

## Monte Carlo Analysis for Prediction of Noise from a Construction Site

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**Abstract:** The large number of operations involving noisy machinery associated with construction site activities result in considerable variation in the noise levels experienced at receiver locations. This paper suggests an approach to predict noise levels generated from a site by using a Monte Carlo approach. This approach enables the determination of details regarding the statistical uncertainties associated with noise level predictions or temporal distributions. This technique could provide the basis for a generalised prediction technique and a simple noise management tool.

**Keywords:** Noise, Prediction, Construction, Stochastic

### INTRODUCTION

Noise arising from construction activities is a common problem in many places. The noise levels detected at the receiver can be regarded as random variables in a stochastic process and the interactions between these variables are complex. However, in reality, the noise generated at the source by the operation of construction equipment will vary with time. This is typically due to conditions occurring when some operations items in the project may be off, idling, operating under light load, or variation not only affects the distance between the source

and observer but also alters the effect of screening, ground cover, and other mitigating factors.

The current procedure, BS 5228 (1997), deals with the above mentioned variation by using certain gross simplifications and/or requires the user to repeat the already cumbersome analysis using different sets of parameters. The use of Monte Carlo techniques has been suggested to enable prediction of a set of noise levels weighted by their probabilities and governed by stochastic factors or temporal distribution. This approach has an advantage over the currently used procedure since it yields information regarding the temporal distribution of noise levels arising from site operations and produces a mean level associated with a standard deviation. The mean level is equivalent to an equivalent noise level ( $L_{Aeq}$ )

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corresponding to that of the typical work day yielded by the current BS 5228 (1997).

The importance of temporal distribution in subjective response was recognised in the early days of environmental noise research, and a number of complex noise units were proposed which involved temporal parameters. Lately, the significance of temporal distribution has been stressed by Raimbault and Dubois (2005) who suggested that the assessment of an acoustic environment also depends on information regarding the content of the sound. This group pointed out that sound quality cannot be determined by  $L_{Aeq}$  alone. In fact, temporal distribution for the workday period is of current interest in research on environmental noise. For example, this issue has been recognised in recent contemporary work on soundscape by Yang and Kang (2005) and Wong et al. (2004).

The factors which determine the temporal distribution of noise levels experienced at a receiver due to site operations can be summarised as follows:

- Acoustic characteristics of each item of noise-producing equipment (sound power level, operational cycle, directivity, etc.).
- Location of each item of noise-producing equipment.

- Proportion of time during which each item operates concurrently or nonconcurrently with other items of equipment.

In construction site noise prediction, the Monte Carlo approach was suggested by Carpenter (1997) and was first developed by Waddington and Lewis (2000), who investigated the variation in noise level from a well-defined area at a site by taking into consideration the random power of the source and its random location. The Monte Carlo technique has also been used by Gilchrist et al. (2003) to study sound from construction site operations by considering the random operating status of each machine. However, Waddington and Lewis (2000) and Gilchrist et al. (2003) did not produce a temporal distribution in their analysis.

The Monte Carlo approach employs numerical modelling techniques and requires the following:

1. A list of noise source variables (stochastic variables) that affect the noise at the receiver,
2. Generation of the variables in the form of a specific probability distribution (such as uniform, normal or exponential), and

3. Sets of deterministic equations. The model generates a random number used to sample the stochastic variables from the assumed probability distribution and input them to specified deterministic equations. The random number is normally a pseudo-random number uniformly distributed over the specified 0 to 1 interval. Figure 1 shows the relationship between the random number generated by the computer and the stochastic variable,  $g$ , assumed to have a normal distribution.

