Thammasat Int. J. Sc. Tech., Vol. 13, No. 1, January-March 2008

Hybrid Procedure for Optimal Design of Public Announcement System for Adequate Audibility

Krisada Asawarungsaengkul
Industrial Engineering Program
Sirindhorn International Institute of Technology
Thammasat University, Pathum Thani 12121, Thailand

Suebsak Nanthavanij
Engineering Management Program
Sirindhorn International Institute of Technology
Thammasat University, Pathum Thani 12121, Thailand

Abstract

This paper discusses an analytical hybrid procedure for an optimal design of a public announcement (PA) system so that voice messages can be adequately heard by intended listeners in a designated area. The PA system design emphasizes three design specifications, namely, input power of loudspeaker, number of loudspeakers, and their locations in the area. Generally, the area can be defined according to the characteristic of ambient noise as (1) constant-noise area, and (2) time-dependent-noise area. Initially, the input power of loudspeakers is estimated. Then, the PA system problem is mathematically formulated and solved. The solution yields a minimum number and location of loudspeakers. For the area where ambient noise is time-dependent, two noise situations are defined, low-noise and high-noise. Two mathematical models are formulated, one for the high-noise situation and the other for the low-noise situation. The solution of the first model yields the minimum number and location of loudspeakers for the high-noise situation. Based on the solution of the first model, the second model is then solved for the low-noise situation. The new solution describes which loudspeakers should be turned off so as to prevent the announcement sound level to be too loud. A numerical example is given to demonstrate the proposed design procedure.

Keywords: Ergonomics, public announcement system, noise, optimization, audibility

1. Introduction

The public announcement (PA) system is a communication system in which information is given to intended listeners in a designated area. In general, a PA system is used to convey voice messages to listeners for various purposes, such as general information, warning, prohibition, and emergency. The PA system consists of a message announcer, amplifier, and a set of loudspeakers installed at pre-defined locations. A live message announcer (a human speaker) normally speaks into a microphone which will transform the voice announcement into electrical signals, be amplified (to increase the sound level) by the amplifier, and be sent to the loudspeakers. The loudspeakers then convert electrical signals to sound waves. The sound level generated by a loudspeaker depends on the input power and the loudspeaker's sensitivity level. The sensitivity is defined as the sound level per watt per meter (as measured at a 1-m distance from the loudspeaker). More often, the human speaker is replaced by a recorder/player unit if the messages can be pre-recorded for multiple announcements.

The PA system is commonly found in both business and public places. For the former, the noise environment is relatively quiet, constant with time, uniform, and well controlled. Examples are the environments in business offices and business buildings. For the latter, ambient noise is rather time-dependent, nonuniform, and greatly affected by other noise sources in the area. Examples of public places are bus stations, train stations, subway stations, university campuses, and shopping malls. At those places, noise levels at different locations in the area are different ranging from quiet to very noisy. They can vary with time depending on the existence of noise sources. Consider a subway station platform as an example. While subway commuters are waiting for the subway train to arrive, the noise level is relatively quiet. However, when the train approaches the platform, the noise level increases significantly and then decreases as the train comes to a complete stop. Then, the noise level increases and decreases again when the subway train leaves the platform.

While the PA system is installed in the business and public places to convey voice messages, its effectiveness in both places can differ significantly. At the subway station platform, the announcement coming out from the loudspeakers can be quite easily heard when the train has not yet arrived at the station. While the train is arriving, the announcement is barely audible and perhaps only those commuters standing near the loudspeakers can comprehend the announcement message. Increasing the input power of the loudspeakers to increase the announcement sound level might not be a good solution since the announcement will then be too loud during the quiet period. For another example, consider a university campus where the announcement is to be made to students in the library and in the cafeteria. Due to such vast differences in ambient noise levels between the two areas, it is essential that the announcement sound level must be different for both areas. This can be achieved by using loudspeakers with different sensitivity levels, selecting the appropriate number of loudspeakers for each area, and installing them at appropriate locations.

The PA system problem can be viewed as a variant of the auditory warning system problem. The loudspeakers in the former are identical to the alarm devices in the latter. For the auditory warning system, the design objective is to determine the sound level of a alarm device, and the optimal number and location of the alarm devices. This objective is similar to that of the PA system problem. Recommendations and guidelines for the ergonomic design of a auditory warning system can be found in Kantowitz and Barry [1], Sanders and McCormick [2], Stanton and Edworthy [3], Edworthy and and Hards [4].

