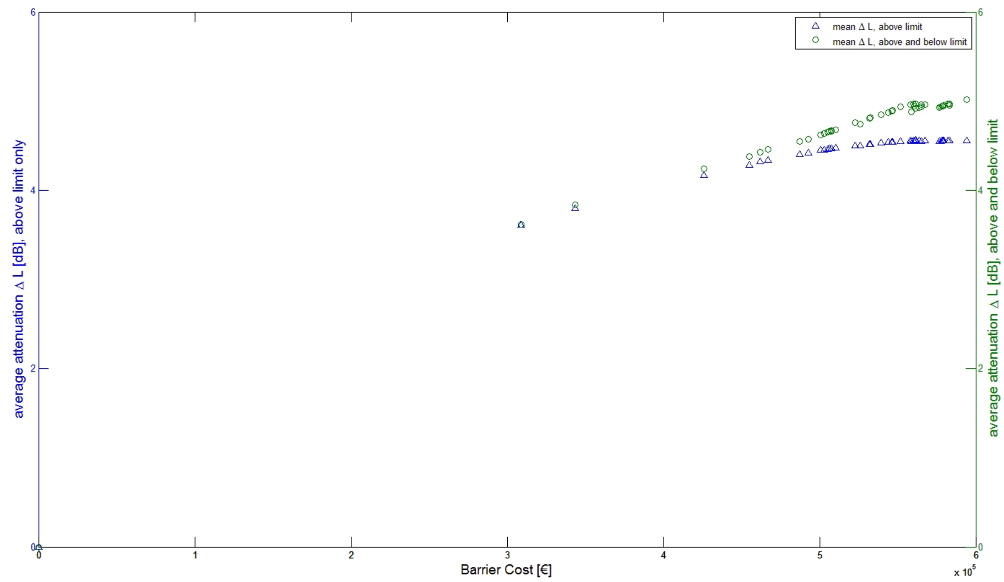

Figure 3 – Example “A”: barrier cost based plot showing the attenuation averaged across all receivers. *P* was varied from 0 to 15000 in steps of 300. Results are shown, when considering either attenuation above the noise limit only or total attenuation, below and above limit.

3.2. Example “A”

Example A is a small town next to a motorway. It is an interesting small example to study, as the motorway forms a remarkable 180 degree curve around it all of its 18 houses are located in a similar distance to the noise