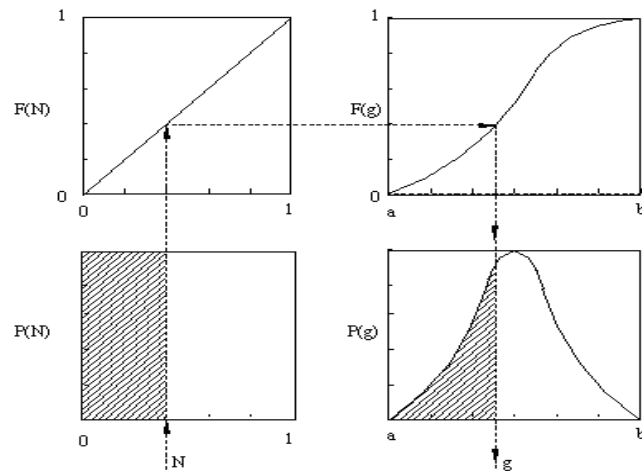


Figure 1. Relationship between the Random Numbers Generated by the Computer and the Stochastic Variable  $g$

When a random number,  $N$ , is selected from a uniform distribution,  $P(N)$ , the value of  $N$  points to a value in the cumulative distribution probability,  $F(N)$ . This value then points to an associated value in the assumed cumulative distribution of the stochastic variable  $F(g)$ . Subsequently, this will in turn point to a value in the stochastic variable distribution,  $g$ . The process actually equates the hatched areas under the uniform distribution  $P(N)$  and  $P(g)$ . The areas under the  $P(N)$  curve from 0 to 1 and under the  $P(g)$  curve from  $a$  to  $b$  are both equal to 1. When a large number of random numbers are chosen, the set of associated  $g$  values will be sampled from  $P(g)$  in a non-biased way such that a histogram of the chosen  $g$  values will mimic the original function  $P(g)$  (Haron and Oldham, 2004).

In this paper, the determination of a basic temporal noise level distribution for a single source and multiple noise sources will be highlighted. Stochastic variables such as the random position and its duty cycle are used, and the model employs the important noise sources of earth-moving machinery that moves randomly around the site (Koyasu, 1984; Ferguson, 1995; Beaman and Jones, 1977). All simulations are carried out using computer models implemented in MATLAB 7.2. The results of simulations using the Monte Carlo method are compared with results obtained from that of BS 5228 (1997).

## BASIS OF MODELLING USING THE MONTE CARLO APPROACH

The approach developed in this paper is different from that of the current procedure, BS 5228 (1997) in that the noise generation and propagation processes are represented statistically. The noise levels predicted are represented by mean values with a standard deviation. The model uses the same method developed by Waddington and Lewis (2000) where simulations of the time history are based upon sampling the noise from the site operations over the relevant operational period. Each site operation is assumed to take place over a well-defined subarea and a noise source is assumed able to be located at any point in that subarea with equal probability. In this section, the application of the Monte Carlo method to simulate the noise level distribution from a single noise source is first considered by taking into consideration the random position of the equipment and its duty cycle.

### A Single Noise Source with Single Operating Cycle

The model considers the site area with width  $w$  and depth  $d$  and a receiver located at a distance,  $r$ , from the sub-site centre. A noise source can be located at random positions in that subarea with equal probability (see Figure 2).

The coordinates of the location of the equipment,  $x_i$  and  $y_i$ , can be defined using two random numbers,  $M_i$  and  $N_i$ , respectively where:

$$x_i = w (M_i - 0.5) \quad (1)$$

$$y_i = d (N_i - 0.5) \quad (2)$$

The sound intensity at a receiver from a particular source location is obtained by assuming hemispherical radiation over a hard surface and is given by:

$$I_{ij} = \frac{W_a}{2\pi r_{ij}^2}, \quad (3)$$

Where  $W_a$  is the acoustic power of the source, and  $r_{ij}$  is the distance from source position  $(x_i, y_i, z_s)$  to the receiver  $(x_r, y_r, z_r)$  given by:

$$r_{ij} = ((x_i - x_r)^2 + (y_i - y_r)^2 + (z_s - z_r)^2)^{0.5} \quad (4)$$

The sound pressure level at the receiver is found by:

