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On Evaluation and Localization of Auditory Warning Devices for Adequate Audibility

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*This paper presents an analytic procedure to assist safety practitioners in evaluating the audibility of an existing auditory warning system in their workplaces. Two alarm location models are described: (a) a model with an unknown signal sound level, and (b) a model with a known signal sound level. A heuristic algorithm to determine a minimum number of alarm devices and their locations so that the warning signals can be clearly heard by workers is also proposed. The algorithm considers the ambient noise level, noise levels generated by individual machines, locations where workers are likely to be present, and noise levels at worker locations. From the numerical examples and the computation experiment, both the optimization and heuristic approaches yield solutions that satisfy the 15-dB*A *constraints. The heuristic approach is efficient in solving large alarm location problems due its capability to find near-optimal solutions within reasonable computation time.*

multi-alarm location problem auditory warning device audibility evaluation industrial noise hazard

1. INTRODUCTION

To comply with the safety regulations and standards, employers are required to install alarm devices in their facilities to alert workers of hazardous and dangerous situations. Alarm devices may generate auditory signals, visual signals, or both types of signals when hazardous or dangerous situations are detected. Among them, the use of auditory signals seems to be a better choice for industrial facilities than the use of other types of signals. This is mainly due to the fact that workers can perceive (hear) the signals even if they are not watching or are working in areas where they cannot see the alarm devices. Design guidelines and recommendations related to auditory warning systems can be found in several ergonomics and safety publications [1, 2, 3, 4]. The characteristics of the auditory signals such as intensity, frequency, duration, type, etc., have been discussed in depth in the literature [2, 5, 6]. The International Organization for Standardization (ISO) has also published international standards on auditory danger signals for workplaces: Standards No. ISO 7731:2003 [7] and ISO 11429:1996 [8].

When studying the safety regulations and standards relevant to the auditory warning system, it is found that some parts are called specifications while some are called performance. Specification standards specify explicitly what must be done while performance standards tend to be vague and employers might have all kinds of latitude to set up their own version of an auditory warning system in their workplace [9]. For example, the

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U.S. Occupational Safety and Health Administration (OSHA) standards discuss the "employee alarm system" (in part 1901.95) as a reference for the design of an alarm system [10]. However, OSHA only enforces the installation of the alarm system without giving details such as the number of alarm devices and their locations. As a result, the number of alarm devices found in most industrial facilities and their locations tend to be determined using a "convenience" basis rather than an objective basis. Examples of common alarm locations are at the corner of the facility, on the wall over the entrance/exit, and on the ceiling of the facility. For any workplace, given the number of alarm devices and the locations where they are presently installed, it is worthwhile to ask the following question: "Is the audibility of the auditory warning system adequate for alerting workers of dangerous situations?"

Nanthavanij and Yenradee [11] and Nanthavanij [12] considered the number of alarm devices, location, and the signal sound level as important factors that had a significant effect on the audibility of the auditory warning system. They presented an analytical method for predicting the location of an alarm device based on the ambient noise level, the location and sound level of other sound generating sources, and the location of workers in the workplace. The method, however, is limited to only single alarm location problems. Later, Nanthavanij and Yenradee proposed an analytical method for predicting an optimal number, location, and signal sound level of alarm devices [13]. The alarm location problem was formulated as a nonlinear programming problem and can be solved with appropriate optimization software tools. The method yields a minimum number of identical alarm devices, their locations on the ceiling of the facility, and the recommended signal sound level of the alarm device. Nevertheless, this method has three limitations: (a) an alarm device that can produce the signal sound level according to the recommendation might not be commercially available, (b) workers can only be present at the same locations as the machines, and (c) large alarm location problems might not be solvable since the alarm location problem is a combinatorial optimization problem. Lee and Kong [14] presented an extended study on the alarm location problem proposed by Nanthavanij and Yenradee [13]. They discussed the optimization approach for three workplace situations. The use of hearing protection for workers was added to the alarm location model and solved with LINGO, an optimization software.

In this paper, we firstly present an analytic procedure to evaluate the audibility of an existing auditory warning system in the workplace. Next, two optimization models to determine a minimum number of alarm devices and their locations based on the workplace noise conditions are formulated and discussed. Then, we propose a heuristic algorithm to determine the number of alarm devices (with a known signal sound level) and their locations for generating audible auditory warnings. The proposed algorithm is also intended to minimize a maximum combined signal sound level among the given worker locations. Numerical examples are presented and solved with the optimization and heuristic approaches. Then, their solutions are compared and discussed. A computation experiment is also conducted to investigate the efficiency of the heuristic algorithm.

Although this paper emphasizes the audibility of alarm systems, readers should be aware that it is not the only factor that warrants the effectiveness of auditory warnings. There are other cognitive and behavioral issues that also need to be considered. Recently, Edworthy, Hellier, Titchener, et al. discussed the design of heterogeneity in auditory alarm sets [15]. They reported that a newly-designed set of the auditory alarm was easier to learn than the extant set. For further reading on auditory warnings, see Lazarus and Höge [16]; Hellier, Edworthy, and Dennis [17]; Edworthy [18]; Edworthy and Hellier [19]; Guillame, Pellieux, Chastres, et al. [20]; Arrabito, Mondor, and Ken [21]; Wogalter, Conzola, and Smith-Jackson [22]; Jang [23]; Chan and Ng [24]; Keller and Stevens [25]; Lee and Chan [26]; Watson and Sanderson [27]; and Hellier, Edworthy, Weedon, et al. [28]. Additionally, the heuristic algorithm proposed in this paper does not consider the effect of age on auditory signal detection. Laroche, Tran Quoc, Hétu, et al. developed a computer program called Detectsound that considered the effect of age on auditory sensitivity and frequency selectivity [29]. The ultimate goal of their program was to serve as a tool for assessing the audibility of warning signals and for designing safe sound signals. However, the program only dealt with existing alarm systems. It did not recommend the number and location of alarm devices. Furthermore, Zheng, Giguère, Laroche, et al. presented a psychoacoustic model to facilitate the installation of acoustic warning devices in noisy settings, which is a major modification of Detectsound [30]. It was developed to be able to apply to a wider range of situations based on the noise field, the hearing status of workers, and the wearing of hearing protective devices.

