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Acoustics and Sustainability:

How should acoustics adapt to meet future demands?

Optimisation of Noise Control Design for Environmental Noise Impact, Occupational Health & Safety Noise Exposure, Sustainability Impact and Construction Cost by Multi-Objective Combinatorial Optimisation

Dave J. Davis (1)

(1) Parsons Brinckerhoff, Brisbane, Australia

ABSTRACT

Acoustic design for new industrial plant must often consider a combination of design goals, achieving not only environmental and safety noise level targets, but must also contribute to the project's value management efforts and aim for the best possible sustainability outcome. These requirements are often contradictory and sometimes mutually exclusive, yet the acoustic designer must attempt to balance the overall design with the best possible compromise. A method is proposed which provides acoustic designers with a systematic procedure for adopting the most appropriate noise control strategy solution within the design parameters.

NEED FOR THE METHOD

In the absence of a systematic method, attempts to balance more than one design criteria is usually undertaken by giving one or two of the design goals the highest priority to achieve a high degree of success for these one or two parameters at the expense of the others.

A process is needed whereby disparate design mandates can be integrated into a cohesive approach, enabling an objective analysis and ensuring that all parameters are given due consideration.

OPTIMISATION AS A DESIGN TOOL

Optimisation of acoustical design problems are known to be relatively difficult because of the high non-linearity of the acoustical design parameters and the multi-dimensional physical properties of available materials such as the frequency-dependent sound absorption and transmission behaviour.

When the optimisation goal is to find the design which achieves the best balance or combination of construction materials to achieve more objectives than the simple goal of achieving compliance with the noise level limit, a multi-objective optimisation method is required.

Various methods have been employed for different types of multi-objective acoustical design optimisation problems, such as the Adjoint Variable method (Dong *et al* 2004), the Conjoint Analysis method (Grissom *et al* 2006), utilising Approximation Techniques (Hambric 1995), and hybrid Combinatorial Optimisation/Nonlinear Programming (Davis 2008).

Additionally, the real-world limitations of available construction materials means that the set of feasible solutions is discrete, and so any attempt to formulate an optimisation procedure for multi-objective acoustical design must follow a combinatorial approach rather than a continuous, discrete or (mixed) integer programming method.

A mathematical optimisation procedure is superior to an iterative engineering design procedure such as TRIZ, whereby improvement of one design parameter leads to a degradation in other design parameter(s), which requires other design modifications to compensate for that degradation, and so on. Methods like these are valuable in cases where a truly original solution to a unique design problem is required. However, for repetitive design tasks such as selecting the construction materials of an industrial building, manually iterative design methods like TRIZ are unlikely to ever lead to a truly optimised overall design solution.

A method is required whereby a large number of available construction materials can be compared quickly and effectively to ascertain their relative suitability for the design task at hand, while satisfying several independent design goals.

In the case where an assessment is required of the suitability of these materials for several concurrent and incompatible goals, it is necessary to compare the successfulness of each design using a multi-criteria analysis.

There are several manual multi-criteria decision analysis [MCDA] methods widely used in the engineering and architectural design fields, which are essentially just decision matrices that are heavily reliant upon subjective input data. A multi-objective optimisation procedure is superior to a simple decision matrix, since it can be based on quantifiable “satisfiability” success functions rather than subjective assessments of the various options’ successfulness.

For the case of the noise control design of an industrial building, there are two degrees of freedom which determine the acoustical outcomes: (i) the dissipation of sound energy within the building by absorption, and (ii) the transmission of sound energy through the building’s walls. These are the two design spaces available to the acoustical designer to achieve the noise level goals.

The current paper focuses on selecting the best combination of materials within these degrees of freedom to achieve the design target noise levels inside and outside the building, while also considering the total capital cost of the building, and the total sustainability impact of the building.

However, the nature of the sound reduction properties of physical materials usually means that good performance in one respect corresponds to poor performance in one or more of the other measures. The four design goals are therefore mutually independent and incompatible.

