Analytical Procedures for Designing an Optimal Noise Hazard Prevention Program

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Abstract. Two extreme and one mixed procedures for designing a noise hazard prevention program are discussed in this paper. The two extreme design procedures (engineering-based and HPD-based) yield upper and lower bounds of the total noise control cost, respectively; while the mixed design procedure provides an optimal noise hazard prevention program within a given total budget. The upper bound of the workforce size for job rotation is approximated using a heuristic procedure. Six optimization models are developed and utilized by the mixed procedure to eliminate or reduce excessive noise levels (or noise exposures) in an industrial workplace. The mixed procedure also follows the OSHA's hierarchy of noise control. A numerical example is given to demonstrate the application of the proposed design procedures.

Keywords: Noise Hazard Prevention, Engineering Controls, Administrative Controls, Hearing Protection Devices, Job Rotation, Optimization

1. INTRODUCTION

Noise-induced hearing loss is one of the most common occupational diseases and the second most self-reported occupational illness or injury (NIOSH, 1998). Exposure to high noise levels is a leading cause of hearing loss and may also result in other harmful health effects. A major cause that contributes to this problem is a lack of effective noise hazard prevention program in the workplace.

An effective noise hazard prevention program requires a workplace noise control. Three noise control approaches are generally recommended: (1) engineering approach, (2) administrative approach, and (3) the use of hearing protection devices (HPDs). The details of engineering controls can be found in Harris (1979), Beranek and Ver (1992), Cheremisinoff (1993), Ridley (1994), Wilson (1994), and Bies and Hansen (1996). Topics such as a development of quieter machines, noise reduction methods, noise absorption materials, and process

change for noise reduction are also discussed in the literature (Richards, 1981; Vajpayee *et al.*, 1981; Docherty and Corlett, 1983; Cops, 1985; Li and Halliwell, 1985; Baek and Elliott, 1995; Bahrami *et al.*, 1998; Lee and Ng, 1998; Sorainen and Kokkola, 2000; Bilawchuk and Fyfe, 2003).

For the administrative approach, job rotation is perhaps the most recommended method to reduce the worker's exposure to loud noise. Nanthavanij and Yenradee (1999) developed a *minimax* work assignment model (i.e., a job rotation model) to determine an optimal set of work assignments for workers so that the maximum daily noise exposure that any worker receives is minimized. For large-sized job rotation problems, a genetic algorithm was developed to determine near-optimal *minimax* work assignments (Nanthavanij and Kullpattaranirun, 2001; Kullpattaranirun and Nanthavanij, 2005). Yaoyuenyong and Nanthavanij (2003) also developed a simple heuristic for solving large job rotation problems. When noise levels are excessive, Nantha-

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vanij and Yenradee (2000) recommended that the number of workers be greater than the number of machines/workstations where workers must attend. A mathematical model was developed to determine the minimum number of workers for working in noisy work areas so that their daily noise exposures do not exceed the permissible limit.

Various types of HPD and their properties have been widely discussed in Harris (1979), Beranek and Ver (1992), Cheremisinoff (1993), Ridley (1994), and Wilson (1994). In addition, research studies on the development and testing of effective HPDs were carried out by Behar and Kunov (1999), Crabtree and Behar (2000), Birch *et al.* (2003), and Buchweiller *et al.* (2003). Resistance to using HPDs by workers was also studied by Feeney (1986).

In situation where the noise level exceeds 90 dBA, a noise conservation program is required (OSHA, 1983). According to the OSHA's hierarchy of noise control, engineering controls are to be considered first. If they are not feasible or insufficient, administrative controls such as job rotation should be considered next. The use of HPDs is to be used as the last resort of noise reduction. HPDs should be used to assist, not to replace, engineering and administrative controls. However, employers tend to provide HPDs (earplugs, earmuffs, etc.) to workers for noise protection without attempting to apply engineering and administrative controls. The main reasons for not considering them are a large capital investment that is normally required for engineering controls and the difficulty in implementing engineering and administrative controls.

Sanders and McCormick (1993) recommended that a combination of noise controls be used to achieve the desired level of abatement. However, to find an appropriate combination of noise controls is a difficult task especially when requirements such as allocated budget and permissible noise level need to be concurrently considered. In this paper, we propose three analytical procedures for designing a noise hazard prevention program. Methods to determine bounds of the total noise control cost and the workforce for job rotation are discussed. Using a mixed procedure and the given noise control budget, we show how an optimal noise hazard prevention program can be designed.