2. AUDIBILITY EVALUATION OF THE AUDITORY WARNING SYSTEM

Examples of guidelines for a sufficient detection of auditory signals are as follows:

- in quiet work environments, an auditory signal ~40–50 dB*A* above the absolute threshold is normally sufficient to be detected [2];
- in noisy work environments, a minimum level of 15 dB*A* above the masked threshold to ensure detectability and a maximum level of 25 dB*A* above the masked threshold to guard against annoyance and disruption are recommended [31].

In this paper, we consider an auditory warning system to be adequately audible if it meets the signal intensity requirement of Standard No. ISO 7731:2003, which states that the auditory signal is clearly audible if the signal sound level exceeds the level of ambient noise by at least 15 dB*A* [7]. For workers with normal hearing or mild hearing loss, the signal sound level (measured at the worker's ear) shall be not under 65 dB*A* to ensure its audibility [7]. For convenience, the term "sound level" is used in this paper to represent the "sound pressure level".

2.1. Evaluation Procedure

Notations

$\bar{I}a_i$	total alarm signal sound intensity (W/m^2) at worker location i
$\bar{I}m_i$	total (ambient and machine) noise intensity (W/m^2) at worker location i
L_{alarm}	signal sound level (*A*-weighted decibels) of the alarm device, measured at 1 m
$\bar{L}a_i$	combined alarm signal sound level (*A*-weighted decibels) at worker location i
$\bar{L}m_i$	combined noise level (*A*-weighted decibels) at worker location i
L_{ab}	ambient noise level (*A*-weighted decibels)
L	sound pressure level (*A*-weighted decibels)
L_j	sound level generated by machine j (measured at 1 m) (*A*-weighted decibels)
h	ceiling height (meters)
I_{ab}	ambient sound intensity (watts per square meter)
I_j	sound intensity of machine j, at 1-m distance (watts per square meter)
m	number of worker locations in the considered facility
n	number of noise generating machines in the considered facility
P_{alarm}	sound power of the alarm device (watts)
$P_{\text{alarm}}^{\max}$	maximum allowable sound power of the alarm device (watts)
r	number of alarm devices necessary for the considered facility
(xa_k, ya_k)	(x, y) co-ordinates of alarm device k (meters)
(xm_j, ym_j)	(x, y) co-ordinates of machine j (meters)
(xw_i, yw_i)	(x, y) co-ordinates of worker location i (meters)
dm_{ij}	distance between worker location i and machine j (meters)
da_{ik}	distance between all worker locations i and the single alarm device k (meters)

For practicality, it is assumed that all noise sources are pointed sources and their heights are at the same level as the worker's ear. The effect of sound absorption/reflection facility is assumed to be negligible. In practice, if the facility size is large with high ceiling or noise sources are located not too close to a wall or corner, this assumption will satisfactorily hold.

The procedure to evaluate the audibility of an auditory warning system is as follows:

1. From the layout map of a workplace, determine the (x, y) co-ordinates (meters) of all machine and worker locations (on the factory floor), and of the existing alarm devices (on the ceiling or on the walls). Also, determine the ceiling height of the workplace.
2. Using the Euclidean distance system, determine all paired distances between the machine and worker locations, and between the alarm device and worker locations.
3. For each machine and alarm device, determine the machine noise and alarm signal sound level (at 1-m distance from the source) (*A*-weighted decibels).
4. Determine the ambient noise level (*A*-weighted decibels) without the presence of machine noise and alarm signal sound levels.
5. At each worker location, determine the combined machine noise level (from all machines) to which the ambient noise level is added and determine the combined signal sound level (from all alarm devices) separately using the following equations:

$$\bar{L}m_i = 10\log_{10}\left[10^{\frac{L_{\text{ab}}-120}{10}} + \sum_{j=1}^{n}\left(\frac{10^{\frac{L_j-120}{10}}}{(xw_i - xm_j)^2 + (yw_i - ym_j)^2}\right)\right] + 120 \text{ (dB}A\text{)}, \quad (1)$$

$$\bar{L}a_i = 10\log_{10}\left[\sum_{k=1}^{m}\left(\frac{10^{\frac{L_{\text{alarm}}-120}{10}}}{(xw_i - xa_k)^2 + (yw_i - ya_k)^2 + h^2}\right)\right] + 120 \text{ (dB}A\text{)}. \quad (2)$$

6. If the difference between the combined signal sound level and the combined noise level (from the ambient and all machine noise) is under 15 dB*A* at any worker location, the auditory warning system is not adequately audible.

Example 1 in section 2.2. demonstrates this evaluation procedure.

2.2. Example 1

Suppose that a workplace is a rectangular-shaped machine shop, with its respective width and length of 20 and 12 m ($x \times y$). The ceiling height is 6 m. In this machine shop, there are seven machines and six locations where workers are present. Table 1 displays the machine location co-ordinates and noise levels generated by these machines (at 1-m distance). The ambient noise level is 65 dB*A*. Table 2 also shows the (x, y) co-ordinates of the six worker locations. Currently, an alarm device with its signal sound level of 120 dB*A* (at 1-m distance) is installed on the ceiling at the (10, 6) co-ordinates.