For instance, a wall cladding that is very heavy and therefore has good sound transmission loss will usually require a large amount of energy to extract the raw material from its source, process/manufacture it into a usable product, transport it to site and install it in the final configuration, which would consume relatively large amounts of energy and therefore have a high sustainability impact.

In the current paper, a method is proposed to assist the acoustical designer when faced with the task of selecting the best possible combination of materials that will give a suitable level of sound absorption in the building as well as a suitable sound transmission reduction, while achieving a balance of several incommensurable goals including capital cost and the sustainability impact of the construction materials used.

DESCRIPTION OF THE PROPOSED METHOD

The proposed method is a multi-objective combinatorial optimisation procedure, which is effectively a mathematical formulation of a multi-criteria decision analysis. The proposed method uses a suite of pre-determined design goals, priorities, weightings and penalties in an objective manner to optimise the overall outcome for all of the design parameters. The method is a useful tool to assist during the early design stages of a project, in contrast to the more subjective MCDA methods commonly used in multi-disciplinary design projects which can only be used once several design options have been progressed to an advanced stage of completion.

Several different methods exist to undertake a multi-criteria decision analysis following a mathematical procedure. Two methods in particular are amenable to utilisation in an acoustical design application: the Weighted Goal Programming Method and the Weighted Global Criterion Method.

The Weighted Goal Programming Method

The Weighted Goal Programming Method is formulated as follows:

Minimise

$$Z(X)=\left[\sum_{i=1}^{j}\left(w_i^+ d_i^+ + w_i^- d_i^-\right)^p\right]^{1/p}, \qquad p \geq 1 \tag{1a}$$

subject to

$$\begin{aligned}
&g_i(X) \leq 0, && i=1,2,\ldots,m\\
&f_i(X)+d_i^+ - d_i^- = b_i, && i=1,2,\ldots,j\\
&d_i^+ \geq 0, && i=1,2,\ldots,j\\
&d_i^- \geq 0, && i=1,2,\ldots,j\\
&d_i^+ d_i^- = 0, && i=1,2,\ldots,j\\
&w_i^+ \geq 0, && i=1,2,\ldots,j\\
&w_i^- \geq 0, && i=1,2,\ldots,j
\end{aligned} \tag{1b}$$

Where X is the vector of variables within the degrees of freedom, $Z(X)$ is the overall objective function to be minimised, $f_i(X)$ is the objective function of individual goals, $g_i(X)$ are the boundary conditions of the feasible design space, b_i is the goal set for the i^{th} objective, d_i^+ and d_i^- are the exceedance or the compliance deviations from the i^{th} goal, respectively, and w_i^+ and w_i^- are the weights assigned to the deviations. The exponent p is usually given a value of 2.

The Weighted Goal Programming Method is undertaken in a series of steps, whereby the objective functions are optimised in a priority sequence. The procedure uses ordinal ranking or pre-emptive priorities by assigning incompatible goals to very different priority levels and by applying weighting factors to goals at the same priority level. Thus the Achievement Function for the Weighted Goal Programming Method component of the entire problem is formulated as follows:

Minimise

$$Z=\sum P_k\left[\sum_{i=1}^{j}\left(w_{ik}^+ d_i^+ + w_{ik}^- d_i^-\right)^p\right]^{1/p}, \qquad p \geq 1 \tag{2}$$

Where k is the sequential priority number, with the assumption that Priority P_k is much greater than P_{k+1}.

The Goal Programming Method is commonly described in the literature as being a sequential form of Linear Programming, however it can also be used for combinatorial optimisation.

The Weighted Global Criterion Method

The Weighted Global Criterion Method is somewhat different, whereby a preselected global criterion function is minimised. For instance, this function could be the weighted sum of the (usually squared) relative distances of the individual objectives from their respective feasible ideal solutions or from a preselected target goal value.

