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How should acoustics adapt to meet future demands?

Maximising the cost-effectiveness of noise control treatments for overland conveyors by engineering optimisation

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ABSTRACT

Environmental noise limits for overland conveyors can be difficult to achieve even with costly noise reduction treatments, particularly in retro-fit situations. Different conveyor systems require different strategies to achieve noise reduction, and often require a combination of methods to achieve the overall environmental targets. In cases where the overall noise targets can be achieved by alternative combinations of different treatments, the overall cost-effectiveness of the noise control program can be maximised using engineering optimisation methods. This paper presents a general method for selection of the type and extents of noise mitigation required to achieve the environmental goals for the maximum value for money. This paper is an updated version of a paper presented at the 'Dust & Noise Management in Mining' conference in Perth, Australia, June 2008.

INTRODUCTION

The design of noise control treatments is often undertaken with a high degree of conservatism, however in most cases the capital cost of this conservatism is unknown, and often is not recognised or even acknowledged. Nearly all fields of engineering are subject to the requirements of efficient design, and in these fields when a safety factor is incorporated it is a basic requirement that this safety factor be stated clearly, and the cost implications understood. The engineering design of noise control treatments is no exception; however it is rare to see noise control design undertaken with the aim of achieving the noise design goals for the maximum value for money.

Modern noise modelling software packages do not incorporate a universal method to provide this feature, as the primary purpose of these packages is usually to model the noise as accurately as possible, rather than to be used as noise control design tools.

This paper presents a method for designing noise control treatments of overland conveyors for the minimum possible capital cost in a mathematically precise and robust manner. The method can be extended to the design of noise control treatments for other noise sources, by adopting a similar overall approach and design philosophy to the one described.

GENERAL APPROACH

In order to achieve the required noise limits for an overland conveyor for the minimum cost, the principles of engineering optimisation can be used. The total cost can be represented by a mathematical function, and by finding the minimum of this function within the applicable boundary constraints, the overall cost will be minimised.

Although the objective cost function is linear for the example of a conveyor, the constraint function(s) are not, therefore the appropriate optimisation algorithm to be used is a nonlinear programming technique with nonlinear constraints. Specifically, the technique used is the Generalised Reduced Gradient technique (Lasdon *et al* 1978).

The total Insertion Loss of combinations of some types of conveyor noise control treatments are not linearly additive, for example the combination of vibration isolation devices and sheet metal cladding will give a different overall Insertion Loss than the sum of the individual treatments. These non-linear effects can be incorporated into the engineering optimisation process, however for the purposes of demonstration, the noise reduction treatments discussed in this paper are assumed to be additive and independent.

DETAILED APPROACH

For an overland conveyor, the cost of each individual noise control treatment is equal to the cost per meter of the treatment's length (c_i) multiplied by the length of the treatment (x_i). The total cost is simply the sum of these, as shown in equation (1):

$$\text{total cost} = f(X) = \sum_{i=1}^{n} c_i \cdot x_i, \qquad x_i \geq 0 \qquad (1)$$

For the purposes of demonstrating the procedure, a maximum of three noise control treatments is discussed, i.e. the objective function is shown in equation (2):

$$f(X) = c_1 \cdot x_1 + c_2 \cdot x_2 + c_3 \cdot x_3 \qquad x_i \geq 0 \qquad (2)$$

This is the objective function to be minimised, subject to constraints.

The three treatments chosen are:
- Low-noise Idlers [LNI's]
- Cladding, and
- Noise barrier

It is assumed that several different options are available for each of these:
- 3 types of low-noise idlers: A, B and C
- 3 types of cladding: A, B and C
- 2 types of noise barriers: A and B

The assumed Insertion Loss of each of these noise treatment options are shown in Table 1.

Table 1 – Insertion Loss of treatments (dBA).

Treatment	Treatment Type		
	A	B	C
LNI	4	7	10
Cladding	6	11	15
Barrier	5	8	

The assumed costs per meter of each of these treatments is shown in Table 2.

Table 2 – Cost per meter of noise treatments ($/m).