TABLE 1. Location Co-Ordinates and Noise Levels Generated by Machines (Example 1)

	Location Co-Ordinate (m)		Noise Level
Machine	(*x*)	(*y*)	(dB*A*)
M1	3	2	87
M2	8	2	95
M3	12	2	94
M4	17	4	90
M5	17	7	95
M6	10	10	100
M7	3	7	95

TABLE 2. Location Co-Ordinates of Worker Locations (Example 1)

	Location Co-Ordinate (m)	
Worker Location	**(*x*)**	**(*y*)**
WL1	3	4
WL2	8	4
WL3	12	4
WL4	17	4
WL5	15	7
WL6	5	7

Firstly, we determine the paired distances between the seven machines and six worker locations. Letting dm_{ij} be the distance between worker location i (where $i = 1, 2, \dots, 6$) and machine j (where $j = 1, 2, \dots, 7$), the Euclidean distance equation is

$$dm_{ij} = \left[\left(xw_i - xm_j\right)^2 + \left(yw_i - ym_j\right)^2\right]^{1/2} \text{ (m).} \quad (3)$$

Table 3 shows the worker location–machine paired distances.

Next, we determine the paired distances between all worker locations (xw_i, yw_i) and the single alarm device (xa_k, ya_k), or da_{ik}, where $i = 1, 2, \dots, 6$ and $k = 1$. Note that h represents the ceiling height (meters).

$$da_{ik} = \left[\left(xw_i - xa_k\right)^2 + \left(yw_i - ya_k\right)^2 + h^2\right]^{1/2} \text{ (m).} \quad (4)$$

From Equation 4, the worker location–alarm device paired distances are

$da_{11} = 7.3$ m,
$da_{21} = 2.8$ m,
$da_{31} = 2.8$ m,
$da_{41} = 7.3$ m,
$da_{51} = 5.1$ m,
$da_{61} = 5.1$ m.

Using Equations 1 and 2, the combined noise level from the ambient and all machines and the signal sound level from the alarm device at any worker location can be calculated. Table 4 shows the combined noise levels, signal sound levels, and their differences at all six worker locations.

It can be concluded that the alarm signal sound levels reaching all worker locations are not adequately audible since all differences are under 15 dB*A*. This is perhaps due to the following reasons: (a) only one alarm device is not sufficient, (b) its location is not appropriate, and (c) the signal sound level generated by the alarm device is not high enough.

TABLE 3. Distances Between Worker Location and Machine Location, dm_{ij} (meters)

	Machine						
Worker Location	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**
WL1	2.0	5.4	9.2	14.0	14.3	9.2	3.0
WL2	5.4	2.0	4.5	9.0	9.5	6.3	5.8
WL3	9.2	4.5	2.0	5.0	5.8	6.3	9.5
WL4	14.1	9.2	5.4	0.0	3.0	9.2	14.3
WL5	13.0	8.6	5.8	3.6	2.0	5.8	12.0
WL6	5.4	5.8	8.6	12.4	12.0	5.8	2.0

TABLE 4. Combined Noise and Signal Sound Levels and Their Differences

	Combined Sound Level (dB*A*)		
Worker Location	**From 7 Machines**	**From Alarm Device**	**Difference (dB*A*)**
WL1	88.79	100.51	11.72
WL2	91.23	103.57	12.34
WL3	90.84	103.57	12.73
WL4	92.08	100.51	8.43
WL5	91.16	102.08	10.92
WL6	91.01	102.08	11.07

Notes. Difference = alarm signal sound level – combined noise level.

3. ALARM LOCATION MODELS

The alarm location problem is intended to determine a minimum number of alarm devices and the locations where they should be installed so that a maximum combined signal sound level at any worker location in the workplace is minimized. One important requirement of the alarm location problem is that the combined signal sound level at any worker location must exceed the combined noise level at that location by at least 15 dB*A*. While an increase in the alarm signal sound level will result in fewer alarm devices that are required, the differences between the combined signal sound level and the combined noise level (called signal–noise differences) at some worker locations might, however, be increased. On the other hand, when decreasing the alarm signal sound level, the signal–noise differences at some worker locations might decrease, but the number of alarm devices that are required for audible auditory warnings will increase. The former argument is in favor of cost reduction, not workplace noise control. The latter argument puts more emphasis on the noise situation than the cost of the auditory warning system. An appropriate alarm location model must consider both arguments and attempt to minimize not only the number of alarm devices but also the signal–noise difference at any worker location.

The assumptions for the alarm location problem are as follows:

- all alarm devices are identical, i.e., they generate equal signal sound level;
- all alarm devices will be installed on the ceiling of the facility,
- the signal sound level and machine noise level are not time-dependent.

3.1. Alarm Location Model (With Unknown Signal Sound Level)

To enhance its usefulness, the original alarm location model is slightly modified to cope with the situation in which workers might not be located at the machine locations and the difference of 15 dB*A* is now required. The modified alarm location model with an unknown signal sound level can be written as follows:

$$\text{minimize } P_{\text{alarm}}$$

subject to

$$B_i\left[\sum_{k=1}^{r}\frac{1}{\left(xw_i-xa_k\right)^2+\left(yw_i-ya_k\right)^2+h^2}\right]^{-1}\le P_{\text{alarm}}\ \forall i$$

$$\begin{array}{rcll} P_{\text{alarm}} & \le & P_{\text{alarm}}^{\max} & \\ xa_k,\ ya_k & \ge & 0 & \forall\ k \\ P_{\text{alarm}} & \ge & 0 & \end{array}$$

where

$$B_i=4\times10^{1.5}\pi\left[I_{\text{ab}}+\sum_{j=1}^{n}\frac{I_j}{dm_{ij}^2}\right](\text{W/m}^2). \quad (5)$$

To solve this alarm location model, it is necessary to know the number of alarm devices r. Therefore, a trial-and-error procedure is used. Firstly, assume that $r = 1$ and substitute it in the model. If an optimal solution can be found, then only one alarm device is necessary. If it is infeasible to find the solution, the number of alarm devices is then increased by 1 ($r = r + 1$) and the trial-and-error procedure continues. The solution will provide the locations of individual alarm devices and the signal sound level of the alarm device. For more details on the model formulation, see Nanthavanij and Yenradee [13].