The solution is found by minimising the Achievement Function $F(X)$, which often takes the following form:

Minimise

$$F(X)=\left[\sum_{i=1}^{k}\left(w_i \cdot \frac{f_i(X_i^*)-f_i(X)}{f_i(X_i^*)}\right)^p\right]^{1/p} \tag{3a}$$

subject to

$$\begin{aligned}
&g_j(X) \leq 0, \quad j=1,2,\ldots,m\\
&w_i \geq 0
\end{aligned} \tag{3b}$$

where the exponent p is usually 2, and X_i^* is the ideal solution for the i^{th} objective function when the i^{th} goal is considered in isolation.

Discussion of the methods

Each of the Goal Programming and the Global Criterion Methods have limitations in the practical application of acoustical design. In practical applications, neither method is particularly reliable to find the best overall design.

For instance, the basic form of the Goal Programming Method does not allow for an alternative form of "compromise" solution for non-critical design parameters (low priority goals). Additionally, inherent in the process is the assumption that sequentially lower priorities are substantially less important than preceding goals. A significant criticism of the Goal Programming method is that it is likely to miss the Pareto-optimal solution points.

Similarly, the Global Criterion Method is also not ubiquitous for practical acoustical design problems, since it does not allow for situations where the achievement of some goals are non-negotiable, such as a fixed budget and/or a fixed maximum environmental noise level. Neither does it allow for cases where you may wish to regard the overachievement of one or more goals as irrelevant.

Thus the general observation that there is 'no free lunch in search and optimisation' holds true for the case of the current multi-objective problem. While both methods are useful for multi-objective acoustical design problems (Proos *et al* 2001), neither the Goal Programming nor the Global Criterion multi-objective optimisation methods can be relied upon exclusively as the sole tool sufficient to optimise the acoustical design of an industrial building when simultaneously considering noise level, cost, and sustainability impact.

Therefore a hybrid method is proposed, comprised of the Weighted Goal Programming Method and the Weighted Global Criterion Method, both of which are adaptable for combinatorial optimisation problems.

If one or more goals are regarded as non-negotiable, such as a maximum allowable environmental noise level and/or a fixed maximum capital cost, then the Weighted Goal Programming Method should be used for these first Priorities, and then a compromise solution for the remaining goals can be found using the Weighted Global Criterion Method.

IMPLEMENTATION OF THE METHOD

Sustainability Impact

A quantifiable measurement is required to assess a building's "sustainability impact". The concept of Embodied Energy [EE] is one method to estimate a building's environmental sustainability impact. Specifically, it is a measure of the amount of energy required to manufacture, supply and install a material at the building site, and some measures also include the energy required to ultimately disassemble, recycle, or dispose of the product at the end of its life. This energy quantity can also be converted into a proportional mass of carbon dioxide emitted to produce that energy. A building construction material's embodied energy value is therefore a useful quantity to allow a numerical analysis of the sustainability impact of a complete building.

Some building construction elements are common for all buildings, irrespective of the types of cladding or internal sound absorptive lining material that may be used, such as the concrete slab flooring, footings and structural steel supports. In this paper, only the construction materials that are within the acoustical designer's degrees of freedom have been considered.

A note on Embodied Energy

There are many different established methods to calculate the Embodied Energy of construction materials. No international consensus has yet been reached as to standardisation of these methods, yet they all yield results measured in energy units. Care must be taken to ensure that the same procedure has been used to calculate the embodied energy of the different construction materials being investigated.

Scaling

With both the Weighted Goal Programming and the Weighted Global Criterion Methods, scaling of the various objective goal functions is critical, to avoid biasing. For design parameters which are quantified in linear scales, including capital cost ($) and embodied energy (MJ), scaling is achieved by normalising the measures as follows:

$$d_i^+ = \frac{\text{predicted value}}{\text{goal}} - 1, \quad d_i^+ \ge 0, \quad \left(\frac{\text{predicted value}}{\text{goal}}\right) \ge 1 \qquad (4a)$$

$$d_i^- = \frac{\text{goal}}{\text{predicted value}} - 1, \quad d_i^- \ge 0, \quad \left(\frac{\text{goal}}{\text{predicted value}}\right) \ge 1 \qquad (4b)$$

However, in the case of acoustical design, scaling is particularly important for the acoustical design goals because of the logarithmic measure of noise levels in decibels.