2. NOISE HAZARD PREVENTION

Every noise problem can be broken down into three parts: (1) a noise source that transmits sound, (2) a path along which sound is transmitted, and (3) a hearer. As such, a noise problem can be controlled by attacking the noise at the source, along its transmission path from the source to the hearer, and at the hearer.

Generally, there are three noise control approaches, namely, engineering controls, administrative controls, and use of HPDs.

2.1 Engineering Controls

Engineering controls are procedures that reduce the sound level either at the machine or within the hearing zone of the workers. Examples of common engineering controls are listed below (Olishifski and Standards, 1988).
1. Maintenance
2. Substitution of machines
3. Substitution of processes
4. Reduction of the driving force of vibrating surfaces
5. Reduction of the response of vibrating surfaces
6. Reduction of the sound radiation from the vibrating surfaces
7. Reduction of the sound transmission through solids
8. Reduction of the sound produced by gas flow
9. Reduction of noise by reducing its transmission through air

2.2 Administrative Controls

Administrative controls are procedures to reduce the exposure of workers to noise rather than reducing the noise level. Examples of the administrative controls are as follows (Olishifski and Standards, 1988; Asfahl, 1999; Goetsch, 2002).
1. Rotating workers from a high-noise location to a location with lower noise so that their daily noise exposures are reduced.
2. Transferring workers who are particularly susceptible to noise to work in a less noisy work area.
3. Allowing workers to take shift brakes in a quiet rest area.
4. Changing the production schedules so that exposure times to loud noise are reduced.
5. Interrupting production runs with preventive maintenance to give workers quiet time.

2.3 Use of HPDs

The use of HPDs to reduce the noise exposures should not be applied unless the noise reduction through engineering and administrative controls are ineffective or have reached their limits. There are two basic types of HPDs: passive and active. The passive HPDs are the most common in industry, and include earplugs, ear canal caps, and earmuffs. The active HPDs are earplugs, canal caps, earmuffs, or even noise-attenuating helmets that incorporate electronic components and transducers. Active HPDs provide active noise cancellation, communications features, and attenuation which is level-dependent. They reduce noise by introducing destructive cancella-

tion by applying opposite-phase sound waves at the ears.

3. OPTIMIZATION MODELS FOR NOISE CONTROLS

In this section, mathematical models for selected noise controls are formulated. It is assumed that machines are the only noise sources in the workplace.

C_j length of time (hour) spent at worker location j
cb_v cost of installing barrier v
ch_l cost of using hearing protection device l
cs_{tu} cost of reducing noise at machine t using engineering control method u
d_{tj} Euclidean distance between machine t and worker location j
EB budget for engineering controls
EC total cost of engineering controls
F total worker-location changeover
f_j number of worker-location changeovers at worker location j
HB budget for HPDs
HC total cost of HPDs used
L_{ab} ambient noise level (dBA)
$\overline{L}_j$ combined noise level (dBA) at worker location j
L_t noise level (dBA) measured at machine t (at 1-m distance)
L'_t noise level (dBA) measured at machine t (at 1-m distance) after noise reduction
m number of workers in the current workforce
M number of available workers in the *new* workforce
n number of worker locations
NRb_{jv} amount of noise (dBA) reduced at worker location j after installing barrier v
NRh_l amount of noise (dBA) reduced after wearing HPD type l
NRs_{tu} amount of noise (dBA) reduced at machine t after applying engineering control method u
p number of work periods per workday
q number of machines (noise sources)
r number of engineering control methods to reduce noise at the machine
s number of engineering control methods to block the noise transmission path
TB total budget for the noise control program ($TB = EB + HB$)
W_i 8-hour TWA that worker i receives, dBA
w_j noise weight per work period at worker location j
w_{max} maximum noise weight per work period
x_{ijk} 1 if worker i is assigned to worker location j in work period k; 0 otherwise
y_i 1 if worker i is assigned; 0 otherwise

yb_v 1 if noise reduction using barrier v is applied; 0 otherwise
yh_{jl} 1 if HPD l is used at worker location j; 0 otherwise
ys_{tu} 1 if noise reduction at machine t using engineering control method u is applied; 0 otherwise
z number of HPD types