Treatment	Treatment Type		
	A	B	C
LNI	800	1000	1500
Cladding	1500	3000	4000
Barrier	2000	4500	-

The relative cost-effectiveness of each of these treatments is shown in Figure 1.

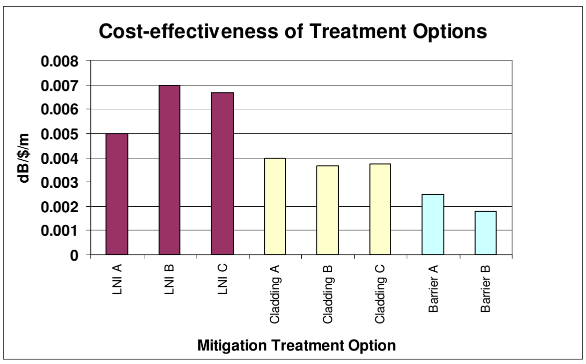

Figure 1 – Cost-effectiveness of treatments [dB/$/m]

The noise level received at a receptor from a segment of conveyor length Δx at a distance x along the conveyor's length depends on the perpendicular distance of the receptor to the noise source y, as shown in Figure 2.

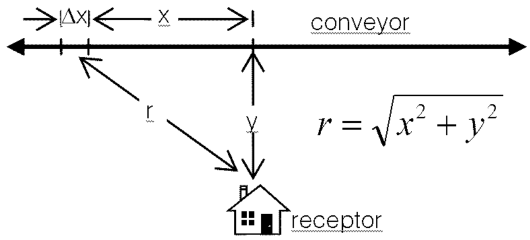

Figure 2 – Receptor geometry

Assuming hemi-spherical sound propagation (i.e. reflective ground), and ignoring atmospheric and topographical shielding effects, the untreated noise level received at the receptor from segment Δx is shown in equation (3).

$$L_0(x) = 10\log\left|\frac{p_0^{\,2}}{p_{ref}^{\,2}}\right|$$

$$= 10\log\left|\frac{W \cdot \Delta x}{W_{ref}}\right| - 10\log\left|2\pi \cdot r^2\right| \qquad (3)$$

$$= 10\log\left|\frac{W \cdot \Delta x}{W_{ref}} \cdot \frac{1}{2\pi \cdot (x^2 + y^2)}\right|$$

where W is the sound power of the noise source per meter, and W_{ref} is 10^{-12}Watts.

The noise reduction of individual treatments is effectively an adjustment coefficient a_i to be applied to the sound power of the noise source. In regions where noise treatment i is applied, the sound power per meter will be $W \cdot a_i$ Watts/m,

where

$$a_i = 10^{-IL_i/10} \qquad (4)$$

and where IL = Insertion Loss (dB)

If more than one treatment is applied to a segment of conveyor, the attenuated sound power per meter of the treated segment of conveyor will be $W \cdot a_1 \cdot a_2 \cdot a_3 \cdot \ldots$ Watts/m,

For the purposes of this example, the relative lengths & locations of the different treatments have been adopted as shown in Figure 3.

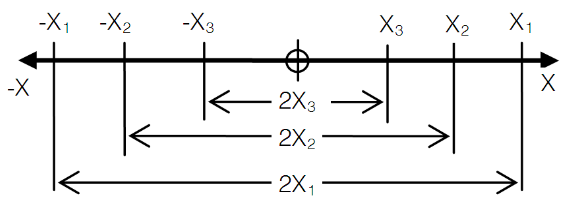

Figure 3 – Noise treatment geometry

Where

$$x_1 \geq x_2 \geq x_3 \geq 0$$

Assuming that noise treatment number 1 exists between $-x_1 \geq x \geq x_1$, and that noise treatment number 2 exists between $-x_2 \geq x \geq x_2$ and noise treatment number 3 exists between $-x_3 \geq x \geq x_3$, then the total noise level received at distance y from a conveyor with the three combined noise treatments is shown in equation (5):

$$L_{tot} = \int_{-\infty}^{\infty} L(x) \cdot dx$$
$$= \int_{-\infty}^{-x_1} L_0(x) dx$$
$$+ \int_{-x_1}^{-x_2} L_0(x) - IL_1 dx$$
$$+ \int_{-x_2}^{-x_3} L_0(x) - IL_1 - IL_2 dx$$
$$+ \int_{-x_3}^{x_3} L_0(x) - IL_1 - IL_2 - IL_3 dx$$
$$+ \int_{x_3}^{x_2} L_0(x) - IL_1 - IL_2 dx$$
$$+ \int_{x_2}^{x_1} L_0(x) - IL_1 dx$$
$$+ \int_{x_1}^{\infty} L_0(x) dx \qquad (5)$$

An example graph of the noise level received at the receptor from a mitigated conveyor is shown in Figure 4.