In the proposed method, the estimated noise levels are scaled relative to the target environmental and occupational noise levels in a manner similar to the conversion of phons into sones, where a difference of 10 phon corresponds to a change in sones by a factor of 2. The method adopted in this paper is that a difference of 10 dB(A) between the predicted noise level and the target noise level criterion is regarded as an exceedance or compliance by a factor of 2. Thus the deviations d^+, d^- representing the underachievement or overachievement of the noise level goals, respectively, have been determined according to the relationship:

$$d_i^+ = 2^{(\text{predicted-goal})/10} - 1, \quad d_i^+ \ge 0, \quad (\text{predicted - goal}) \ge 0 \qquad (5a)$$

$$d_i^- = 2^{(\text{goal-predicted})/10} - 1, \quad d_i^- \ge 0, \quad (\text{goal - predicted}) \ge 0 \qquad (5b)$$

where the predicted and the goal noise levels are given in dB(A).

The subtraction of 1 from the 2^x term results in the deviation representing a percentile difference in loudness. Thus, if $d_i^+ = 1$, the resultant noise level is twice as loud as the target noise level, equal to a noise level that is 100% louder than the goal. Similarly if $d_i^- = 1$ then the goal would be 100% louder than the resultant predicted noise level.

THE PROPOSED HYBRID METHOD

The proposed hybrid method firstly uses the Weighted Goal Programming Method to sequentially evaluate the Achievement Function for those objectives which have had a Priority assigned to them, and then to use the Weighted Global Criterion Method to evaluate the other components of the Achievement Function for the remaining objectives.

The first part of the process involves undertaking the Goal Programming method on all of the objectives including the prioritised objectives with appropriately selected weightings of each objective at each priority. For the purposes of scaling, the Achievement Function has been formulated with deviations in percentage from the target value of the objective function for each goal. The proposed Goal Programming method's Achievement Function is formulated as follows:

$$Z(X) = \sum P_k \left[\sum_{i=1}^{j} \left(w_{ik}^{+} d_i^{+} + w_{ik}^{-} d_i^{-} \right)^2 \right]^{1/2} \qquad (6)$$

Where P_k are scalar constants selected by the management representing the relative importance of the sequentially prioritised goals, and w_{ik} are scalar weighting factors applied to the deviations of each objective which can vary with different priority levels.

The second part of the process involves undertaking the Global Criterion method on the remaining objectives. For the purposes of scaling, the Achievement Function has been formulated with deviations in percentage from the minimum value of the objective function for each goal. The proposed Global Criterion method's Achievement Function is formulated as follows:

$$F(X) = \sqrt{\left(\sum_{i=1}^{k} \left(w_i \delta_i \right)^2 \right)} \qquad (7)$$

where δ_i is the deviation of the objective's value from the minimum value of the objective function for each goal. For the noise level objectives, the deviations are measured in percentage of difference in loudness, as described above.

The value of the Achievement Function *F*(*X*) obtained for the non-prioritised goals is then added to the sub-total of the Achievement Function *Z*(*X*) obtained earlier for the weighted prioritised goals via the Goal Programming method.

EXAMPLE CASE STUDY

Formulation of the example case

To illustrate the proposed method, an example case study is presented whereby several different construction materials have been selected, the objectives which are assigned as Priorities have been nominated, and priority values and weighting factors have been chosen.