One drawback of this alarm location model is that it might yield a solution that may not be usable. Specifically, the alarm device that will generate the signal sound level equal to the recommended level may not be commercially available. Often, alarm devices are manufactured with preset signal sound levels which cannot be adjusted. It is more reasonable to assume that the alarm signal sound level is known in advance and is a constant in the alarm location model. As a result, the problem objective is only to find a minimum number of alarm devices and their locations.

3.2. Alarm Location Model (With Known Signal Sound Level)

Here, we propose a revised alarm location model by assuming that the signal sound level of the alarm device is known. The objective function and the constraints are revised since the constraint on the alarm signal sound level is no longer necessary.

To make the alarm signal clearly audible at any worker location, the combined signal sound level at worker location *i* should be

$$\bar{L}a_i - \bar{L}m_i \geq 15 \ \ \forall i. \qquad (6)$$

From basic equations, it can be shown that

$$\bar{I}a_i \geq 10^{1.5}\,\bar{I}m_i \ \forall i. \qquad (7)$$

From the relationship between sound level (L) and sound intensity (I), we can derive the equations for $\bar{I}a_i$ and $\bar{I}m_i$:

$$\bar{I}a_i = \sum_{k=1}^{r} \frac{10^{\left(\frac{L_{\text{alarm}}-120}{10}\right)}}{da_{ik}^2}\ (\text{W/m}^2)\ \forall i, \qquad (8)$$

$$\bar{\ }m_i = I_{\text{ab}} + \sum_{j=1}^{n} \frac{10^{\left(\frac{L_j-120}{10}\right)}}{dm_{ij}^2}\ (\text{W/m}^2)\ \forall i. \qquad (9)$$

From Inequality 7 and Equations 8 and 9, we obtain Inequality 10:

$$\sum_{k=1}^{r} \frac{10^{\left(\frac{L_{\text{alarm}}-120}{10}\right)}}{da_{ik}^2} \geq 10^{1.5}\left[I_{\text{ab}} + \sum_{j=1}^{n} \frac{10^{\left(\frac{L_j-120}{10}\right)}}{dm_{ij}^2}\right]$$

$$\sum_{k=1}^{r} \frac{1}{da_{ik}^2} \geq \frac{10^{1.5}}{10^{\left(\frac{L_{\text{alarm}}-120}{10}\right)}}\left[I_{\text{ab}} + \sum_{j=1}^{n} \frac{10^{\left(\frac{L_j-120}{10}\right)}}{dm_{ij}^2}\right] \forall i. \qquad (10)$$

Setting the right-hand side of Inequality 10 to A_i, the expression is reduced to

$$\sum_{k=1}^{r} \frac{1}{da_{ik}^2} \geq A_i\ \forall i. \qquad (11)$$

Let us denote y_k as a binary integer variable such that $y_k = 1$ if alarm device k is chosen to be installed in the facility, and $y_k = 0$ otherwise. Thus, the *revised* alarm location model can be written as follows:

minimize

$$\sum_{i=1}^{m}\left[\left(\sum_{k=1}^{r} \frac{1}{(xw_i - xa_k)^2 + (yw_i - ya_k)^2 + h^2} \cdot y_k\right) - A_i\right]$$

subject to

$$\sum_{k=1}^{r} \frac{1}{(xw_i - xa_k)^2 + (yw_i - ya_k)^2 + h^2} \cdot y_k \geq A_i \forall i$$

$$xa_k,\ ya_k \geq 0 \qquad \forall\, k$$

$$y_k = \{0,\ 1\} \qquad \forall\, k$$

where

$$A_i = \frac{10^{1.5}}{10^{\left(\frac{L_{\text{alarm}}-120}{10}\right)}}\left[I_{\text{ab}} + \sum_{j=1}^{n} \frac{10^{\left(\frac{L_j-120}{10}\right)}}{dm_{ij}^2}\right] \forall i.$$

Firstly, the number of alarm devices r must be specified. If r is too small, a feasible solution will not be found. If r is too large, some alarm devices will not be installed (some $y_k = 0$). Additionally, if r is set too large, the size of the alarm location problem becomes large and the problem may not be solvable.

4. HEURISTIC APPROACH

In this section, we introduce a heuristic algorithm to determine a near-optimal number and location of alarm devices when the alarm signal sound level is known. The algorithm systematically installs one alarm device at a time, at a location considered to be the most appropriate under the given situation. A required condition (adequate signal perception) must be checked every time an alarm device is installed. If the required condition is not satisfied, another alarm device will then be installed.

When the first alarm device is being considered, its location will be on the ceiling between the worker location with the largest signal–noise difference and another worker location with the next largest signal–noise difference. From these two worker locations, the algorithm finds the radius of a circle on the ceiling (representing the coverage of the alarm signals) in which the worker location with the largest signal–noise difference is located on its circumference. The location of the alarm device will be on a straight line that connects the two worker locations, and is far from the worker location with the largest signal–noise difference by a distance equal to the circle radius. Then, Inequality 11 will be checked. If the signal–noise difference at any worker location is under 15 dB*A*, an additional alarm device will be considered. The location of the next alarm device will be determined using the same logic as that for the first alarm device. The procedure will stop when Inequality 11 is satisfied at all worker locations.