For a workplace where workers are present at various locations during an 8-hour workday, it is necessary to determine an 8-hour time-weighted average (8-hour TWA) sound level that each worker receives. A formula to determine an 8-hour TWA for worker i is

$$W_i = 16.61\left[\log_{10}\left\{\sum_{j=1}^{n}\frac{C_j}{8}\left(2^{\frac{\overline{L}_j-90}{5}}\right)\right\}\right]+90 \qquad (1)$$

At worker location j, its noise weight per work period can be determined from the combined noise level $\overline{L}_j$ as follows.

$$w_j = \frac{1}{p}\times 2^{\left(\frac{\overline{L}_j-90}{5}\right)} \qquad (2)$$

To prevent the daily noise exposure from exceeding 90 dBA, the total noise weight that any worker receives within an 8-hour workday must not be greater than 1.

3.1 Models of Engineering Controls

Here, we consider only controlling at the machine and controlling along the path (blocking the noise transmission path by a barrier). Controlling at the machine implies that the machine noise is reduced, and all worker locations will benefit from such noise control. Controlling along the path, however, will reduce the noise levels at those worker locations where the barrier can block the noise transmission path).

The first model (E1) is a cost-based model that is intended to *minimize the total cost* when applying feasible engineering controls (i.e., reducing the machine noise and/or blocking the noise transmission path by a barrier) such that the combined noise level at any worker location does not exceed 90 dBA. The second model (E2) is a safety-based model that is intended to *minimize the maximum noise weight per work period* among all worker location j's such that the resulting total cost does not exceed the allocated engineering control budget EB.

Model E1: Minimizing the Total Cost of Engineering Controls

Minimize $\left[\sum_{t=1}^{q}\sum_{u=1}^{r}\left(cs_{tu}\times ys_{tu}\right)+\sum_{v=1}^{s}\left(cb_v\times yb_v\right)\right]$

subject to

$$w_j \leq \frac{1}{p} \qquad j = 1, \ldots, n$$

$$\overline{L}_j = 10 \log \left[10^{\left(\frac{L_{ab} - 120}{10} \right)} + \sum_{t=1}^{q} \frac{10^{\left(\frac{L'_t - 120}{10} \right)}}{d_{tj}^2} \right] + 120$$

$$- \sum_{v=1}^{s} NRb_{jv} yb_v \qquad j = 1, \ldots, n$$

$$L'_t = L_t - \sum_{u=1}^{r} NRs_{tu} ys_{tu} \qquad t = 1, \ldots, q$$

$$ys_{tu}, yb_v = \{0, 1\} \qquad \forall t, u, v$$

Model E2: Minimizing the Maximum Noise Weight per Work Period

Minimize $\quad w_{max}$

$$w_j \leq w_{max} \qquad j = 1, \ldots, n$$

$$\left[\sum_{t=1}^{q} \sum_{u=1}^{r} \left(cs_{tu} \times ys_{tu} \right) + \sum_{v=1}^{s} \left(cb_v \times yb_v \right) \right] \leq EB$$

$$\overline{L}_j = 10 \log \left[10^{\left(\frac{L_{ab} - 120}{10} \right)} + \sum_{t=1}^{q} \frac{10^{\left(\frac{L'_t - 120}{10} \right)}}{d_{tj}^2} \right] + 120$$

$$- \sum_{v=1}^{s} NRb_{jv} yb_v \qquad j = 1, \ldots, n$$

$$L'_t = L_t - \sum_{u=1}^{r} NRs_{tu} ys_{tu} \qquad t = 1, \ldots, q$$

$$ys_{tu}, yb_v = \{0, 1\} \qquad \forall t, u, v$$

3.2 Models of Administrative Controls

Since job rotation has been widely recommended in the literature and the mathematical models of the job rotation problem are available, we therefore consider only job rotation as an effective means for administrative control in this paper. Its objective is to rotate workers among worker locations so that the maximum daily noise exposure that any worker receives does not exceed 90 dB*A*.

The following assumptions are required for the application of job rotation.
1. The maximum work duration (for workers and machines) per day is eight hours.
2. A workday can be divided into p periods. Job rotation occurs at the end of the work period.
3. Each worker location requires only one worker to attend per work period.
4. Each worker can attend only one worker location per work period.

5. The worker's efficiency is independent of the task that he/she is assigned to perform. Similarly, the task output is independent of the worker.