As for the quantitative design approach, Nanthavanij and Yenradee [5] and Nanthavanij [6] developed an analytical method to predict the location of a single alarm device by considering the influence of ambient noise, location and sound level of other noise sources, and worker locations in the workplace. Later, Nanthavanij and Yenradee [7] developed a predictive method for the multiple alarm devices problem. Briefly, a nonlinear mathematical model was developed to represent the multiple alarm devices problem. One of the constraints required that the alarm sound level reaching each worker location must sufficiently exceed the overall noise level so as to be clearly heard by workers. According to the ISO 7731: 2003 [8], a worker is considered to have successfully detected the alarm signal if and only if the combined alarm sound level (from all alarm devices installed in the workplace) reaching the worker is at least 15 dBA higher than the combined noise level. Asawarungsaengkul and Nanthavanij [9] developed a heuristic procedure to solve the large-sized multiple alarm devices problem.

In this study, the PA system problem is treated by using a similar approach that was applied to the multiple alarm devices problem [7]. The paper is organized as follows. Firstly, we describe the PA system problem, give assumptions, and define the notation used in the model formulation. Next, we explain the design procedure including the determinations of the input power of loudspeaker, and the number and location of loudspeakers for the designated area. Then, we give a numerical example to demonstrate the proposed design procedure. Finally, the conclusion is given.

2. Public Announcement (PA) System Problem

The PA system problem can be stated as follows. For a given area where there are several locations with the presence of intended listeners, an optimal PA system is designed such that all listeners at individual locations can adequately hear the announcement using the minimum number of loudspeakers. The system design specifications include the input power of loudspeaker, and the number and location of loudspeakers. It is essential that the announcement sound level must be loud enough to be heard adequately at noisy locations, yet not be too loud at quiet locations. Specifically, at any location, the combined sound level from all loudspeakers must exceed the combined noise level by at least 15 dB*A*.

2.1 Assumptions

The PA system problem is based on the following assumptions.

1. All loudspeakers are identical, i.e., they have the same sound power.
2. All loudspeakers are installed at the ceiling.
3. There are no effects of sound absorption and/or reflection from the ceiling, floor, walls, or sound barriers.
4. All noise sources are a pointed source. Noise is propagated from the source equally in all directions.
5. Locations where intended listeners are present are known and can be represented by a pair of x and y coordinates in the Euclidean system.
6. Noise levels at all listener locations are known.

In this paper, the area where the PA system is to be installed can be divided into two types, a type-I area and a type-II area, depending the characteristic of ambient noise.

Type-I area: an area where the ambient noise level is relatively low and constant. In this area, the number of noise sources is small and their noise levels are also low. Examples of type-I areas are: classroom, library, business office, restroom, and hospital.

Type-II area: an area where the ambient noise level is rather high and time-dependent. For simplicity, two noise situations are considered for type-II areas, namely, a low-noise situation and a high-noise situation. Examples of type-II area are: subway train platform (the low-noise situation is observed when no trains are at the station platform; the high-noise situation is the one when the subway train is approaching the platform) and student recreation area at a university campus (the low-noise situation is the one when classes are in session; the high-noise situation is the one during the class-break period or the lunch period.)

Additionally, two types of loudspeakers are considered in this paper, low-sensitivity and high-sensitivity.

2.2 Notation

The mathematical model of the PA system problem follows the notation shown below.

d_{ij} = Euclidean distance between listener location i and loudspeaker j $= \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + h^2}$
h = ceiling level height (m)
$\overline{I}_i$ = sum of noise intensity at location i (W/m^2)
$\overline{Is}_i$ = sum of loudspeaker sound intensity at location i (W/m^2)
L_{ab} = ambient noise level (dB*A*)
$\overline{L}_i$ = area (combined) noise level at location i (dB*A*)
Ls = sound level of loudspeaker (dB*A*)
$\overline{Ls}_i$ = combined sound level from all loudspeakers at location i (dB*A*)
m = number of listener locations
n = number of loudspeakers
$P_{\max}$ = maximum loudspeaker sound power (W)
Q = maximum x co-ordinate of the area
R = maximum y co-ordinate of the area
(x_i, y_i) = (x, y) co-ordinates of listener location i
(x_j, y_j) = (x, y) co-ordinates of loudspeaker j

2.3 Determination of Loudspeaker Sound Level

The loudspeaker sound level can be determined using the following procedure.