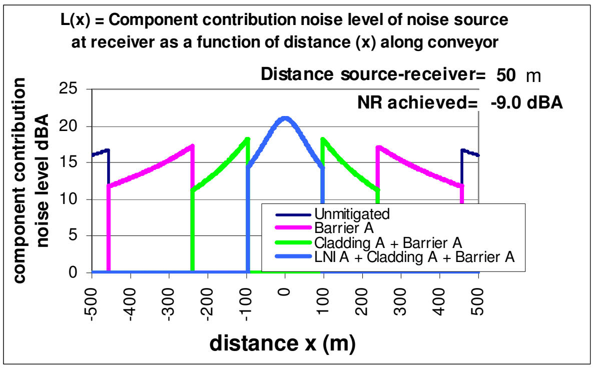

Figure 4-. Component contribution noise level from mitigated conveyor

By definition,

$$L_0(x) = 10\log\left|\frac{p_0^{\;2}(x)}{p_{ref}^{\;2}}\right| \qquad (6)$$

and

$$L_{tot}(x) = 10\log\left|\frac{p_{tot}^{\;2}(x)}{p_{ref}^{\;2}}\right| \qquad (7)$$

The noise level criteria can then be written as shown in equation (8):

$$p_{tot}^{\;2} = p_{criteria}^{\;2} \qquad (8)$$

where $p_{tot}^{\;2}$ = the total received (sound pressure)^2 with noise treatments of any length, and $p_{criteria}^{\;2}$ = the required total (sound pressure)^2.

Combining equations (3) to (8), the nonlinear constrained optimisation problem can therefore be written as shown in equations (9) and (10):

Minimise:

$$f(X) = c_1 \cdot x_1 + c_2 \cdot x_2 + c_3 \cdot x_3 \qquad (9)$$

subject to:

$$p_{tot}^{\;2} - p_{criteria}^{\;2}$$
$$= \frac{W}{W_{ref}} \cdot \frac{p_{ref}^{\;2}}{2\pi} \cdot \frac{2}{y} \cdot \left[\frac{\pi}{2}\right.$$
$$+ (a_1 - 1) \cdot \tan^{-1}\left(\frac{x_1}{y}\right)$$
$$+ a_1 \cdot (a_2 - 1) \cdot \tan^{-1}\left(\frac{x_2}{y}\right) \qquad (10)$$
$$\left. + a_1 \cdot a_2 \cdot (a_3 - 1) \cdot \tan^{-1}\left(\frac{x_3}{y}\right)\right] - p_{criteria}^{\;2} = 0$$

and $x_1; x_2; x_3 \geq 0$

and $x_1 \geq x_2 \geq x_3$

The optimisation process is illustrated graphically for the two dimensional case (i.e. the combination of two noise treatments) in Figure 5.

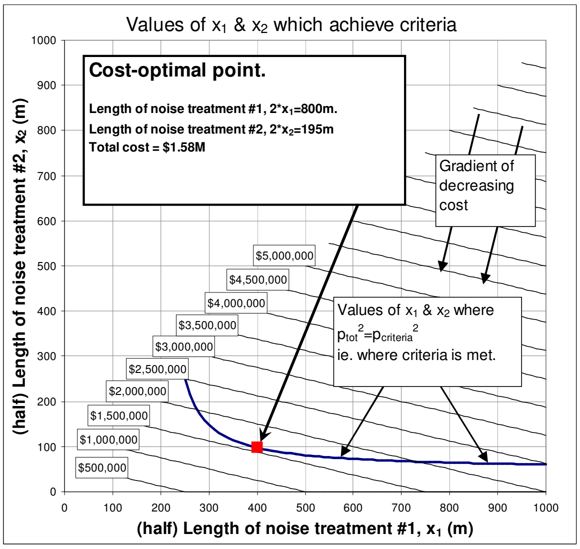

Figure 5: Example 2-dimensional boundary constraint function and cost gradient, showing optimal minimal cost solution.