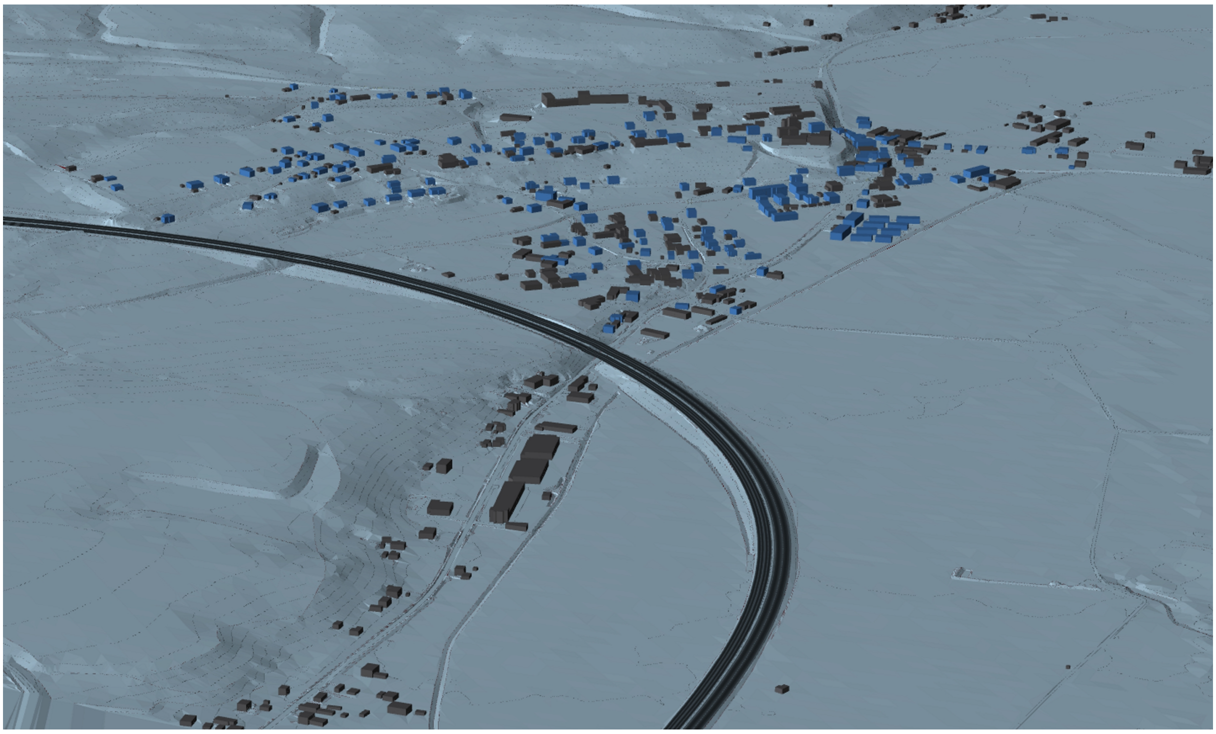

Figure 4 – Example “B”: a 3D view of the town and motorway, created with IMMI planning software. Houses eligible for noise protection are shown in blue.

barrier. Noise barriers, with heights comfortably below the maximum allow barrier height, protecting every receiver can be designed. A constant barrier segment length of 80 m is used. All results are given as A-weighted sound levels in dB.

Figure 1 shows the optimized noise barrier at $P = 10200$. The calculated starting value is already a good fit, because receivers are at a similar distance to the noise barrier and have similar noise immission levels with no wall present. Table 1 shows the noise immission levels in dB for all 18 receivers. Values for the optimized barrier are close to the noise limit for every receiver 50 dB, this is an indication that indeed the optimal barrier has been found. From an economical standpoint it is desireable that receivers are protected to within the noise limit, but no more.

Figure 2 shows an example of a noise penalty based pareto chart. When increasing noise penalty P the optimizer uses more barrier surface area, leading to increased barrier costs and a reduced number of receivers above the noise limit. The user has a comprehensive overview to decide how much budget he is willing to spend for the noise barrier and how many receivers above the noise limit he has to accept.

Figure 3 shows an example of a cost based pareto chart. Average attenuation across all receivers is shown, the axis on the left considers attenuation above the noise limit only, while the axis on the left shows total attenuation, above and below the noise limit. Note how the attenuation above limit only levels off more quickly, because fewer receivers remain above the limit. We can see a clear indication of diminishing returns in noise barrier efficiency with climbing costs.

3.3. Example “B”

Example B is a town along a curved section of a motorway. It is remarkable for its two separated clusters of houses approaching the motorway closely (Figure 4). Due to the curved shape, noise barrier effectiveness quickly diminishes towards the beginning and the end of the curve, allowing us to demonstrate the capabilities of the algorithm

A selection of optimized walls at $P = 2000$, 10000 and 65000 are shown in Figure 5. We can observe the wall being optimized with two distinct sections, the larger of them, from wall baseline 2000 meter to 2500 meter protecting the cluster of houses close to the motorway shown in the center of Figure 4.

Note the sharp, clearly defined outer noise barrier edges. This somewhat counter intuitive behaviour was observed across all examples optimized so far. At $P = 65000$ the maximum barrier height of 5 meter is hit and still the sharp edges are maintained. This clear indication of where a noise barrier should and shouldn’t be built is a strength of the optimization algorithm.

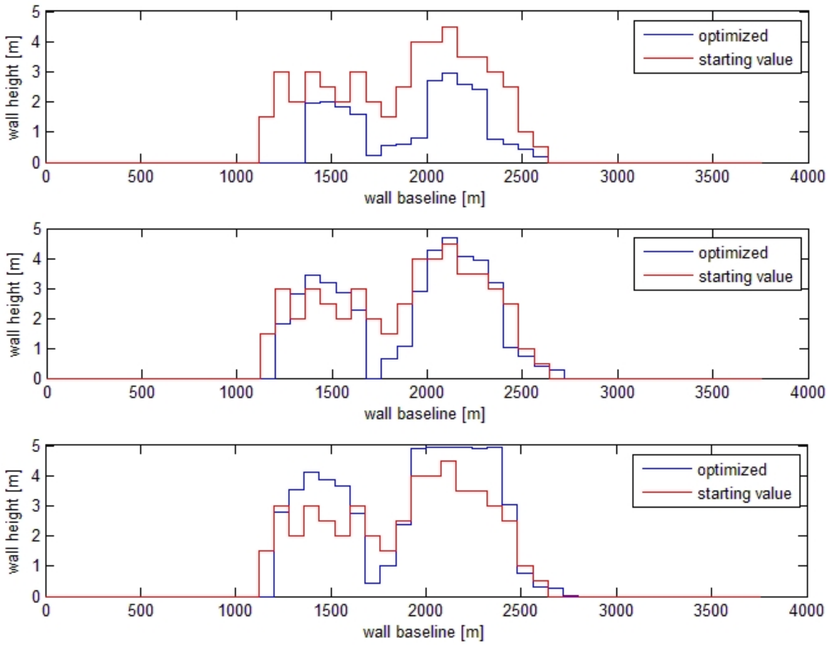

Figure 5 – Example “B”: optimized noise barriers. $P = 2000$ (top), $P = 10000$ (middle), $P = 65000$ (bottom).