For Type-I Area:

1. Set $L_{\text{ab,min}}$ equal to the lowest ambient noise level (dB*A*) in the area.
2. Set S equal to the sensitivity (dB*A*/W/m) of the low-sensitivity loudspeaker.
3. Determine the sound level of loudspeaker for the area with the lowest ambient noise level, Ls(initial), from:

$$Ls(\text{initial}) = L_{\text{ab,min}} + 33 \qquad (1)$$

where: $Ls(\text{initial}) \leq 10\log(P_{\max}) + S$

4. Determine the input power (in Watt, W) of loudspeaker P from:

$$P = 10^{\frac{Ls(\text{initial})-S}{10}} \tag{2}$$

5. Determine the sound level of loudspeaker from:

$$Ls = 10\log(P) + S \tag{3}$$

For Type-II Area:

Set S equal to the sensitivity (dBA/W/m) of the high-sensitivity loudspeaker. Compute the sound level of loudspeaker Ls using Eq. (3).

2.4 Model Formulation

Two mathematical programming models are developed for the PA system problem. The first model, Model A, is used to determine the optimal number and location of loudspeakers. This model is applicable for both type-I and type-II areas.

For the type-II area, the result of Model A applies to the high-noise situation. In order to determine the solution for the low-noise situation, the second model, Model B, must be applied. The result of Model B will recommend the optimal number and location of loudspeakers that are required for the low-noise situation so that the announcement will not be too loud. Basically, Model B will use the result of Model A to determine which loudspeakers should be turned on and which should be turned off so as to prevent the announcement from being too loud.

Readers should note that the use of both models will provide the solution for only one area, i.e., the area under investigation. If the building or place has several sections or areas with different ambient noise characteristics, they must be separately considered to determine the number and location of loudspeakers for those areas. Nevertheless, the input power of all loudspeakers is the same.

2.4.1 Model A

Model A, which is used to determine the optimal number and location of loudspeakers for type-I and type-II areas (high-noise situation), is a nonlinear programming model. Its objective is two-fold:

1. To determine the minimum number of loudspeakers for that area.

2. To determine the optimal location of those loudspeakers.

It is noted that an important constraint that the model must satisfy is that the announcement sound level must exceed the noise level by at least 15 dBA at every listener location.

Let n' be an estimated number of loudspeakers for the designed area. If n' is too large, the PA system problem becomes large and the computation time can be very long. On the other hand, if n' is too small, the problem is infeasible to solve.

To estimate the number of loudspeakers n' that will be just sufficient for the PA system problem, the following two methods can be utilized. Firstly, Method I is applied to estimate n'. If a feasible solution cannot be found from Model A, then estimate n' using Method II.

Initially, determine B_i from:

$$B_i = \frac{10^{1.5}}{10^{(L_s-120)/10}} \cdot \overline{I}_i \qquad i = 1,\ldots,m$$

Method I:

$$n' = \sum_{i=1}^{m}\left(\frac{B_i}{1/h^2}\right) \tag{4}$$

Note that n' must be rounded to the next larger integer.

Method II: This method consists of 3 steps.

1. Calculate $\frac{1}{h^2}$ and $\left(\frac{1}{B_i} - h^2\right)^{1/2}$ for all i's.

2. Based on the results from Step 1,

2.1 if $\frac{1}{h^2} < B_i$, then $n_i = \frac{B_i}{1/h^2}$ for all i's.

Round n_i to the next larger integer.

2.2 if $\frac{1}{h^2} > B_i$ and $\left(\frac{1}{B_i} - h^2\right)^{1/2} <$

$\max\{Q/2, R/2\}$, then $n_i = 1$ for all i's.

2.3 if $\frac{1}{h^2} > B_i$ and $\left(\frac{1}{B_i} - h^2\right)^{1/2} >$ $\max\{Q/2,\ R/2\}$, then $n_i = 0$ for all i's.