With n noise treatments, the nonlinear constraint function is an n-dimensional concave surface. The 3-dimensional case is shown in Figure 6.

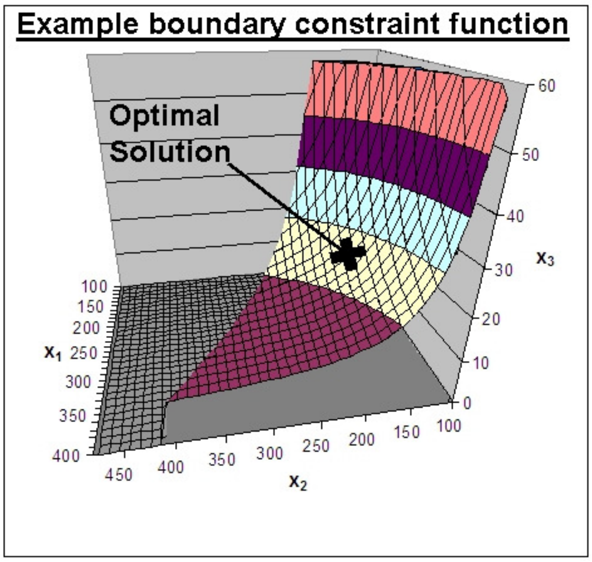

Figure 6: Example 3-dimensional boundary constraint function, showing optimal minimal cost solution

The sensitivity of the procedure to small changes in the required level of noise reduction with a fixed selection and sequence of noise treatments is illustrated in Figure 7.

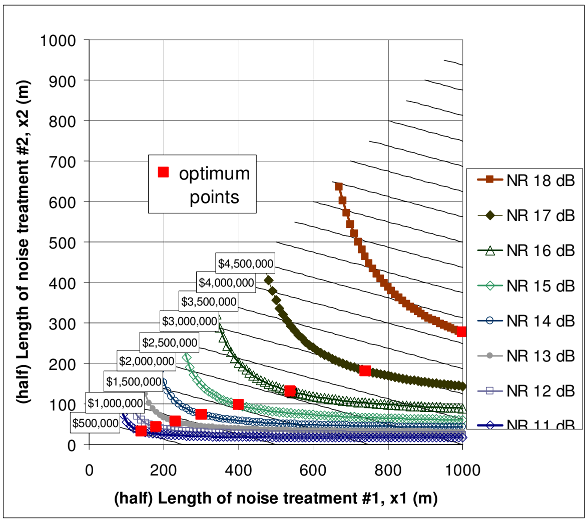

Figure 7 – Sensitivity of boundary constraint function to required noise reduction (dB)

IMPLEMENTATION OF THE METHOD

Since the most cost-efficient arrangement of the three treatment options is unknown, the procedure must be repeated for all permutations of the relative lengths of the treatments in order to find the design that achieves the minimum overall cost.

For example, taking the combination of treatments LNI B, Cladding C and Barrier A, the optimisation process must be undertaken for all of the permutation cases shown in Table 3. Additionally, the calculations must also be undertaken for cases where only two or one of the noise treatments are used, i.e. x_3=0 and x_2=x_3=0.