A heuristic algorithm to determine the number and location of alarm devices consists of the following steps:

step 1: Determine the (x, y) co-ordinates of all machines (xm_j, ym_j) and worker locations (xw_i, yw_i). Also, determine the ceiling height (h).

step 2: Determine the ambient noise level (L_{ab}) and convert it to the ambient noise intensity (I_{ab}).

step 3: Determine the machine noise level (at 1-m distance) generated by machine j (L_j) for all js. Then, determine the total noise intensity at worker location i $(\overline{Im}_i)$ for all is.

step 4: At each worker location i, determine A_i.

step 5: Set the number of alarm devices $r = 1$.

step 6: Calculate C_i for all is from the following equation. For $r = 1$, set $C_i = A_i$. For $r \geq 2$,

$$C_i = A_i - \sum_{k=1}^{r-1} \frac{1}{da_{ik}^2}.$$

Let D_i be the Euclidean distance between worker location i and alarm device k. Calculate D_i for all is from the following equation. For $r = 1$, set $D_i = \frac{1}{\sqrt{C_i}}$. For $r \geq 2$,

$$D_i = \left[A_i - \sum_{k=1}^{r-1} \frac{1}{da_{ik}^2} \right]^{-1/2}.$$

If $C_i \leq 0$, set $D_i = M$ where M is a very large number.

step 7: Let R_i be the radius of a circle with its center at worker location i. Determine R_i for all is from the following equation:

for $D_i \geq h^2$, $R_i = \sqrt{D_i^2 - h^2}$,
for $D_i < h^2$, $R_i = 0$,
for $D_i = M$, $R_i = M$.

step 8: Among all worker locations, select the worker location i with the largest C_i. Let the selected worker location be worker location i^*, D_i be D_{i^*}, and R_i be R_{i^*}.

step 9: Find worker location i^{**} $(i^{**} \neq i^*)$, where $C_{i^{**}}$ is the largest among the remaining C_i's, not including C_{i^*}.

step 10: If $R_{i^*} = 0$, install an alarm device above worker location i^*. Its location will then be at the $(xa_r = xw_{i^*}, ya_r = yw_{i^*})$ co-ordinates. Then, proceed to step 12.

step 11: If $R_{i^*} > 0$, find the location co-ordinates of the alarm device from the following equations. Firstly, let $\theta = \tan^{-1}\left[\left| \frac{yw_{i^{**}} - yw_{i^*}}{xw_{i^{**}} - xw_{i^*}} \right| \right]$.

If $xw_{i^*} = xw_{i^{**}}$, then set $\theta = 90°$.

For xa_r:
if $xw_{i^*} = xw_{i^{**}}$, then $xa_r = xw_{i^*}$,
if $xw_{i^*} < xw_{i^{**}}$, then $xa_r = xw_{i^*} + R_i\cos\theta$,
if $xw_{i^*} > xw_{i^{**}}$, then $xa_r = xw_{i^*} - R_i\cos\theta$.
For ya_r:
if $yw_{i^*} = yw_{i^{**}}$, then $ya_r = yw_{i^*}$,
if $yw_{i^*} < yw_{i^{**}}$, then $ya_r = yw_{i^*} + R_i\sin\theta$,
if $yw_{i^*} > yw_{i^{**}}$, then $ya_r = yw_{i^*} - R_i\sin\theta$.

Note that both xa_r and ya_r must be within the facility area. That is, the (x, y) co-ordinates of alarm device r must be such that $0 \leq xa_r \leq x_f$ and $0 \leq ya_r \leq y_f$, where x_f and y_f are the limits on the (x) co-ordinate and (y) co-ordinate of the facility, respectively. If xa_r or ya_r is beyond x_f or y_f, respectively, set the co-ordinate equal to the corresponding limit.

step 12: Check if the following condition is satisfied:

$$\sum_{k=1}^{r} \frac{1}{da_{ik}^2} \geq A_i \ \forall i.$$

If yes, proceed to step 13 (and r becomes r^*). Otherwise, set $r = r + 1$ and return to step 6.

step 13: The number of alarm devices that are necessary for the given facility is r^*. Each alarm device is to be installed at the (xa_k, ya_k) co-ordinates, where $k = 1, \ldots, r^*$.

5. NUMERICAL EXAMPLES

This section presents two alarm location problems. In each problem, the number and location of alarm devices are determined using the heuristic and optimization approaches. The solutions from both approaches are then compared. Additionally, the signal–noise differences are compared at all worker locations.

5.1. Example 2 (7 Machines – 4 Worker Locations)

Consider a production facility with its dimensions of 30 × 25 m ($x \times y$). The ceiling height is 6 m. There are seven machines and four worker locations in this facility. Table 5 presents the machine location co-ordinates and noise levels (at 1-m distance) generated by the machines. Table 6 shows the (x, y) co-ordinates of four worker locations. The ambient noise level when no machine is operating is 60 dB*A* (yielding the ambient noise intensity of 1.00×10^{-6} W/m^2). An auditory warning system is being designed for this facility. The signal sound level of an alarm device is 125 dB*A* (at 1-m distance).

TABLE 5. Location Co-Ordinates and Noise Levels Generated by Machines (Example 2)

	Location Co-Ordinate (m)		Noise Level
Machine	(x)	(y)	(dB*A*)
M1	5.00	5.00	85.00
M2	5.00	20.00	100.00
M3	15.00	5.00	90.00
M4	15.00	20.00	90.00
M5	25.00	5.00	95.00
M6	25.00	12.50	90.00
M7	25.00	20.00	85.00

TABLE 6. Location Co-Ordinates of Worker Locations (Example 2)

	Location Co-Ordinate (m)	
Worker Location	(x)	(y)
WL1	5.00	18.00
WL2	10.00	6.00
WL3	15.00	18.00
WL4	24.00	12.50

A_1, A_2, A_3, and A_4 can be calculated from the data in Tables 5–6:

location WL1: $A_1 = 0.02525$,
location WL2: $A_2 = 0.00120$,
location WL3: $A_3 = 0.00377$,
location WL4: $A_4 = 0.01101$.