3. The estimated number of loudspeakers n' is computed from $n' = \sum_{i=1}^{m} n_i$.

Then, let N_j^{A} be a binary integer variable (where $N_j^{\mathrm{A}} = 1$ if loudspeaker j is chosen, and $N_j^{\mathrm{A}} = 0$ otherwise) and Z be the number of loudspeakers. Model A can be expressed as follows.

$$\text{Minimize } Z = \sum_{i=1}^{m}\left[\sum_{j=1}^{n'}\left(\frac{1}{d_{ij}^2}\cdot N_j^{\mathrm{A}}\right) - B_i\right]$$

subject to

$$\sum_{j=1}^{n'}\frac{1}{d_{ij}^2}\cdot N_j^{\mathrm{A}} \geq B_i \qquad i = 1,\ldots,m$$

$$B_i = \frac{10^{1.5}}{10^{(L_s-120)/10}}\cdot \overline{I}_i \qquad i = 1,\ldots,m$$

$$x_j \leq Q \qquad j = 1,\ldots,n'$$

$$y_j \leq R \qquad j = 1,\ldots,n'$$

$$N_j^{\mathrm{A}} = (0,1) \qquad j = 1,\ldots,n'$$

Solving Model A will yield these results.

1. The minimum number of loudspeakers n^*.

2. A set of optimal locations, $(x_j, y_j)^*$, of loudspeakers for $j = 1,\ldots, n^*$.

2.4.2 *Model B*

For those areas having two noise situations, Model B is applied to attenuate the announcement sound level for the low-noise situation. This helps to make sure that the announcement will not be too loud when the ambient noise level is low. The solution of Model A gives the number of loudspeakers according to the high-noise situation (or the worst-case solution). To reduce the announcement sound level, it is possible to turn off some loudspeakers. Basically, from the solution of Model A, Model B will determine which loudspeakers should be kept on (or active) and which should be switched off (or inactive).

Letting N_j^{B} be a binary integer variable (where $N_j^{\mathrm{B}} = 1$ if loudspeaker j is chosen, and $N_j^{\mathrm{B}} = 0$ otherwise) and Z the number of loudspeakers, Model B is expressed as follows.

$$\text{Minimize } Z = \sum_{i=1}^{m}\left[\sum_{j=1}^{n^*}\left(\frac{1}{d_{ij}^2}\cdot N_j^{\mathrm{B}}\right) - B_i\right]$$

subject to

$$\sum_{j=1}^{n^*}\frac{1}{d_{ij}^2}\cdot N_j^{\mathrm{B}} \geq B_i \qquad i = 1,\ldots,m$$

$$B_i = \frac{10^{1.5}}{10^{(L_s-120)/10}}\cdot \overline{I}_i \qquad i = 1,\ldots,m$$

$$x_j \leq Q \qquad j = 1,\ldots,n^*$$

$$y_j \leq R \qquad j = 1,\ldots,n^*$$

$$N_j^{\mathrm{B}} = (0,1) \qquad j = 1,\ldots,n^*$$

Note that in Model B, all B_i's must be recomputed since all $\overline{I}_i$'s will be based on the low-noise situation.

3. Design Procedure

The PA system design procedure can be summarized by the following steps.

Step 1: Define the areas where the PA system must be installed.

Step 2: For a designated area, define the (x, y) coordinates of all listener locations. The maximum values of the x-coordinate and y-coordinate must also be determined.

Step 3: Measure the noise levels at all listener locations.

Step 4: Compute the input power of a loudspeaker.

4.1 For type-I area, choose a low-sensitivity loudspeaker. Define the ambient noise level that is constant and lowest. Then, compute the input power of the loudspeaker and the loudspeaker sound level.

4.2 For type-II area, choose a high-sensitivity the loudspeaker. From the input power of the loudspeaker determined in Step 4.1, compute the loudspeaker sound level.

Step 5: Formulate the PA system problem using Model A. Then, solve Model A to optimality.

5.1 For type-I area, the solution will give the optimal number and location of loudspeakers for the designated area.

5.2 For type-II area, the solution will give the optimal number and location of loudspeakers for the high-noise situation of the designated area. Re-formulate the PA system problem using Model B and noise data of the low-noise situation. Based on the number and location of loudspeakers obtained from Model A, solve Model B to optimality. The new solution will be the optimal solution for the low-noise situation.

Step 6: Repeat Steps 2 – 5 for all areas.

4. Numerical Example

Suppose that an effective PA system is being designed for a train station. The station has two areas where voice announcements are meant to be heard. The first area is the ticket office where two officials are stationed to sell tickets. The second area is the train station platform where train commuters wait for the arriving trains.