$$L_{(i,j)} = 10 \log_{10} (I_{(i,j)} / 10^{(-12)}) \quad (5)$$

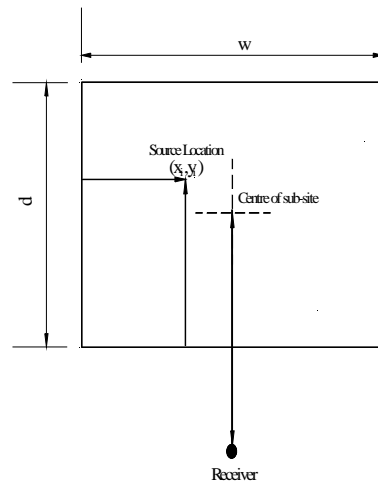


Figure 2. Location of Stochastic Source on Sub-site Area of Operation for Monte Carlo Method

By obtaining a number of samples, a statistical analysis can be carried out to determine the temporal distribution in terms of a probability distribution, PDF, and cumulative distribution function, CDF. It is also possible to determine the value of the mean intensities by summing the sampled intensities and by dividing the number of samples.

The mean level can then be expressed as an equivalent intensity level or equivalent sound pressure level,  $L_{Aeq}$ . The standard deviation can also be obtained.

### A Single Noise Source with Complex Operating Cycle

An item of machinery might typically generate a number of different sound power levels in the course of a workday, depending upon its pattern of use. For example, it might be completely off for  $A\%$  of the workday, be at idle for  $B\%$  of the workday, and operate at full power for  $C\%$  (Waddington and Lewis, 2000; Gilchrist et al., 2003). In order to consider the effect of the operational cycle, another random number,  $N_k$ , can be used to sample whether the machine is operating at full power, idling, or off from a known probability distribution. The appropriate acoustic power of the equipment can then be employed.

### The Noise Level Distribution or Temporal Distribution

Simulation of the sound pressure level variation arising from the operation of a single noise source was carried out using the Monte Carlo method implemented in MATLAB 7.2. The routine was written using the flow chart shown in Figure 3. The model inputs include the dimensions of the site ( $w$  and  $d$ ), and the sound power of the equipment. There are three stages; Stage 1 is determination of the position of the equipment by obtaining random numbers  $N_i$  and  $N_j$  and

obtaining the random power of the source from random number  $N_k$ . Stage 2 is the calculation of the noise level at the receiver. For multiple items of equipment, Stage 1-2 is repeated. Stage 3 involves the analysis of the noise levels after a number of samples have been obtained. Statistical information such as histograms and the frequency of occurrence or probabilities that the noise falls within a specified 1 dB range can be determined. The PDF and CDF are then determined with the vertical axis normalised to a maximum value of one and the horizontal axis relating to the noise levels.

Computations were carried out for a site area of 200 m x 100 m with two situations: 1) an item of equipment with acoustic power of 1 watt ( $W_a = 120\text{dB}$ ) operating continuously, 2) two items of equipment with the same acoustic power but with duty cycles of 20% idle/80% fully on and 20% off/20% idle/60% fully on. For both occasions, a receiver was positioned at 60m from the site centre perpendicular to the site boundary. The height of receiver and source were assumed the same.

Trials showed that large samples up of to 20,000 are required to obtain a smooth PDF curve (see Figure 4a). For an item of equipment operating continuously, the PDF has a uni-modal distribution skewed to the left. The percentage of time exceeded is equal to  $(1-\text{CDF}) \times 100$ . With CDF equal