5.1.1. Locating alarm device No. 1

Initially, set $r = 1$. From steps 6 and 7 of the heuristic algorithm, calculate C_i, D_i, and R_i ($i = 1, \dots, 4$):

location WL1: $C_1 = 0.02525$ $D_1 = 6.29$ $R_1 = 1.90$,
location WL2: $C_2 = 0.00120$ $D_2 = 28.88$ $R_2 = 28.25$,
location WL3: $C_3 = 0.00377$ $D_3 = 16.29$ $R_3 = 15.15$,
location WL4: $C_4 = 0.01101$ $D_4 = 9.53$ $R_4 = 7.40$.

Worker location WL1 has the largest C_i ($C_1 = 0.02525$). Therefore, set $D_{1*} = 6.29$ and $R_{1*} = 1.90$. Next, worker location WL4 has the next largest C_i ($C_4 = 0.01101$). Since $R_{1*} > 0$, the location of the first alarm device is determined with the equations in step 11:

$$\theta = \tan^{-1}\left[\left|\frac{12.50-18.00}{24.00-5.00}\right|\right] = 16.14°.$$

Therefore,

$$xa_1 = 5.00 + (1.90)\cos(16.14°) = 6.83 \text{ m},$$
$$ya_1 = 18.00 - (1.90)\sin(16.14°) = 17.47 \text{ m}.$$

Next, Inequality 11 is checked if the required condition is satisfied at all worker locations.

location WL1: $\left[da_{11}^2\right]^{-1} = 0.02525$, $A_1 = 0.02525$ (satisfied);

location WL2: $\left[da_{21}^2\right]^{-1} = 0.00563$, $A_2 = 0.00120$ (satisfied);

location WL3: $\left[da_{31}^2\right]^{-1} = 0.00970$, $A_3 = 0.00377$ (satisfied);

location WL4: $\left[da_{41}^2\right]^{-1} = 0.00281$, $A_4 = 0.01101$ (unsatisfied).

At worker location WL4, the required condition is not satisfied. Therefore, another alarm device is added.

5.1.2. Locating alarm device No. 2

Next, set $r = 2$. Computations from section 5.1.1. are repeated:

location WL1: $C_1 = 0.00000$ $D_1 = \text{M}$ $R_1 = \text{M}$,
location WL2: $C_2 = -0.00443$ $D_2 = \text{M}$ $R_2 = \text{M}$,
location WL3: $C_3 = -0.00593$ $D_3 = \text{M}$ $R_3 = \text{M}$,
location WL4: $C_4 = 0.00820$ $D_4 = 11.04$ $R_4 = 9.27$.

Since worker location WL4 has the largest C_i ($C_4 = 0.00820$), set $D_{4*} = 11.04$ and $R_{4*} = 9.27$. It is also seen that worker location WL1 has the next largest C_i ($C_1 = 0.00000$). The location of the second alarm device can be determined from the following equations:

$$\theta = \tan^{-1}\left[\left|\frac{18.00 - 12.50}{5.00 - 24.00}\right|\right] = 16.14°.$$

Therefore,

$$xa_1 = 24.00 - (9.27)\cos(16.14°) = 15.10 \text{ m},$$
$$ya_1 = 12.50 + (9.27)\sin(16.14°) = 15.08 \text{ m}.$$

Again, Inequality 11 is checked if the required condition is satisfied at all worker locations:

location WL1: $\left[da_{11}^2\right]^{-1} + \left[da_{12}^2\right]^{-1} = 0.03208$, $A_1 = 0.02525$ (satisfied);

location WL2: $\left[da_{21}^2\right]^{-1} + \left[da_{22}^2\right]^{-1} = 0.01255$, $A_2 = 0.00120$ (satisfied);

location WL3: $\left[da_{31}^2\right]^{-1} + \left[da_{32}^2\right]^{-1} = 0.03215$, $A_3 = 0.00377$ (satisfied);

location WL4: $\left[da_{41}^2\right]^{-1} + \left[da_{42}^2\right]^{-1} = 0.01101$, $A_4 = 0.01101$ (satisfied).

Since Inequality 11 is satisfied at all four worker locations, the solution is found. This facility needs two alarm devices (with each device generating a 125-dB*A* auditory signal sound level). Both alarm devices should be installed on the ceiling at (6.83, 17.47) and (15.10, 15.08) co-ordinates.

We also solve this problem using LINGO[1] version 12, an optimization software. By formulating the problem using the *revised* alarm location model (see section 3.2.) and solving it, it is found that the minimum number of alarm devices r^* needed for this facility is also two devices. They are to be installed at the (2.85, 19.02) and (30.00, 6.35) co-ordinates. Table 7 shows the combined alarm signal sound levels and the combined noise levels based on both solution approaches at the four worker locations. Both approaches yield the results that satisfy the 15-dB*A*-difference con-

TABLE 7. Comparison of Combined Signal Sound Level and Combined Noise Level Based on the Heuristic (*r* = 2) and Optimization (*r = 2) Approaches (Example 2)**

Worker Location	Combined Noise Level (dB*A*)	Combined Signal Level (dB*A*)		Signal–Noise (dB*A*)*	
		Heuristic	Optimization	Heuristic	Optimization
WL1	94.02	110.06	109.02	16.04	15.00
WL2	80.79	105.99	102.92	25.20	22.13
WL3	85.76	110.07	104.00	24.31	18.24
WL4	90.42	105.42	105.42	15.00	15.00
			average signal–noise difference	20.14	17.59
			SD	5.36	3.39
			maximum difference	25.20	22.13
			minimum difference	15.00	15.00
			SNR index	.74	.85

Notes. * = the required signal–noise difference is at least 15 dBA; SNR = signal–noise ratio.