The ticket office is the type-I area. Its ambient noise is relatively constant at 65 dBA. Its dimensions are 5 m × 5 m. The ceiling height is 4.5 m. Listener locations and noise levels in the ticket office are given in Table 1. The train station platform is the type-II area. The platform dimensions are 50 m × 50 m. Listener locations and noise levels at the platform are also given in Table 1.

For this problem, the sensitivity levels of low-sensitivity and high-sensitivity loudspeakers are assumed to be 85 and 95 dB*A*/W/m^2, respectively.

Table 1. Listener Locations and Noise Levels for the Ticket Office and Train Station Platform

Ticket Office				Train Station Platform				
Location	Coordinate (m)		Noise (dBA)	Location	Coordinate (m)		Noise (dB*A*)	
	x	*y*			*x*	*y*	Low	High
1	2.0	0.5	65	1	2.0	1.5	68	74
2	3.0	0.5	65	2	3.0	1.5	69	74
				3	15.0	15.0	68	77
				4	35.0	15.0	70	76
				5	10.0	25.0	74	83
				6	20.0	25.0	75	83
				7	30.0	25.0	76	85
				8	40.0	25.0	76	84

For the ticket office, and based on the formulas and models in Section 2 and the design procedure in Section 3, we obtain the following results. Using low-sensitivity loudspeakers (S = 85 dB*A*/W/m),

$Ls(\text{initial}) = 65 + 33 = 98$ dB*A*

$P = 10^{\frac{98-85}{10}} = 20$ W
$Ls = 10\log(20) + 85 = 98$ dB*A*
$B_1 = 0.0159$
$B_2 = 0.0159$
$n' = 1$

From Model A, the optimal location of the loudspeaker is at (2.5, 5.0). The loudspeaker sound levels at both listener locations are 81.90 dB*A* equally (16.90 dB*A* above the noise level).

For the train station platform where there are eight listener locations, the high-sensitivity loudspeaker (95 dB*A*/W/m) is used. From the input power of 20 W, the loudspeaker sound level is:

$Ls = 10\log(20) + 95 = 108$ dB*A*

From the given noise data (high-noise situation) in Table 1, all 8 B_i's can be computed.

$B_1 = 0.0126$ $B_2 = 0.0126$
$B_3 = 0.0251$ $B_4 = 0.0200$
$B_5 = 0.1000$ $B_6 = 0.1000$
$B_7 = 0.1585$ $B_8 = 0.1259$

Based on $n' = 12$ (from the estimation procedure), the result of Model A shows that ten loudspeakers ($n^* = 10$) are needed for the train station platform. Once again, readers are reminded that the ten loudspeakers are for the high-noise situation.

Next, Model B is used to obtain the solution for the low-noise situation. With the new noise data (low-noise situation), the solution indicates that among the ten loudspeakers, only four loudspeakers will be sufficient. The optimal number and location of loudspeakers for the train station platform are presented in Table 2.

Table 2. Design Solution for the PA System for the Train Station Platform

Loudspeaker	Location Coordinate		Noise Situation	
	x	*y*	Low-Noise	High-Noise
1	29.0	27.0	Off	On
2	29.0	27.0	Off	On
3	20.0	26.0	On	On
4	29.0	27.0	Off	On
5	10.0	27.0	Off	On
6	0.0	14.0	On	On
7	41.0	28.0	On	On
8	10.0	27.0	Off	On
9	41.0	28.0	Off	On
10	41.0	28.0	On	On

Additionally, the combined sound level of the announcement at the eight listener locations can be computed. It can be seen that under either low-noise situation or high-noise situation, the difference between the announcement sound level and noise level is at least 15 dB*A* at every listener location.