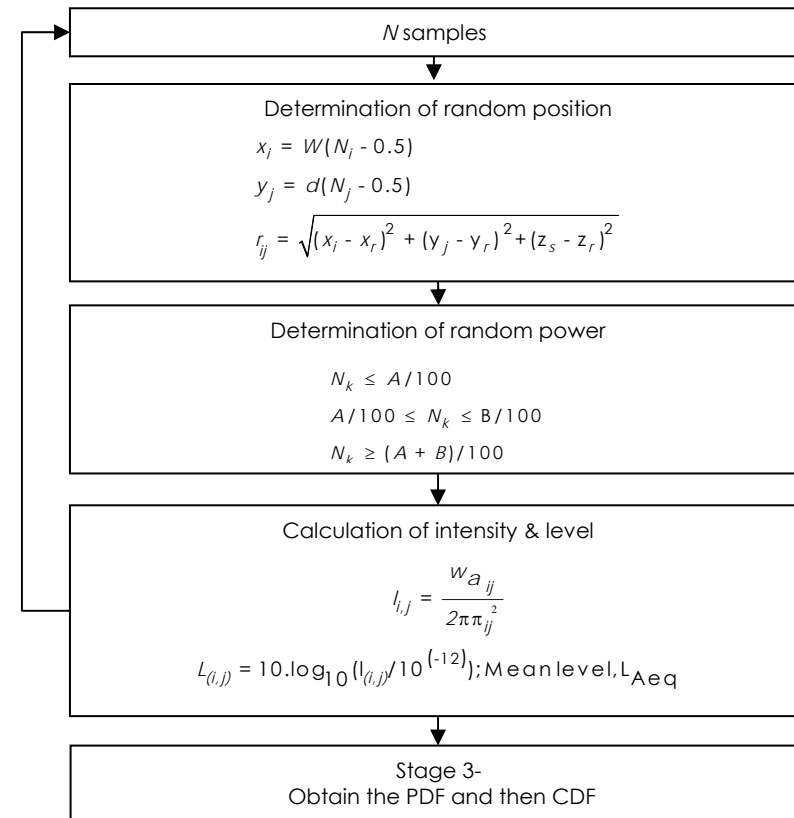


Figure 3. Flow Chart for Monte Carlo Method Simulation for Single Piece of Equipment

to 0.1,  $L_{90}$ , the level exceeded 90% of the time, can also be predicted and can be assumed as the basis for assessing background noise, which is prominent in most standards.  $L_{10}$  is the noise level exceeded 10% of the time, represents the peak noise level, and also can be obtained on the same way.  $L_{10}$  roughly equates to the higher annoying levels, which is a value required in the Department of Environment (DOE, 2004) guidelines or regulation. Note that

$L_{50}$  is *not* equal to  $L_{Aeq}$ , as it is in logarithmic units. When replaced with two items of equipment with different duty cycles, the PDF changes to a bi-modal shape with two peaks corresponding to idle mode and full power on mode, respectively (see Figure 4b). It can be observed that the temporal distribution is also affected by the sound power levels corresponding to the duty cycle.