The first model (A1) is intended to determine a set of feasible work assignments for the current workforce such that the total worker-location changeover is minimized. The worker-location changeover occurs when a worker moves from one worker location to another. To some extent, productivity might be affected due to possible needs for learning and adapting to a new task. Thus, it is necessary to keep the number of worker-location changeovers as few as possible.

The second model (A2) considers the situation in which more workers are required for job rotation due to excessive noise levels in the workplace. The model objective is to determine a minimum number of workers (in the workforce) to be rotated among the given worker locations such that none of the workers receives the daily noise exposure beyond 90 dB*A*.

It is worth noting that the models of administrative controls do not consider costs since such controls do not need any equipment investment or workplace modification. It is assumed that any incurred costs due to a decline in productivity will be absorbed by the production department. In a case where more workers are needed for job rotation, it is also assumed that they are existing workers (perhaps from other departments), not new workers. If job training is required, the training cost will be absorbed by the human resource department.

Model A1: Minimizing the Total Worker-Location Changeover

At worker location j, a formula to determine the number of worker-location changeovers f_j is

$$f_j = \sum_{k=1}^{p-1} \left[1 - \sum_{i=1}^{m} \left(x_{ijk} \times x_{i,j,k+1} \right) \right] \quad j = 1, \ldots, n \quad (3)$$

For all n locations, the total worker-location changeover F is

$$F = \sum_{j=1}^{n} \sum_{k=1}^{p-1} \left[1 - \sum_{i=1}^{m} \left(x_{ijk} \times x_{i,j,k+1} \right) \right] \quad (4)$$

Model A1 can be expressed as follows.

Minimize $\quad \sum_{j=1}^{n} \sum_{k=1}^{p-1} \left[1 - \sum_{i=1}^{m} \left(x_{ijk} \times x_{i,j,k+1} \right) \right]$

subject to

$$\sum_{j=1}^{n} \sum_{k=1}^{p} w_j x_{ijk} \leq 1 \qquad i = 1, \ldots, m$$

$$\sum_{j=1}^{n} x_{ijk} = 1 \qquad i = 1, \ldots, m; k = 1, \ldots, p$$

$$\sum_{i=1}^{m} x_{ijk} \quad = \quad 1 \qquad\qquad j = 1,\ldots, n;\, k = 1,\ldots, p$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} x_{ijk} \quad \leq \quad p \qquad\qquad i = 1,\ldots, m$$

$$x_{ijk} \quad = \quad \{0, 1\} \qquad\qquad \forall i, j, k$$

Model A2: Minimizing the Number of Workers in the Feasible Workforce

Letting M be the number of available workers in the workforce where $M > n$, model A2 can be expressed as follows.

Minimize $\qquad \sum_{i=1}^{M} y_i$

subject to

$$\sum_{j=1}^{n}\sum_{k=1}^{p} w_j x_{ijk} \quad \leq \quad y_i \qquad\qquad i = 1,\ldots, M$$

$$\sum_{j=1}^{n} x_{ijk} \quad \leq \quad 1 \qquad\qquad i = 1,\ldots, M;\, k = 1,\ldots, p$$

$$\sum_{i=1}^{M} x_{ijk} \quad = \quad 1 \qquad\qquad j = 1,\ldots, n;\, k = 1,\ldots, p$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} x_{ijk} \quad \leq p \cdot y_i \qquad\qquad i = 1,\ldots, M$$

$$x_{ijk}, y_i \quad = \quad \{0, 1\} \qquad\qquad \forall i, j, k$$

3.3   Models of the Selection of HPDs

If the use of HPDs is necessary, the number of worker locations where HPDs are required should be as few as possible. In practice, HPDs should be worn at the worker locations that are very noisy only. Two mathematical models for selecting appropriate HPDs are developed as shown below. Note that both models consider job rotation and the use of HPDs concurrently.

The first model, H1, is intended to determine a minimum number of HPDs based on the given HPD budget HB and the number of workers m (current workforce). The model also yields the type of HPD and the worker location where HPD must be worn. The second model, H2, is used to determine a minimum number of HPDs when all available workers M are considered for job rotation.