The construction materials investigated for the examples given in this paper are as follows:

- Wall/roof cladding panel types:
  - Type 1. sheet steel
  - Type 2. pre-cast concrete panel
  - Type 3. strawboard panel
- Internal wall/roof sound absorptive lining types:
  - Type 0. Nil
  - Type 1. glass fibre wool insulation
  - Type 2. mineral wool insulation
  - Type 3. polyester insulation
  - Type 4. exposed strawboard with ~200mm air-space

The physical properties of these materials are shown in Tables 1 and 2. The data shown are indicative only and should not be regarded as typical.

The physical properties of the example wall & roof cladding materials are shown in Table 1.

Table 1. Cladding Materials

Cladding Type	Type 1	Type 2	Type 3
	Sheet steel	Pre-cast concrete panel	Straw-board
Thickness (mm)	0.55	100	50
Mass (kg/m^2)	4.3	240	11.5
Cost (\$/m^2)	50	150	20
Embodied Energy (MJ/m^2)	208.8	480	12.6

The physical properties of the example sound absorptive materials that are available for lining the inner surfaces of the building's walls and roof are shown in Table 2.

Table 2. Internal sound absorptive lining materials

Internal lining type	Type 1	Type 2	Type 3	Type 4
	Glass fibre wool	Mineral fibre wool	Poly-ester insula-tion	Ex-posed straw-board
Thickness (mm)	50	50	50	50
Mass (kg/m^2)	1.6	3	2.4	11.5
Cost (\$/m^2)	25	20	13	10
Embodied Energy (MJ/m^2)	48.5	43.8	128.9	12.6

The target goals selected for each of the objectives are shown in Table 3.

Table 3. Target Goals for objectives

Total Budget	Embod-ied Energy MJ	Environmental Noise Level dB(A)	OHS Noise Level dB(A)
\$350,000	400,000	35	80

The physical dimensions of the building are shown in Table 4. The distance to the external receiver was assumed to be 50m.

Table 4. Physical dimensions of industrial building

Length m	Width m	Height m
25	50	10

The combined sound power level of the sources within the building are shown in Table 5 and the distance to the internal receiver was assumed to be 5m.

Table 5. Combined sound power level of noise sources

f(Hz)	SWL dB(lin)
31.5	92.4
63	91.2
125	90.7
250	91.5
500	91.8
1000	93.2
2000	95.1
4000	93.9
8000	92.4

The assumed sound radiation directivity pattern of the building's walls and roof were as shown in Figure 1 and Table 6 (from Parzych 1999)

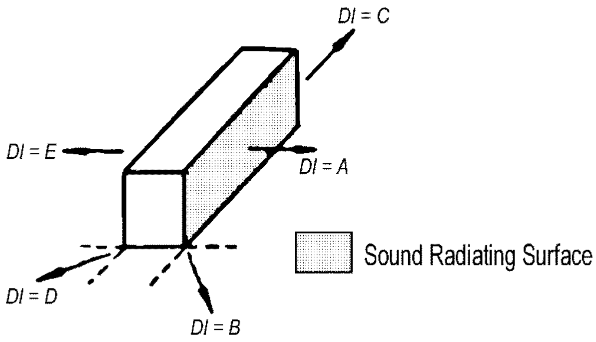

Figure 1. Directivity directions (from Parzych 1999)

Table 6. Wall/roof sound radiation directivity pattern (from Parzych 1999)

f(Hz)	Directivity of Wall Radiation					
	DI = A	DI = B	DI = C	DI = D	DI = E	DI = roof
31.5	0	0	0	0	0	-5
63	0	0	0	-6	-6	-5
125	0	0	-1	-8	-8	-5
250	0	0	-2	-13	-13	-5
500	0	0	-3	-19	-19	-5
1000	0	0	-4	-24	-24	-5
2000	0	0	-4	-25	-25	-5
4000	0	0	-4	-25	-25	-5
8000	0	0	-4	-25	-25	-5

The calculated results of the four design objectives for each of the material combinations are shown in Tables 7 to 10. Calculated values which achieve the goals are designated with (*).