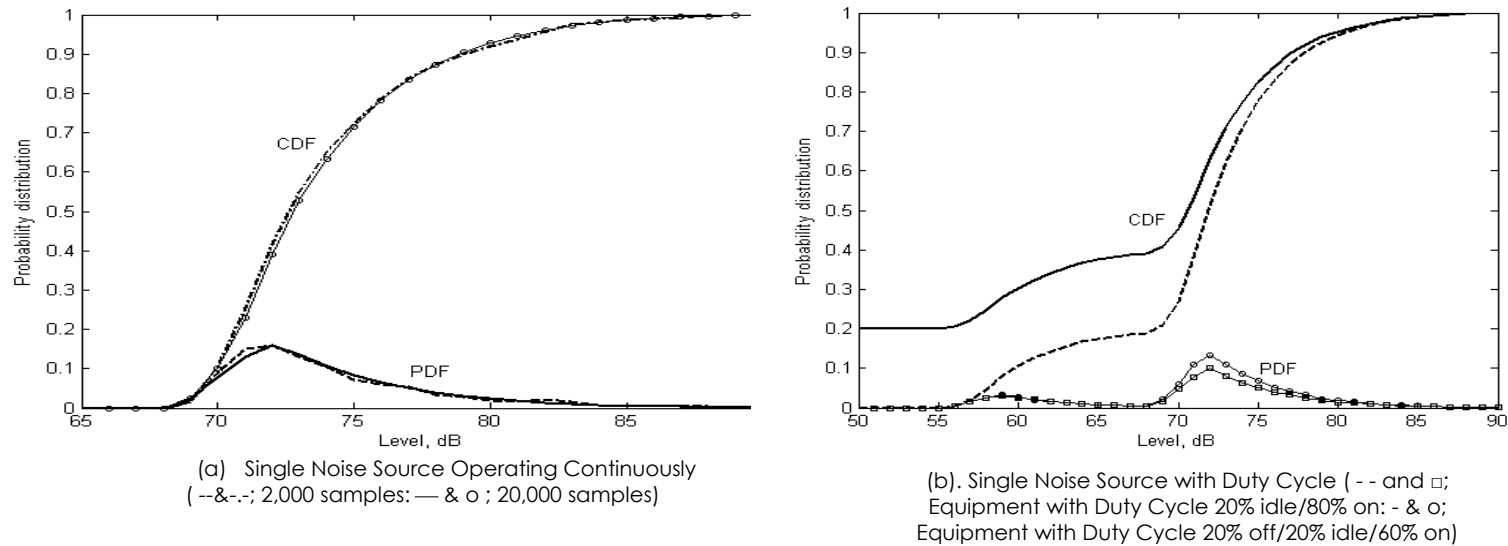


Figure 4. PDF and CDF of Single Noise Source Simulation

## PREDICTION OF NOISE LEVELS FROM MULTIPLE SOURCES

Normally, a number of noise sources are in simultaneous operation, and therefore it is possible for an item of equipment to be operating either concurrently or nonconcurrently with any other item of equipment. Only concurrent operation will be considered in this paper. To obtain the temporal distribution, probability laws (Ayyub and McCuen, 2003; Kapadia et al., 2005; Kottegoda and Rosso, 1998; Taylor and Karlin, 1998) are employed. The combined probability distribution for equipment operating concurrently can be determined using a method first proposed by Nelson (1972, 1973a, 1973b). Noise-producing equipment are called events "A<sub>*n*</sub>", where *n* is number of equipments. Consider a simple case of two items of equipment A<sub>1</sub> and A<sub>2</sub>, working concurrently. The total working period is *T* hours, known as the sample space, whilst PDF(A<sub>1</sub>) and PDF(A<sub>2</sub>) are the PDF for events A<sub>1</sub> and A<sub>2</sub>, respectively.

The combined probability distribution for equipment operating concurrently can be determined using the intersection law (Ayyub and McCuen, 2003; Kapadia et al., 2005; Taylor and Karlin, 1998). The method was first proposed by Nelson (1972, 1973b) for a combination of noise level distributions in traffic noise prediction. When two items of equipment work concurrently over a period of *T* hours, the PDF's for each event, PDF(A<sub>1</sub>) and PDF(A<sub>2</sub>), are

easily determined. Each PDF is represented by a set of number pairs, one relating to a noise level (centre of class interval) and one to the corresponding probability such that

- L<sub>1i</sub> and P<sub>1i</sub> where i=1,2,5..m for PDF(A<sub>1</sub>)
- L<sub>2j</sub> and P<sub>2j</sub> where j=1,2,5..m for PDF(A<sub>2</sub>)

Subscript 1 and subscript 2 refer to PDF(A<sub>1</sub>) and PDF(A<sub>2</sub>), respectively, as shown in Figure 5. L refers to the level, P to the probability of that level, and *i* and *j* refer to particular samples of the first and second distribution, respectively.

The combined probability that the noise level from PDF(A<sub>1</sub>) is L<sub>1i</sub> when the level from PDF(A<sub>2</sub>) is L<sub>2j</sub> is given by:

$$P_{ij} = P_{1i} \cdot P_{2j} \quad (6)$$

The combined noise level arising from the contributions of both distributions is given by:

$$L_{ij} = 10 \log_{10} \left[ 10^{(L_{1i})/10} + 10^{(L_{2j})/10} \right] \quad (7)$$