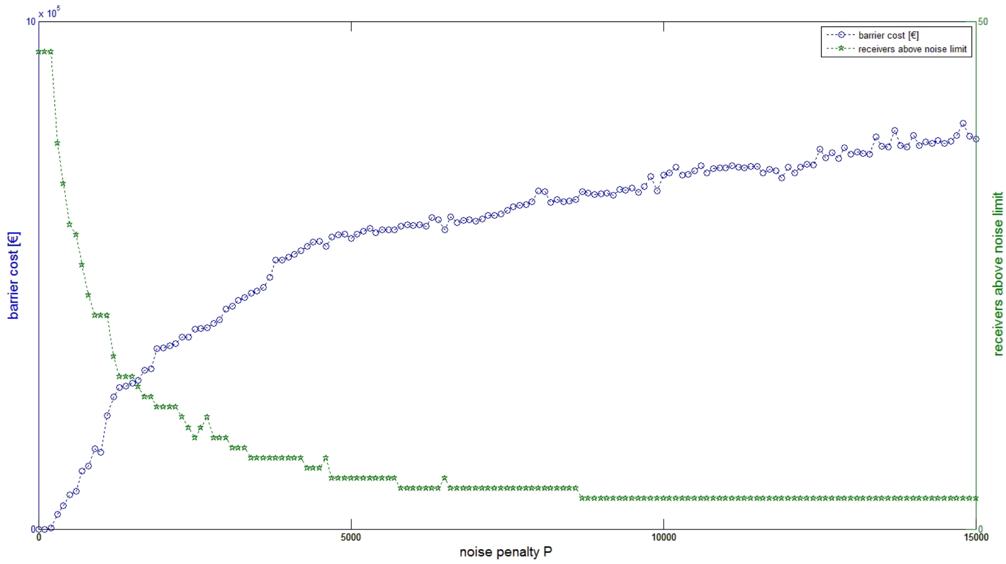

Figure 6 – Example “B”: noise penalty based plot of barrier cost vs. number of receivers above noise limit. Optimizations for a noise penalty range from 0 to 15000 with steps of 100.

Figure 6 shows an example of the noise penalty based plots. For economic considerations the number of receivers protected to within noise limits is the most important indicator of noise barrier efficiency. The small fluctuations can be explained by be the discontinuous objective function, a small change in barrier height can decide whether a receiver is below the limit. Plotting against P allows the engineer to identify and analyze noise penalty ranges of special interest.

Figure 7 shows an example of the pareto based plots, giving a better idea of cost to barrier efficiency behaviour. Only attenuation occurring above the noise limit at each receiver is factored into this plot. The asymptotic behaviour is expected as more and more receivers are below the limit at more expensive barriers.