Table 7. Construction cost of material combinations ($)

Type of internal lining	Cladding panel type		
	1	2	3
0 (nil)	$137,500*	$412,500	$55,000*
1	$206,250*	$481,250	$123,750*
2	$192,500*	$467,500	$110,000*
3	$173,250*	$448,250	$90,750*
4	$165,000*	$440,000	$82,500*

Table 8. Total Embodied Energy of material combinations (MJ)

Type of internal lining	Cladding panel type		
	1	2	3
0 (nil)	574,200	1,320,000	34,650*
1	707,575	1,453,375	168,025*
2	694,650	1,440,450	155,100*
3	928,675	1,674,475	389,125*
4	608,850	1,354,650	69,300*

Table 9. Environmental (external) noise level with different material combinations dB(A)

Type of internal lining	Cladding panel type		
	1	2	3
0 (nil)	47.0	16.2*	44.5
1	30.5*	7.9*	39.3
2	30.2*	7.8*	39.3
3	31.2*	8.7*	39.6
4	31.3*	8.8*	40.4

Table 10. OHS (internal) noise level with different material combinations dB(A)

Type of internal lining	Cladding panel type		
	1	2	3
0 (nil)	82.9	82.5	80.7
1	72.0*	72.0*	72.0*
2	72.2*	72.2*	72.2*
3	72.4*	72.4*	72.4*
4	74.1*	74.1*	74.1*

As shown in Tables 7 to 10, there is no combination which achieves all of the objective goals.

The square-root sum of squares of the unweighted deviations from each goal are shown in Figure 2.

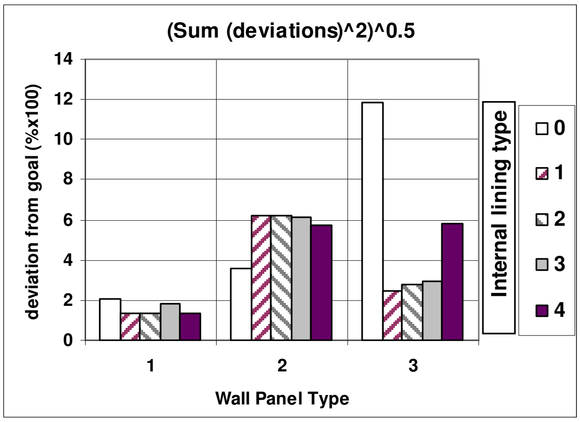

Figure 2. Root sum of squares of unweighted deviations from the goals

The example design case demonstrated below is for a typical industrial building with various pre-selected Priorities and importance weightings.

The problem is set up as follows:

- Priority 1 = Cost
- Priority 2 = Environmental Noise Level
- Non-prioritised objectives:
  - OHS Noise Level
  - Embodied Energy

The Priority and deviation weighting factors for the first stage of the solution (the Goal Prgramming Method) are shown in Table 11.

Table 11. Priority and deviation weightings for Prioritised Objectives

Design Parameter	Priority 1		Priority 2	
	P_1=10		P_2=7	
	w_i^+	w_i^-	w_i^+	w_i^-
Cost	10	0	5	1
EE	2	2	2	2
Env. Noise	4	1	10	0
OHS Noise	3	1	3	1

The Priority 1 components of the Achievement Function are shown in Figure 3.

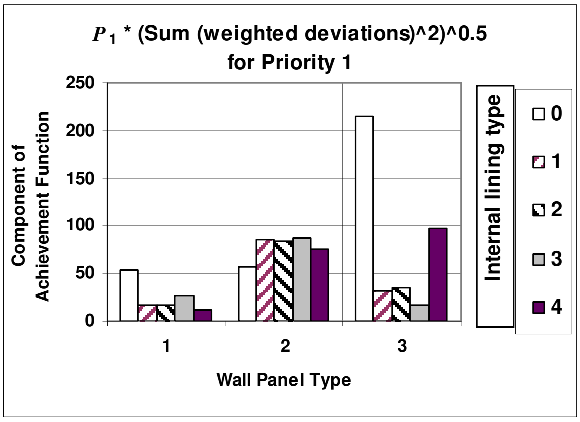

Figure 3. Priority 1 component of the Achievement Function

The Priority 2 components of the Achievement Function are shown in Figure 4.