Table 3: Example of permutations of relative lengths of noise treatments

Longest x_1	Intermediate x_2	Shortest x_3
LNI B	Nil	nil
LNI B	Cladding C	nil
LNI B	Cladding C	Barrier A
LNI B	Barrier A	nil
LNI B	Barrier A	Cladding C
Cladding C	Nil	nil
Cladding C	LNI B	nil
Cladding C	LNI B	Barrier A
Cladding C	Barrier A	nil
Cladding C	Barrier A	LNI B
Barrier A	Nil	nil
Barrier A	LNI B	nil
Barrier A	LNI B	Cladding C
Barrier A	Cladding C	nil
Barrier A	Cladding C	LNI B

The remaining variables investigated for the current example were:

- Separation distance from the conveyor to the receiver, y, chosen as:
  - 10m,
  - 25m,
  - 50m,
  - 100m,
  - 250m,
  - 500m, and
- Level of overall noise reduction required, chosen as:
  - 5dB,
  - 10dB,
  - 15dB,
  - 20dB,
  - 25dB, and
  - 30dB

In total, this results in more than 10,000 calculation scenarios, yielding approximately 4,700 valid computations leading to solutions.

RESULTS

The permutations of the input variables modelled (including separation distances, the required levels of noise reduction and all of the possible combinations of noise treatment options) gives a prohibitively large number of solutions to include in entirety, therefore only an indicative summary of results for several representative cases is provided.

Results are shown in Figure 8 for an example case where the distance to receiver is 50m and the required noise level reduction is 15dB. These results show the optimised minimum-cost design for all of the combinations of noise reduction treatments which achieve the noise level criteria, Of these, the specific combination of treatments which achieves the noise level for the minimum overall cost is then identified by simply finding the minimum of this set of successful results.

Of those successful combinations shown in Figure 8, the specific combination and the lengths of individual treatments which gives the minimum overall cost is LNI type C with Cladding type B and Barrier type A, as shown in Table 4.

Table 4: Optimum solution for *y*=50m, noise reduction required = 15dB

Treatment Type	Length required (m)	Cost ($)
LNI C	3040	$4,57M
Cladding B	681	$2,04M
Barrier A	179	$0,36M
	Total cost	**$6,97M**

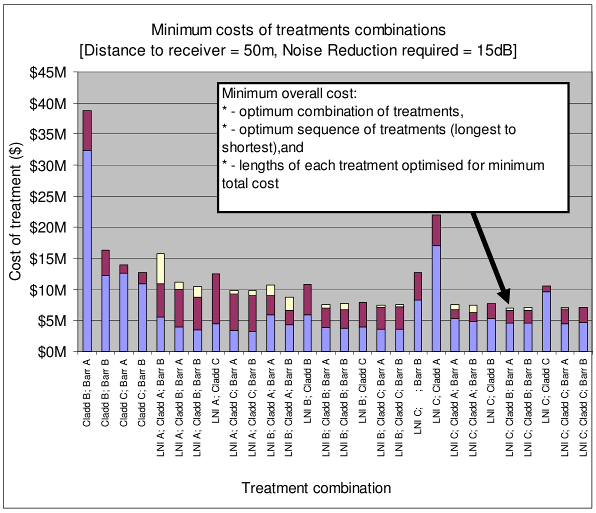

Figure 8: Summary of optimisation results for *y* = 50m, noise reduction required = 15dB

Since the permutation & non-linear programming optimisation procedure is computer-automated, results can also be easily obtained for all of the other cases of required noise level reduction. A summary of the minimum cost solutions for the case of *y*=50m for the various required noise reductions of 5, 10, 15 and 20dB is shown in Figure 9.

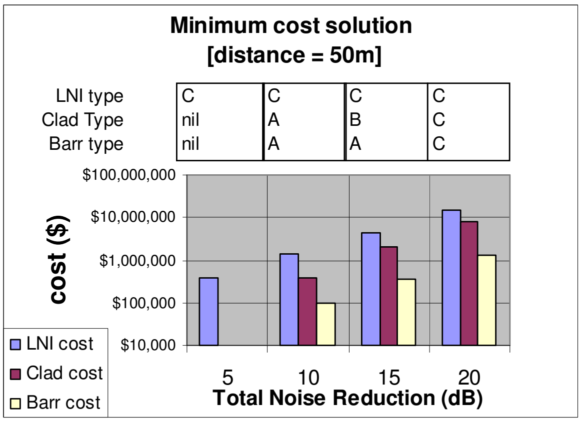

Figure 9: Optimal noise treatment combinations and component cost for various noise reductions, for a separation distance *y* = 50m.

CONCLUSIONS

Clearly, the optimal solution will usually be comprised of different treatment combinations and lengths than a different set of treatments selected based on other design philosophies.