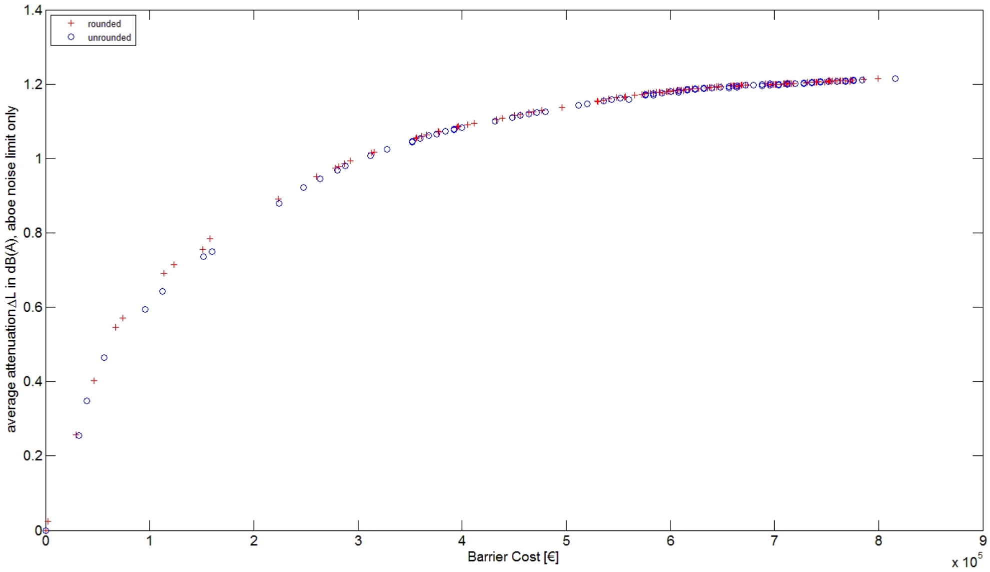

Figure 7 – Example “B”: pareto based plot of barrier cost and average attenuation ΔL in dB(A). Optimizations for a noise penalty range from 0 to 15000 with steps of 100. Errors due to rounding to barrier height segments of 0.5 meter are minimal for higher noise penalties.

4. DISCUSSION

For non-linear functions like our objective function, L-BFGS-B cannot guarantee to find a global optimum. Therefore a good starting value, close to the pareto optimal point, influences the findings of the optimizer positively. The engineers using the optimizer, have to be aware of this and carefully try different starting values. The small fluctuations in the pareto charts occur due to the fact that the optimization algorithm is getting trapped in local minima and the discontinuous nature of the objective function, introduced with the *max()* function (see equation (4)). This behaviour is getting worse as fewer objects remain above the noise limit and noise penalty P increases.

Simulated Annealing is a probabilistic metaheuristic method used in global optimization to find a good approximation of the global optimum. It was shown to be a viable option in noise barrier optimization [8], but it is an inherently slow process, making it unsuitable for pareto front generation. We use it to confirm L-BFGS-B has indeed found a solution that is close to the global optimum. Initial testing has shown that Simulated Annealing and L-BFGS-B results are in good agreement, which is a strong argument to continue using L-BFGS-B. Further investigation is needed on how a combination of both algorithms may be implemented in an optimization application. For instance, Simulated Annealing could be used the estimation of the starting values and feed them to L-BFGS-B.

Also we need to consider the fact that actual noise barriers are built in 0.5 m increments. Rounding our optimization results to 0.5 m accuracy, shows effects that are often larger than the small fluctuations mentioned above. Further investigation is needed to state reliable accuracy requirements.

Subjectively a single moving noise source with varied attenuation due to the gap in the noise barrier may be perceived as more disturbing. We have identified time resolved analysis as a missing issue in the Austrian guidelines. The objective function should be expanded with further research to accurately reflect this issue. Possible strategies are to include a smoothing penalty or add constraint conditions.

Another possible addition to the objective function is receiver specific weighting factors. Certain receivers may be more important (e.g. Hospitals), calling for preferential treatment. This can also include the preference of protecting ground floor receivers over receiver on higher floors, justified with the additional bonus of protecting open space (e.g. gardens). Multifloor buildings with a large number of windows close to the noise barrier may have to be excluded from the objective function altogether, to avoid its complete domination by receivers that remain almost unaffected by noise barriers.

The current objective function allows the definition of cost factors and boundary conditions on a per barrier segment basis. Different segment heights may be associated with different costs per surface area, to account for demanding environments like bridges. The Austrian guidelines for noise barriers could to be expanded to use the full potential of optimization algorithms.

5. CONCLUSIONS

Inverse optimization and pareto charts are an effective tool in the decision making process for optimal noise barrier planning, offering advantages compared to manual forward planning. The optimizer is looking for solutions, where noise barrier elements of defined length are set to their optimal heights, for a given penalization of noise limit violation at defined receiver points. Penalization is set with a scenario specific noise penalty factor P. Increasing P justifies the spending of more money, thus noise barriers of higher cost may be built. Solutions of the optimizer determine how much money should be invested for a given P and translate this investment into the optimal barrier surface area distribution among the noise barrier elements.

In addition it provides us with an outlook of the total costs in conjunction with the number of receivers protected. For each optimal barrier of certain total costs, the number of objects still above a defined threshold can be visualized. This allows us not only to take into account very simple fixed ratios and thresholds for costs, but also to evaluate the benefit of an increase in barrier surface area. A standard could be established that barrier costs are increased as long as a sufficient number of objects are protected additionally. But any further increment could be stopped if the costs to reduce noise immission levels at the remaining receivers above threshold, increase disproportionately. On the other hand it might show situations where a further increment in barrier height and length protects a substantial additional amount of receivers.

With the current decision making process only a few barrier design plans are studied and compared. Each of these alternatives had to be calculated manually. With inverse optimization hundreds of alternatives can be calculated automatically and the results can be studied effectively with pareto charts.

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