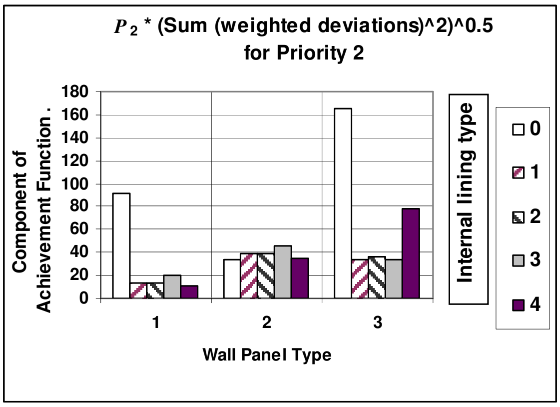

Figure 4.Priority 2 components of the Achievement Function

The second step in the method is to undertake the Global Criterion component of the Achievement Function for those design goals which have not had a Priority assigned to them.

In this example case study, these parameters are the total Embodied Energy and the internal OHS noise level. The importance weightings for these objectives are shown in Table 12.

Table 12. Weightings for Non-Prioritised Objectives

Design Parameter	w_i
EE	2
OHS Noise	3

The Global Criterion Method component of the Achievement Function is shown in Figure 5.

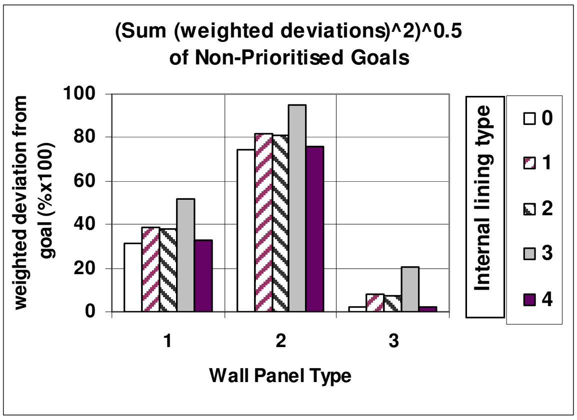

Figure 5. Global Criterion Method component of the Achievement Function

The final step of the procedure is to sum the two Achievement Functions, which is simply to add the values shown in Figures 2, 3 and 4 for each combination of cladding material and inner surface lining. The total Achievment Function is shown in Figure 6.

As shown in Figure 6, the material combination which achieves the best minimum overall Achievement Function according to the priority sequence, the priority weighting factors and the importance weighting factors shown in Tables 11 and 12 is wall panel type 1 (sheet steel) and internal surface lining type 4 (exposed strawboard).

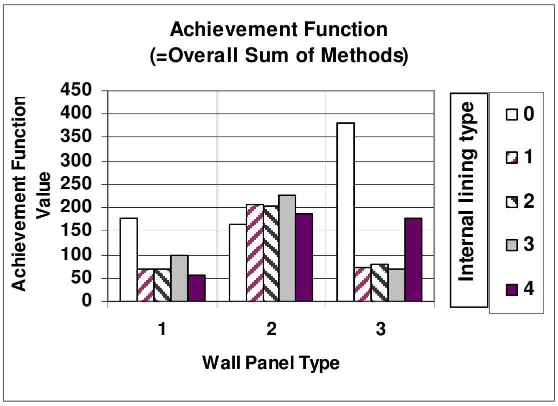

Figure 6. Overall total Achievement Function

The values of the design parameters corresponding to this material combination, and the overachievement or underachievement of the respective goals are shown in Table 13.