Model H1: Minimizing the Number of HPDs for the Current Workforce

Minimize $\qquad \sum_{j=1}^{n}\sum_{l=1}^{z} yh_{jl}$

subject to

$$\sum_{j=1}^{n}\sum_{l=1}^{z} yh_{jl} \cdot ch_l \quad \leq \quad HB$$

$$\sum_{l=1}^{z} yh_{jl} \quad \leq \quad 1 \qquad\qquad j = 1,\ldots, n$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} \frac{1}{p} \cdot 2^{\left(\frac{\bar{L}_j - 90 - \sum_{l=1}^{z} NRh_l \cdot yh_{jl}}{5}\right)} \cdot x_{ijk} \quad \leq \quad 1 \quad i = 1,\ldots, m$$

$$\sum_{j=1}^{n} x_{ijk} \quad = \quad 1 \qquad\qquad i = 1,\ldots, m;\, k = 1,\ldots, p$$

$$\sum_{i=1}^{m} x_{ijk} \quad = \quad 1 \qquad\qquad j = 1,\ldots, n;\, k = 1,\ldots, p$$

$$x_{ijk}, yh_{jl} \quad = \quad \{0, 1\} \qquad\qquad \forall i, j, k, l$$

Model H2: Minimizing the Number of HPDs with $n \leq m \leq M$

Minimize $\qquad \sum_{j=1}^{n}\sum_{l=1}^{z} yh_{jl}$

subject to

$$\sum_{j=1}^{n}\sum_{l=1}^{z} yh_{jl} \cdot ch_l \quad \leq HB$$

$$\sum_{l=1}^{z} yh_{jl} \quad \leq 1 \qquad\qquad j = 1,\ldots, n$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} \frac{1}{p} \cdot 2^{\left(\frac{\bar{L}_j - 90 - \sum_{l=1}^{z} NRh_l \cdot yh_{jl}}{5}\right)} \cdot x_{ijk} \quad \leq 1 \quad i = 1,\ldots, M$$

$$\sum_{j=1}^{n} x_{ijk} \quad \leq \quad 1 \qquad\qquad i = 1,\ldots, M;\, k = 1,\ldots, p$$

$$\sum_{i=1}^{M} x_{ijk} \quad = \quad 1 \qquad\qquad j = 1,\ldots, n;\, k = 1,\ldots, p$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} x_{ijk} \quad \leq \quad p \cdot y_i \qquad\qquad i = 1,\ldots, M$$

$$x_{ijk}, y_i, yh_{jl} \quad = \quad \{0, 1\} \qquad\qquad \forall i, j, k, l$$

4.   DESIGN PROCEDURES

Three analytical procedures for designing a noise hazard prevention program are presented in this section. They are: (1) engineering-based procedure, (2) HPD-based procedure, and (3) mixed procedure.

Initially, it is necessary to obtain the following in-

put data.

- number of work periods per workday
- combined noise level at each worker location
- ambient noise level
- noise level generated by each machine (at 1-m distance)
- feasible methods for reducing noise at the source for each machine, costs, and levels of noise reduced
- feasible methods for blocking the noise transmission path, costs, and levels of noise reduced at affected worker locations
- types of HPD, costs, and noise reduction ratings

4.1 Engineering-based Procedure

The engineering-based procedure for designing a noise hazard prevention program focuses only on engineering controls. The procedure aims to find a set of engineering controls that are able to prevent the workers' noise exposures from exceeding 90 dBA with a minimum total noise control cost. Note that job rotation and the use of HPDs are not considered in this procedure.

Model E1 is applied to determine the minimum total noise control cost for engineering controls. The resulting total cost is viewed as an upper bound of the total noise control budget. Based on the given noise data, the engineering-based procedure recommends a set of feasible engineering controls for controlling noise levels at a minimum total cost.

4.2 HPD-based Procedure

The HPD-based procedure is the opposite of the engineering-based procedure. It is intended to find a set of HPDs to be worn at the worker locations to safely limit the workers' noise exposures. Engineering controls and job rotation are not considered in this procedure.

The procedure evaluates all worker locations and recommends that workers who work at thelocations having the noise levels above 90 dBA wear appropriate HPDs. At each noisy worker location, a feasible HPD with a minimum cost is considered first. If the noise attenuation is insufficient, the more expensive one is then considered. This procedure is repeated for all noisy worker locations.

As a result, the HPD-based procedure yields a lower bound of the total noise control cost.