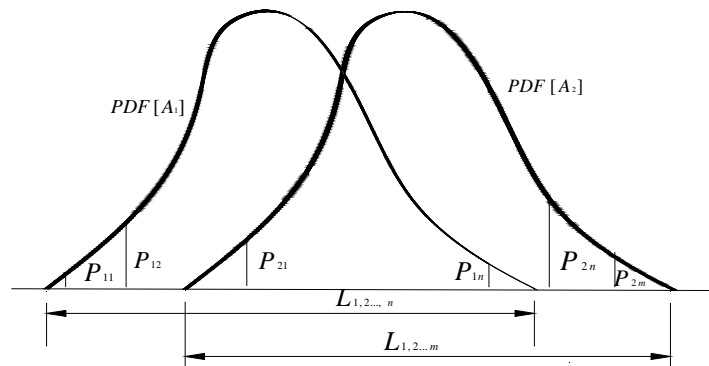


Figure 5. Division of two PDF for Concurrent Combination Operation

The combined PDF is obtained by defining new class intervals and summing the probabilities associated with the levels that fall within these class intervals. This technique is not limited to the combination of levels from two sources but can be applied to any number of sources. The combined probability distributions for the noise levels from concurrent operation were obtained by repeating the procedures shown in the flow chart in Figure 6 for each piece of equipment and combining the obtained PDF using Equations 6 and 7.

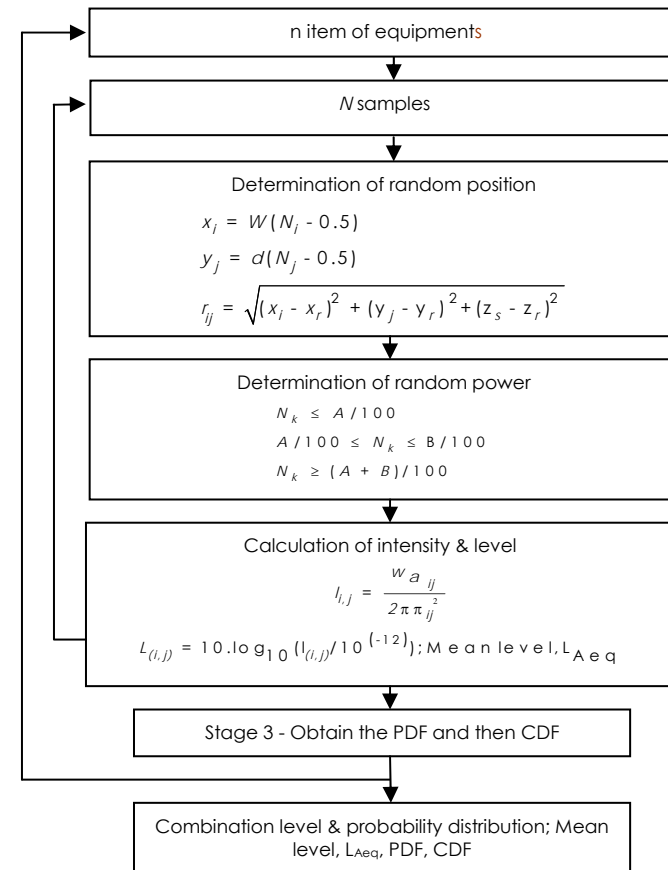


Figure 6. Flow Chart for Monte Carlo Method Simulation for Multiple Sources

### COMPARISON BETWEEN RESULTS FROM MONTE CARLO APPROACH AND BS 5228

Comparison between the results obtained using current procedure BS 5228 and the Monte Carlo simulation were carried out at a site which consisted of three subsites. Each subsite contains one item of equipment (see Figure 7) assumed to be operating over its particular area. All equipment is assumed to be working concurrently over a period of 12 hours. In BS5228, the noise at the receivers is predicted in Annex D, Part 1. Two methods, the activity and the plant sound power level, can be used but in this calculation the latter method was chosen due to the availability of sound power level data. Note that the first approach requires the sound level at a certain distance which is not available in this case. Noise levels were collected at the receiver based on the noise generated by the three items of equipment. Figure 8 shows the calculation steps in the plant sound power level method. Correction factors were applied to the sound power level to account for factors such as distance between the source and receiver, any screening between source and receiver, whether the receiver is in front of a reflecting surface, and periods of operation of plant or equipment. Only the first and the latter factors were available and taken into account in the calculations. The distance between source and receivers is assumed as the distance

between the receiver and the equipment located at the centre of each working area.