Table 13. Comparison of optimised design against goals

	Total Cost \$M	Embodied Energy GJ	Environmental Noise Level dB(A)	OHS Noise Level dB(A)
Target	0.35	0.4	35	80
Result	0.165	0.61	31.3	74.1
Difference	0.185	-0.21	3.7	5.9

Other combinations which achieve almost the same degree of overall success are:

- Wall panel type 1 (sheet steel), with
    - Inner surface lining type 1 (glass fibre) or type 2 (mineral wool), or

- Wall panel type 3 (strawboard), with
    - Inner surface lining type 1 (glass fibre wool), type 2 (mineral fibre wool) or type 3 (polyester fibre wool)

LIMITATIONS OF THE METHOD AND FACTORS TO CONSIDER

Since the Goal Programing Method provides solutions which minimise the deviations from the set goals, it is capable of erroneously penalising certain solutions which achieve extremely good compliance for particular objectives. For instance, in the example cases given, a concrete panel cladding achieves an environmental noise level substantially lower than the target, but the method impartially regards this difference simply as a deviation, neither good nor bad. Similarly, the material combination which results in the "worst" overall Achievement Function is Wall Panel Type 3 with no internal surface lining (ie. Type 0) due the the relatively low cost and embodied energy being substantially less than the goals for these two parameters. Since the crux of the method is to minimise all deviations, an extremely good solution such as in these two examples may be disregarded by the method as quite poor solutions. Since the method regards positive or negative deviations as simply "distance from the goal", the result is a poor overall Achievement Function. However, this type of undesirable conclusion can be avoided by applying a weighting factor of 0 for the compliance deviation for the prioritised goals at the appropriate Priority step. Alternatively, if the acoustical designer would prefer the method to encourage design solutions which achieve results lower than the target for certain objectives, this problem could be rectified by modifying the method by applying a factor of -1 to $(w_i^- d_i^-)^2$ for those objectives. By doing this, the overall Achievement Function may then become negative for those solutions. The optimal solution would then be reached by accepting possibly negative Achievement Function results.

In regards to the construction cost, the method described has considered only the capital cost of the construction materials and the on-site installation cost. However, ideally the comparative assessment of alternative materials should be based on the total life-cycle costs. This is a particularly important consideration for materials specifically chosen for their low sustainability impact (embodied energy) since they can have relatively short lifespans and may require replacement several times over the life of the building leading to a recurring operational cost. Likewise, the total sustainability impact of the building also depends upon the lifespan of the materials used. Therefore the method could be improved by considering the net-present-value of the total lifecycle financial and embodied energy costs.

CONCLUSIONS AND FURTHER DEVELOPMENT

A method has been presented whereby the acoustical design of an industrial building can be undertaken by simultaneously considering the external noise emissions, the internal noise levels, the construction cost and the environmental (sustainability) impact.

The optimal result will be the best combination of available construction materials which achieves the best possible compromise of the target goal values of the various objective design paramaeters, based on a pre-selected priority sequence and importance weightings.

Potential improvements to the method

The example shown in this paper has restricted the input variables to only a few options for wall & roof construction materials and types of internal sound absorptive linings. With more than a few variables, the number of possible combinations rises rapidly, which would require more advanced optimisation routines to reach a solution. If very many different materials were available for selection, one of the more sophisticated optimisation techniques would need to be employed, such as the Branch-and-Bound method, the method of Simulated Annealing, the Genetic Algorithm method and so on.

Further development of the method could be directed toward including the ability to optimise the design such that each of the building's walls and roof could have different panel materials and internal linings. This approach could be developed even further, by allowing each of those walls to have infinitely variable proportions of different construction materials in each wall/roof. However, it is likely that this problem would be strongly NP-hard, and so an approximation method would likely be required (Klein & Young 1999), (Ehrgott & Gandibleux 2004).

The process can be further improved by implementing the procedure using interactive steps and assisted with heuristic algorithms intended to simulate the designer's preferences and decisions (Alves & Climaco 2000).

Still further improvements could be implemented by replacing the first stage of the method with a Meta-Goal Programming process (Rodríguez Uría *et al* 2001).

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