4.3 Mixed Procedure

The mixed procedure sequentially considers engineering controls, administrative controls, and the use of HPDs. The procedure also follows the OSHA's hierarchy of noise control. Initially, a total budget for a noise

hazard prevention program TB is defined. The budget is divided into two portions, one for engineering controls EB and the other for the use of HPDs HB.

To determine an upper bound of the workforce for job rotation, a heuristic called mFFD developed by Yaoyeunyong and Nanthavanij (2004) is applied. mFFD yields the number of workers that are required for job rotation to prevent their noise exposures from exceeding 90 dBA.

The mixed procedure can be described as follows.

1. Using model E1, find feasible engineering controls for reducing machine noise at the source and for blocking the noise transmission path that will prevent the daily noise exposure at each worker location from exceeding the permissible limit (90 dBA) and find a minimum total cost EC^*. If $EC^* \leq TB$, go to Step 12. Otherwise, proceed to Step 2.
2. Using model E2 and setting $EB = TB$, determine feasible engineering controls that minimize a maximum daily noise exposure among all n worker locations and the total cost EC. Next, assume that such engineering controls are implemented. Determine the new combined noise levels at all worker locations.
3. Apply job rotation to the current workforce (m workers). Using model A1, find a set of work assignments with a minimum total worker-location changeover such that all daily noise exposures do not exceed 90 dBA. If an optimal work assignment solution can be found, go to Step 12. Otherwise, proceed to Step 4.
4. From the number of available workers for job rotation M, use model A2 to find a minimum number of workers to attend all n worker locations on a rotational basis such that their daily noise exposures do not exceed 90 dBA. If an optimal workforce m^* can be found, proceed to Step 5. Otherwise, go to Step 6.
5. With the optimal workforce m^*, set $m = m^*$ and use model A1 again to determine the work assignment solution with the minimum total worker-location changeover. Then, go to Step 12.
6. In a case where engineering controls and job rotation are insufficient for controlling the noise levels, the use of HPDs is next considered. Firstly, use the current workforce (m workers) and the original set of noise data (by discarding the recommended engineering controls in Step 2). Model E2 is utilized one more time with the budget for engineering controls $EB = TB - HB$ to determine a maximum daily noise exposure that any worker receives and the total cost EC. Again, assume that the recommended engineering controls are implemented. Determine the new combined noise levels at all worker locations.
7. Setting the revised HPD budget $HB = TB - EC$ and using the new combined noise levels at all n worker