Without following a cost-optimisation approach, the noise treatments would be selected based on some other reasoning, for example:

- The cheapest option (per meter) of each type of noise treatment, or
- The most effective option (highest noise reduction) of each type of noise treatment, or
- The most cost-effective option (highest dB/$/m) of each type of noise treatment

Each of these three strategies for treatment selection may seem likely to achieve the noise criteria for the least possible cost. However, when the optimisation procedure is undertaken, the combination of treatments which yields the optimal solution may in fact be counter-intuitive.

Furthermore, as stated previously, since the currently available software packages are generally not capable of designing for optimum cost, the designer would typically calculate the required lengths of the selected treatments based on a relatively simple method such as solving for the required length of a pre-selected combination of treatments, where the extents of the applied treatments are all equal. With all three treatments being of equal length & location, the noise mitigation strategy is effectively the same as applying one noise treatment comprised of three elements. However, the design strategy of pre-selecting a preferred combination of treatments of equal length does not lead to a minimum-cost solution.

An example of the lengths and corresponding costs which would result from this design strategy, using treatments selected based on the three different reasonings listed above is shown in Figure 10 and Figure 11, compared to the optimal solution.

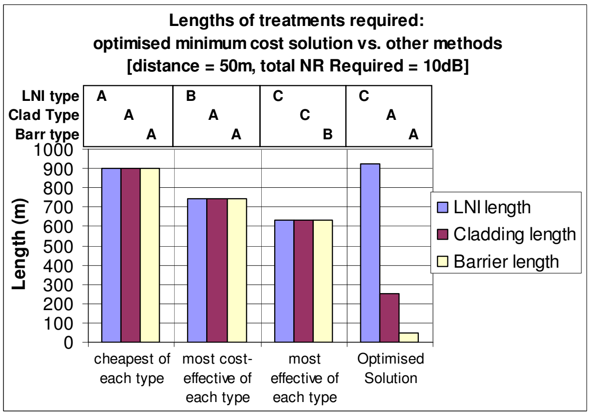

Figure 10: Lengths of noise treatments resulting from an equal-length design strategy compared to the optimal solution

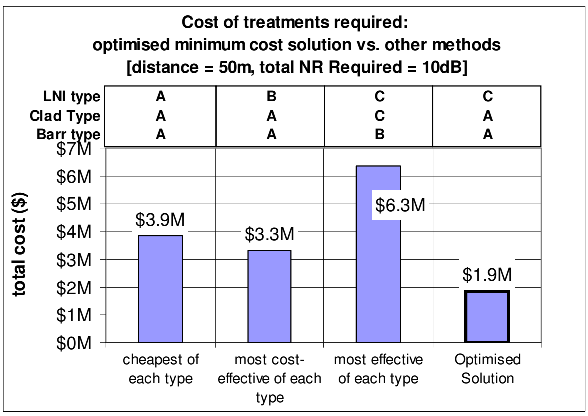

Figure 11: Total cost of noise treatments resulting from an equal-length design strategy compared to the optimal solution

LIMITATIONS AND FURTHER CONSIDERATIONS

The most significant limitations of the method in the example shown are the exclusion of atmospheric effects, topographical shielding, ground absorption and air absorption, which cannot be ignored in practice. If included, the procedure would likely yield substantially different results.

Similarly, the inclusion of spectral information into the procedure would also be likely to give quite different results. In practice, the spectrum of the noise source would need to be included and the spectral noise reduction of treatments should be considered. Fortunately, this additional dimension to the calculations can be incorporated into the procedure relatively easily.

The procedure can also be extended to include an allowance for non-linearly additive treatments, such as vibration isolation devices in conjunction with cladding. The only difficulty would lie in the correct preparation of the objective cost function and constraint function.

The procedure is also quite sensitive to the cost effectiveness of individual treatments, so it is important to accurately establish the capital cost of each treatment including installation labour and expenses. Also, in some cases, the capital cost of noise treatments may be dependent on the quantity purchased. This variable can also be accounted for in the procedure, simply by incorporating this non-linearity into the objective cost function.

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