Table 3. Comparison of Announcement Sound Level and Noise Level at the Listener Locations

Listener Location	Low-noise Situation		High-noise Situation	
	Announcement	Noise	Announcement	Noise
1	86.48	68.00	89.00	74.00
2	86.42	69.00	89.03	74.00
3	88.50	68.00	93.06	77.00
4	87.02	70.00	93.44	76.00
5	89.27	74.00	98.00	83.00
6	95.08	75.00	98.00	83.00
7	90.00	76.00	100.00	85.00
8	95.08	76.00	99.00	84.00

5. Conclusion

This paper presents an analytical method for designing the public announcement (PA) system such that the announced messages can be adequately heard by intended listeners at all locations within the designated area. The method uses both heuristic and optimization approaches to determine the input power of loudspeaker, and to determine the optimal number and location of loudspeakers. For adequate audibility, it is recommended that at any listener location, the announcement sound level exceed the noise level by at least 15 dB*A*. The procedure is designed to consider two types of areas, the area where ambient noise is relatively constant (called type-I area) and the other where ambient noise fluctuates with time (called type-II area). For the latter, two noise situations are defined. They are a low-noise situation and a high-noise situation.

Initially, the input power of loudspeakers is estimated using a heuristic approach. The loudspeakers are divided into two types, namely, low-sensitivity and high-sensitivity. Two mathematical models, Model A and Model B, are developed to determine the optimal number and location of loudspeakers. For type-I area, the loudspeaker sound level is determined by assuming that low-sensitivity loudspeakers are used. Model A is then applied to find the optimal design solution. For type-II area, the loudspeaker sound level is determined by assuming that high-sensitivity loudspeakers are used. Similarly, Model A is applied to obtain the optimal solution based on noise data from the high-noise situation. In order to obtain the optimal solution for the low-noise situation, Model B is applied. Using the result obtained from Model A, Model B recommends that some loudspeakers be turned off (or inactive) during the low-noise situation so as to attenuate the announcement sound levels. When Model B is used, noise data must be the data from the low-noise situation.

From the given example, it is seen that the hybrid procedure is able to provide a design solution that yields the input power of loudspeakers, minimizes the number of loudspeakers to be installed, and gives the exact locations where they should be installed. By comparing between the announcement sound levels and noise levels, the 15-dB*A* minimum difference is satisfied at all listener locations. It is also observed that two or more loudspeakers are sometimes recommended to be installed at the same location. As shown in the example, ten loudspeakers are recommended for the high-noise situation, while only four loudspeakers are recommended for the low-noise situation.

The advantages of the proposed hybrid design procedure can be summarized as follows.

1. It gives guidelines for the design and management of the PA system such that intended listeners at all listener locations can adequately hear the announced messages.
2. It helps to design the effective PA system using the minimum number of loudspeakers.
3. The solution gives exact locations for all loudspeakers so that they can be installed at the right places.
4. The procedure accounts for both low-noise and high-noise situations and gives the design solution that satisfies both situations.

6. Acknowledgments

The authors wish to express their gratitude to the Thailand Research Fund for supporting this research study through the RGJ-PHD grant, No. PHD/0184/2545.

7. Appendix

From the physics of sound [10-14], the following fundamental formulas are used for the conversion between sound power, sound intensity, and sound (pressure) level.

Let I be sound intensity (W/m^2)
I_0 be reference sound intensity (10^{-12} W/m^2)
L be sound (pressure) level (dB*A*)
P be sound power (W)
d be distance (m) between the sound source and point of measurement,

$$I = \frac{P}{4\pi d^2} \qquad \text{(A.1)}$$

$$L = 10\log\left(\frac{I}{I_0}\right) \qquad \text{(A.2)}$$

From Eq. (A.2), I can be expressed as:

$$I = 10^{\left(\frac{L-120}{10}\right)} \qquad \text{(A.3)}$$

From Eq. (A.2), Eq. (A.3), and assuming that $d = 1$, we have:

$$P = 4\pi 10^{\left(\frac{L-120}{10}\right)} \qquad \text{(A.4)}$$

At listener location i, to satisfy the 15-dBA minimum difference, we have:

$$\overline{Ls}_i - \overline{L}_i \geq 15 \qquad \text{(A.5)}$$

Eq. (A.5) can be rewritten as:

$$\left(10\log\overline{Is}_i + 120\right) - \left(10\log\overline{I}_i + 120\right) \geq 15 \quad \text{(A.6)}$$

$$\log\overline{Is}_i - \log\overline{I}_i \geq 1.5 \qquad \text{(A.7)}$$

$$\overline{Is}_i \geq 10^{1.5}\cdot\overline{I}_i \qquad \text{(A.8)}$$

Both $\overline{Is}_i$ and $\overline{I}_i$ can be obtained from the following two formulas.