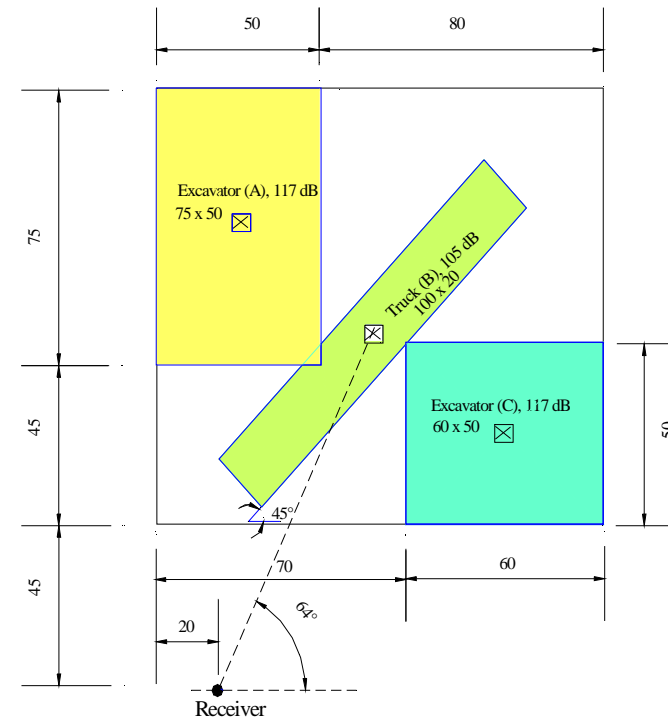


Figure 7. Site Configuration

In the Monte Carlo approach, a total of  $N=20,000$  samples were used to generate random positions of the two items of equipment operating simultaneously. The results of  $L_{Aeq}$  from BS 5228 and the Monte Carlo are the same, i.e., 70.9 dB. However, the results of Monte Carlo are accompanied by standard deviation of 0.3 dB. The PDF and CDF of noise levels during a work day period, weighted by their probabilities corresponding to operation of all items of equipment obtained from the Monte Carlo approach, are shown in Figure 9.