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[1] http://www.lindo.com/index.php?option=com_content&view=article&id=2&Itemid=10

straint. The optimization approach yields a better solution since the differences are closer to 15 dB*A* than those from the heuristic approach. From Table 7, the average signal–noise difference from the optimization approach is 17.59 dB*A*, while the one from the heuristic approach is 20.14 dB*A*.

An ideal lower bound of the signal–noise difference is used as a benchmark for an evaluation of the solution. Based on the 15-dB*A*-difference constraint, the ideal solution is the one in which all signal–noise differences are 15 dB*A* (at all worker locations). The ratio of the ideal lower bound to the average difference is then defined as a signal–noise ratio (SNR) index. Note that the best SNR index is 1.00 (also the largest). Thus, the larger the SNR index is, the better the solution. From Table 7, the SNR index of the solution from the optimization approach is .85, whereas the one from the heuristic approach is .74.

5.2. Example 3 (13 Machines – 7 Worker Locations)

Next, we test the heuristic algorithm on a larger alarm location problem. Let us now consider a rectangular facility with its dimensions of 45 × 35 m ($x \times y$). Its ceiling height is 6 m. In this facility, there are 13 machines and seven locations where workers might be present. Table 8 shows the location co-ordinates and noise levels (at 1-m distance) these machines generate. The ambient noise level is 65 dB*A*. The alarm signal sound level is 120 dB*A* (at 1-m distance). Table 9 shows the location co-ordinates of the seven worker locations.

To facilitate the computation procedure, the heuristic algorithm is coded using the Visual Basic application in Microsoft Excel. Data in Tables 8–9 show that the recommended number

TABLE 8. Location Co-Ordinates and Noise Levels Generated by Machines (Example 3)

Machine	Location Co-Ordinate (m) (*x*)	(*y*)	Noise Level (dB*A*)
M1	5.00	5.00	95.00
M2	5.00	15.00	90.00
M3	5.00	25.00	94.00
M4	15.00	5.00	90.00
M5	15.00	15.00	95.00
M6	15.00	25.00	90.00
M7	25.00	5.00	95.00
M8	25.00	15.00	96.00
M9	25.00	25.00	90.00
M10	33.00	5.00	87.00
M11	33.00	15.00	86.00
M12	33.00	25.00	88.00
M13	38.00	15.00	99.00

TABLE 9. Location Co-Ordinates of Worker Locations (Example 3)

Worker Location	Location Co-Ordinate (m) (*x*)	(*y*)
WL1	5.00	3.50
WL2	5.00	13.50
WL3	5.00	23.50
WL4	25.00	3.50
WL5	25.00	13.50
WL6	25.00	23.50
WL7	40.00	15.00

TABLE 10. Location Co-Ordinates (meters) of Eight Alarm Devices (Example 3)

	Heuristic Approach		Optimization Approach	
Alarm Device	(*x*) Co-Ordinate	(*y*) Co-Ordinate	(*x*) Co-Ordinate	(*y*) Co-Ordinate
A1	40.00	15.00	40.85	14.50
A2	25.00	13.50	40.81	14.48
A3	5.00	3.50	23.71	9.63
A4	25.00	3.50	3.45	0.00
A5	5.00	23.50	25.47	9.52
A6	40.00	15.00	4.95	23.78
A7	19.98	10.99	19.83	8.62
A8	5.00	13.18	0.83	0.00

of alarm devices *r* is eight devices. The optimization approach also yields the minimum number of alarm devices *r** of eight devices. Table 10 shows the location co-ordinates of the eight alarm devices determined from both approaches.

Table 11 shows a comparison of the combined noise level and the combined alarm signal sound level between both solution approaches for all worker locations. The signal–noise differences are quite close to 15 dB*A* for both solution approaches. The average signal–noise differences from the heuristic and optimization approaches are 16.04 and 15.29 dB*A*, respectively. Although the optimization approach still yields a better solution than the heuristic approach, it is surprising that the heuristic approach becomes more effective when solving this problem than the previous one (in example 2). Its SNR index in example 3 is .94, while the one in example 2 is .74. Thus, it is necessary to investigate more alarm location problems with different problem sizes.

6. COMPUTATION EXPERIMENT

To further investigate the effectiveness of the heuristic algorithm, 16 alarm location problems were created. The number of machines in the facility ranged from 6 to 20 machines. The number of worker locations ranged from 10 to 20 locations. The ambient noise level for each problem was randomly set to 60, 65, or 70 dB*A*. The ceiling height was fixed at 6 m. The machine noise levels randomly varied between 80 and 105 dB*A*.

Both solution approaches (heuristic and optimization) were used to find the alarm location solution. The performance indices used in the comparison of solutions are

- the number of alarm devices required for the workplace;
- the average signal–noise difference; and
- the SNR index.

Table 12 shows a comparison of the solutions from the heuristic and optimization approaches.

The heuristic approach is able to yield the same number of alarm devices as those from the optimization approach in 13 problems out of the 16 test problems (or 81.25%). For the remaining three problems, the difference in the number of alarm devices is only one device. When comparing the average signal–noise differences, the average difference from the heuristic approach is greater than that from the optimization approach by not more than 2 dB*A*, irrespective of the problem size. However, when comparing the SNR values, it is found that the SNR index tends to decrease with the problem size. This seems to indicate that as the problem size grows larger, the heuristic approach shows better performance and would yield a solution that is nearer to an optimal solution.