$$\overline{Is}_i = \sum_{j=1}^{n}\left(\frac{10^{\left(\frac{L_s-120}{10}\right)}}{d_{ij}^2}\right) \qquad \text{(A.9)}$$

$$\overline{I}_i = 10^{\left(\frac{L_i - 120}{10}\right)} \tag{A.10}$$

where: $d_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2 + h^2}$

From Eq. (A.9) and Eq. (A.8), we obtain:

$$\sum_{j=1}^{n} \left(\frac{10^{\left(\frac{L_s - 120}{10}\right)}}{d_{ij}^2} \right) \geq 10^{1.5} \cdot \overline{I}_i \tag{A.11}$$

$$\sum_{j=1}^{n} \left(\frac{1}{d_{ij}^2} \right) \geq \frac{10^{1.5}}{10^{\left(\frac{L_s - 120}{10}\right)}} \cdot \overline{I}_i \tag{A.12}$$

Letting $B_i = \frac{10^{1.5}}{10^{\left(\frac{L_s - 120}{10}\right)}} \cdot \overline{I}_i$, then

$$\sum_{j=1}^{n} \left(\frac{1}{d_{ij}^2} \right) \geq B_i \tag{A.13}$$

8. References

[1] Kantowitz, B.H. and Sorkin, R.D., Human Factors: Understanding People-System Relationships, Wiley, New York, 1983.

[2] Sanders, M.S. and McCormick, E.J., Human Factors in Engineering and Design, 7th ed., McGraw-Hill, New York, 1993.

[3] Stanton, N. and Edworthy, J., Auditory Affordances in the Intensive Treatment Unit, Applied Ergonomics, Vol. 29, 1998, pp. 389-394, 1998.

[4] Edworthy, J. and Hards, R., Learning Auditory Warnings: The Effects of Sound Type, Verbal Labeling and Imagery on the Identification of Alarm Sounds, International Journal of Industrial Ergonomics, Vol. 24, 1999, pp. 603-618, 1999.

[5] Nanthavanij, S. and Yenradee, P., On Optimal Location of an Auditory Alarm for Multiple Work Cell Factory Floor. Proceedings of the 10th ISPE/IFAC International Conference on CAD/CAM, Robotics, and Factories of the Future, pp. 756-761, 1994.

[6] Nanthavanij, S., Analytical of Workplace Factors on Auditory Warning Alarm Location, In: Bittner, A.C., Champney, P.C. Taylor and Francis, London, pp. 989-995, 1995.

[7] Nanthavanij, S. and Yenradee, P., Predicting the Optimum Number, Location and Signal Sound Level of Auditory Warning Devices for Manufacturing Facilities, International Journal of Industrial Ergonomics, Vol. 24, pp. 569-578, 1999.

[8] International Standard, ISO 7731: 2001, Ergonomics-Danger Signals for Public and Work Areas-Auditory Danger Signals, International Organization of Standardization.

[9] Asawarungsaengkul, K. and Nanthavanij, S., Analytic Evaluation and Optimal Design of Auditory Warning Systems for Adequate Audibility, Working Paper No. MT-0408, Sirindhorn International Institute of Technology, Thammasat University, 2004.

[10] Harris, C.M., Sound and Sound Levels, In: Harris, C.M. (Ed.), Handbook of Noise Control, 2nd ed., McGraw-Hill, New York, pp. 2.1-2.2.21, 1979.

[11] Piercy, J.E. and Embleton, T.F.W., Sound Propagation in the Open Air, In: Harris, C.M. (Ed.), Handbook of Noise Control. 2nd ed., McGraw-Hill, New York, pp. 3.1-3.16, 1979.

[12] Ostergaard, P.B., Physics of Sound. In: Berger, E.H., Ward, W.D., Morril, J.C., Royster, L.H. (Eds.), Noise and Hearing Conservation Manual, 4th ed., American Industrial Hygiene Association, Akron, OH, pp. 19-36, 1986.

[13] Beraneck, L.L., Basic Acoustical Quantities: Levels and Decibels, In: Beraneck, L.L., Ver, I.L. (Eds) Noise and Vibration Control Engineering, Wiley, New York, pp. 1-24, 1992.

[14] Bies, D.A. and Hansen, C.H., 1996. Engineering Noise Control: Theory and Practice, 2nd ed., E & FN SPON, London, 1996.