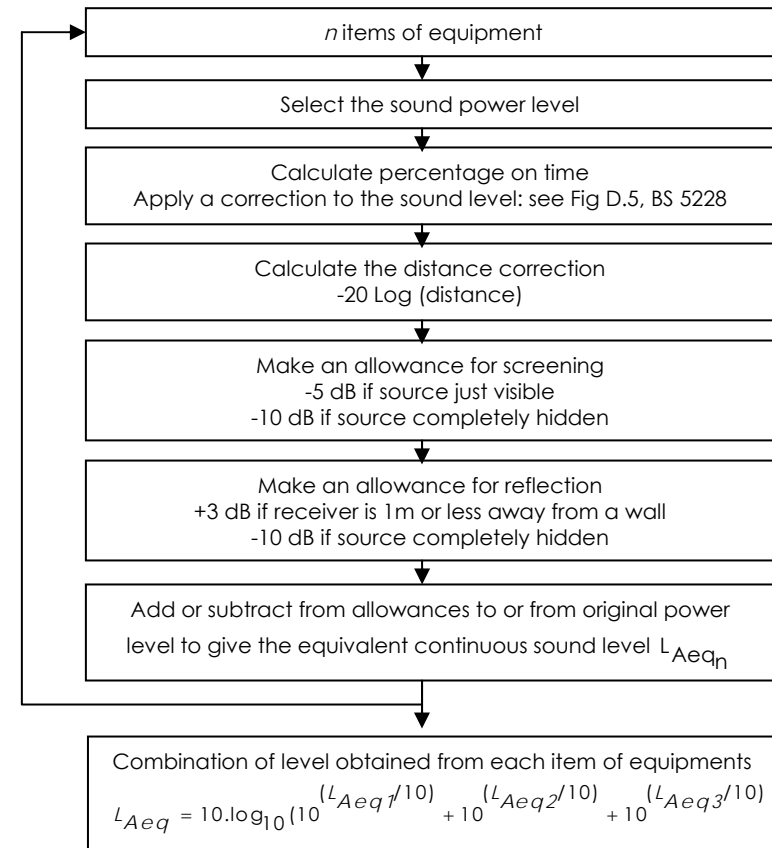


Figure 8. Flowchart for Sound Power Level Method, BS 5228

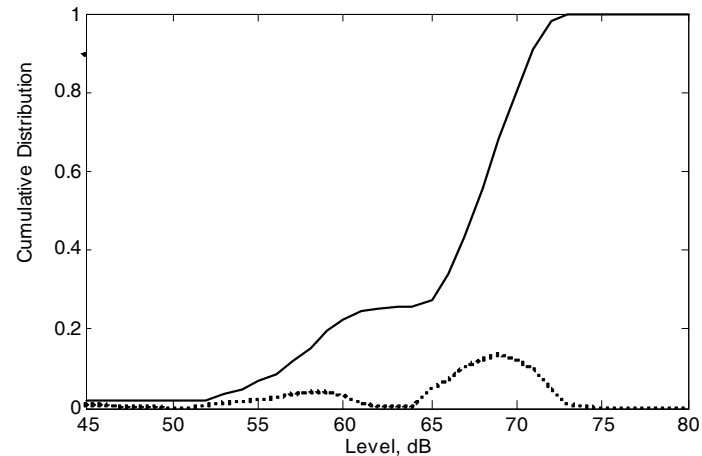


Figure 9. Cumulative Frequency Distribution Corresponding to Operation of All Items of Equipment

## DISCUSSION

While BS 5228 merely predicts the equivalent continuous noise level,  $L_{Aeq}$ , the Monte Carlo approach enables the statistical representation of noise generation and propagation. The final results are the predicted mean noise level (which is assumed similar to  $L_{Aeq}$ ) as well as the standard deviation and the temporal noise level or noise level associated with the probability distribution for a

workday period. The generation of the temporal distribution makes this result different from the result obtained from the current procedure (BS 5228, 1997) and also from the previous Monte Carlo method developed by Waddington and Lewis (2000) and Gilchrist et al., (2003). Through the temporal distribution obtained, the content of sound during one day, such as  $L_{10}$  and  $L_{90}$ , can be determined easily. The temporal noise level distribution can be related or could then be used to predict the  $L_{Aeq}$  experienced over a short time period as usually measured by local authority staff when checking for conformance with a specified level during the construction process (DOE, 2004).

The processing time required for predictions carried out using MATLAB 7.2 was also very short, indicating possible use of available powerful, flexible, and inexpensive modern personal computers. This will enable further investigation of the effect of site parameters on noise levels at receiver locations in the vicinity of the site. It could thus be used as the basis of a prediction technique if employed in a systematic examination of the variation in noise levels with distance for a range of site aspect ratios. Expressions could be obtained to predict the mean sound level and standard deviation as a function of parameters such as distance, site aspect ratio, screening, etc., and to derive simple design charts for planning purposes.

## CONCLUSION

This paper describes the basis of stochastic modelling using a Monte Carlo approach to obtain the temporal noise level distribution arising from construction site operations. The results obtained have shown that this method is capable of predicting the temporal distribution due to either individual noise source or a combination of noise sources. The method has advantages over the present procedure as it enables the determination of any indices required in evaluating the environmental quality. This can facilitate decision-making processes where noise is a potential problem. The method could additionally be used as the basis of an operational management tool. Thus, the construction project manager could rapidly establish the probability of exceeding a specified limiting noise level.

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