TABLE 11. Comparison of Combined Signal Sound Level and Combined Noise Level Based on Heuristic (*r* = 8) and Optimization (*r = 8) Approaches (Example 3)**

Worker Location	Combined Noise Level (dB*A*)	Combined Signal Level (dB*A*)		Signal–Noise (dB*A*)*	
		Heuristic	Optimization	Heuristic	Optimization
WL1	91.68	106.68	106.68	15.00	15.00
WL2	87.63	107.15	104.07	19.53	16.45
WL3	90.78	106.44	105.78	15.66	15.00
WL4	91.81	107.33	106.81	15.53	15.00
WL5	92.87	108.02	107.87	15.16	15.00
WL6	87.79	104.08	103.37	16.29	15.57
WL7	93.11	108.22	108.11	15.11	15.00
			average signal–noise difference	16.04	15.29
			SD	1.60	0.55
			maximum difference	19.53	16.45
			minimum difference	15.00	15.00
			SNR index	.94	.98

Notes. ∗ = the required (signal–noise) difference is at least 15 dBA; SNR = signal–noise ratio.

TABLE 12. Comparison of Solutions From Heuristic and Optimization Approaches

		Number of Alarm Devices		Average Signal–Noise Difference		SNR Index	
n	*m*	Heuristic	Optimization	Heuristic	Optimization	Heuristic	Optimization
6	18	4	4	24.29	23.11	0.62	0.65
6	10	3	3	18.27	17.43	0.82	0.86
8	15	6	6	20.52	20.17	0.73	0.75
8	17	6	6	20.80	20.37	0.72	0.74
10	11	5	5	19.86	18.31	0.76	0.82
10	14	7	7	19.21	18.65	0.78	0.81
12	16	7	6	19.63	19.05	0.76	0.79
12	20	6	6	21.22	19.91	0.71	0.75
14	17	5	5	18.56	17.88	0.81	0.84
14	13	6	6	18.68	17.80	0.80	0.84
16	13	8	7	18.86	17.82	0.79	0.84
16	10	6	6	18.55	18.33	0.81	0.82
18	12	7	7	18.47	18.33	0.81	0.82
18	10	7	7	17.24	17.00	0.87	0.88
20	19	8	7	17.63	16.99	0.85	0.88
20	15	7	7	17.76	16.94	0.85	0.88

Notes. *n* = number of machines, *m* = number of worker locations, SNR = signal–noise ratio.

Additionally, readers should note that one important issue in the use of the optimization approach is an upper bound of the number of alarm devices in the alarm location model. If this upper bound is set to be much higher than the optimal number, the problem may not be solvable. In our computation experiment, we used the solution (the number of alarm devices) from the heuristic approach, which is either equal to or greater than the optimal number by one, as the upper bound. With this technique, it is possible to obtain an optimal solution for large-sized alarm location problems. When we tried to set the upper bound to be three or four devices more than the optimal number, the optimal solution could not be found. Regarding the computation time, the heuristic approach is able to yield the near-optimal solution within a few seconds, whereas the optimization approach needs several minutes or several hours of computation time.

7. CONCLUSION

In this paper, we explain an analytic procedure for evaluating an existing auditory warning system to determine if its alarm signal is adequately audible to alert workers of danger. The audibility requirement is that the combined alarm signal sound level must exceed the combined noise level (from the ambient and all machines) by at least 15 dB*A* at any worker location. We also present two alarm location models. The objective of the models is to determine a minimum number of alarm devices and their locations such that a maximum combined alarm signal sound level at any worker location is minimized, yet still exceeds the combined noise level by at least 15 dB*A*. The first model is applicable for the problems in which the signal sound level of the alarm device is assumed to be unknown, while the second one is for those in which the signal sound level of the alarm device is specified.

We also propose a heuristic algorithm for solving the alarm location problem with a known signal sound level of the alarm device. Initially, the algorithm searches for the “most required” worker location and its “second most required” neighboring worker location. An alarm device is placed at a location (in between these two worker locations) that satisfies the audibility requirement at the “most required” worker location. After placing the alarm device, the audibility requirement is checked at every worker location. The placement of alarm devices continues until the combined alarm signal sound level exceeds the combined noise level by at least 15 dB*A* at every worker location. A computer program is written in Visual Basic application in Microsoft Excel to perform the computation steps.

For small-sized alarm location problems, it is possible to solve the problem using an optimization approach. The solution (the number of alarm devices and their locations) is a local optimum. For large-sized alarm location problems, however, the heuristic approach is more practical than the optimization approach. Although the heuristic approach does not guarantee an optimal solution, it is able to yield a solution that is near-optimal. From the computation experiment, the heuristic approach can yield a minimum number of alarm devices in 81.25% of the test problems. When comparing the average signal–noise differences, the heuristic approach obtains a result that is larger than the minimax difference (from the optimization approach) by not more than 2 dB*A*. More interestingly, the performance of the heuristic approach is found to improve when the problem size increases.

With the analytic procedure presented in this paper, safety practitioners will be able to evaluate the audibility of an existing auditory warning system in their workplaces. The heuristic procedure will also enable them to determine a minimum number of alarm devices and their locations so that workers can adequately hear the alarm signals. To further enhance the effectiveness of the auditory warning system, it is necessary to consider other issues, namely, cognitive, behavioral, and human factors, regarding the design of auditory warnings and human perception of signals. Furthermore, it is possible to use the heuristic algorithm discussed in this paper in conjunction with a computerized model called Detectsound to account for the effect of age on auditory sensitivity and frequency selectivity. Safety practitioners can firstly use the algorithm to determine the number and location of alarm devices and then use Detectsound.

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