locations, model H1 is next utilized to determine the work assignment solution with the use of HPDs for m workers, a minimum number of HPDs for the worker locations with excessive noise levels, and the total cost HC. If a feasible solution can be found, proceed to Step 8. Otherwise, go to Step 9.
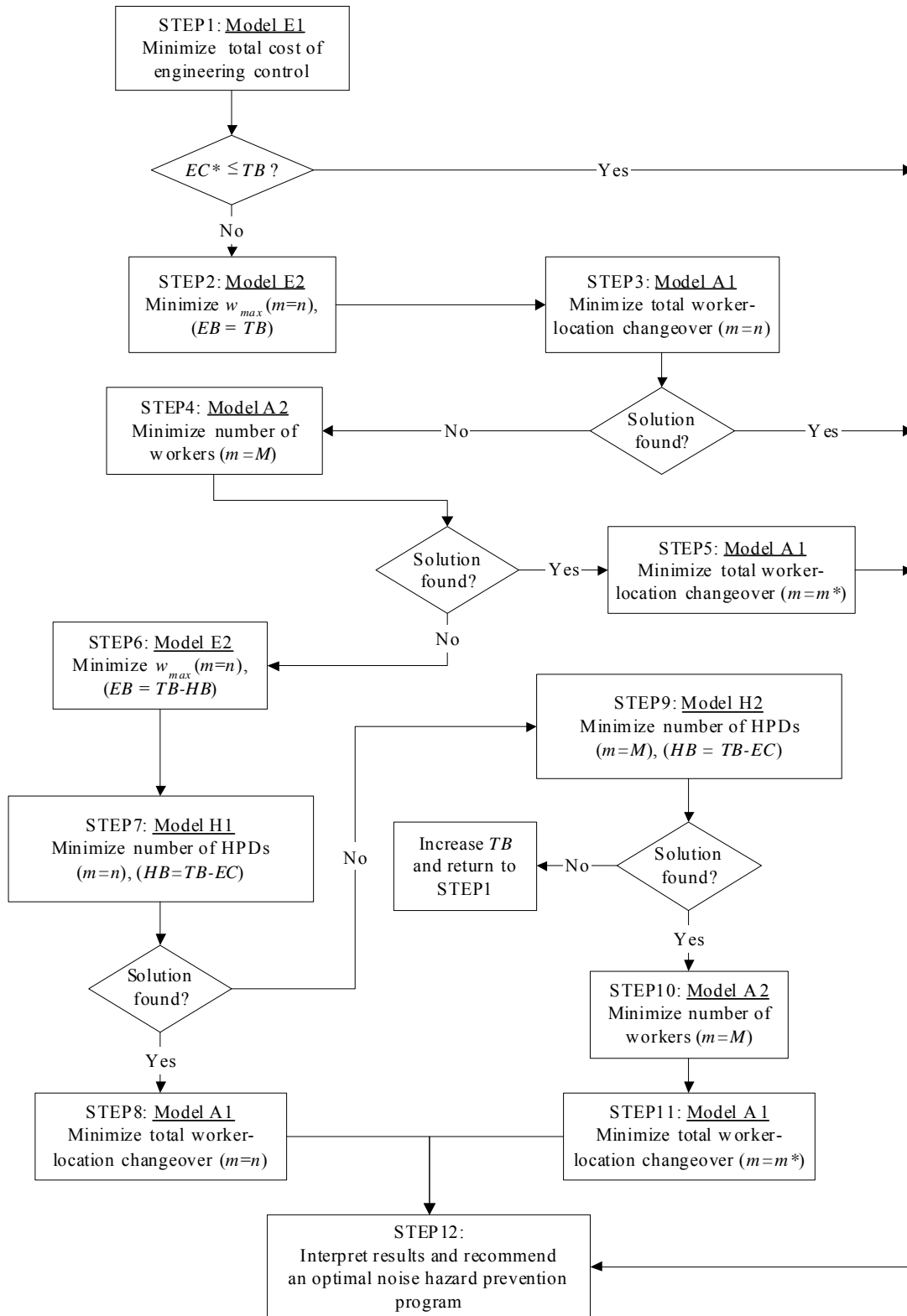

Figure 1. A flow chart depicting the mixed procedure

8. With the use of HPDs at some worker locations, re-compute their noise exposures. Model A1 is then utilized again to determine the work assignment solution with the minimum total worker-location changeover for the new workplace noise data. This step will help to find the solution that not only meets the safety requirement but also helps to enhance the overall productivity. Next, go to Step 12.

9. The use of HPDs is considered with the number of workers $n \leq m \leq M$. Model H2 is utilized to determine not only the work assignment solution with the minimum number of HPDs (based on the HPD budget $HB = TB - EC$) but also the number of workers (from M available workers) for job rotation and their daily work assignments. If the solution (number of HPDs, total cost HC, number of workers for job rotation, work assignments, and noise exposure levels at all worker locations) can be found, go to Step 10. Otherwise, increase the noise control budget TB and, if necessary, revise EB and HB. Then, return to Step 1.

10. Re-compute the noise exposures at worker locations where HPDs are required (from Step 9). Model A2 is utilized again to determine the work assignment solution with the minimum number of workers $m*$ based on the new noise data (with the use of HPDs).

11. Next, set $m = m*$ and use model A1 to determine the work assignment solution (with the use of HPDs) with the minimum total worker-location changeover from Step 10.

12. The result provides an optimal noise hazard prevention program based on the given total budget (and allocated portions for engineering controls and for the use of HPDs). Depending on the given noise data

use of HPDs). Depending on the given noise data and noise control methods, the solution recommends a feasible combination of engineering controls, job rotation, and the use of HPDs that prevent the workers' daily noise exposures from exceeding 90 dBA. Safety, cost, and productivity concerns have also been considered in the mixed procedure.

Figure 1 shows a flow chart that summarizes the mixed procedure.

5. NUMERICAL EXAMPLE

Consider an industrial facility that has five machines (M1, .., M5). At present, there are five workers (W1, …, W5) being assigned to five different worker locations (WL1, …, WL5). If necessary, more workers can be assigned to work in this facility.

Table 1 shows location coordinates of the five machines, machine noise levels, and location coordinates of the five worker locations. The ambient noise level in the facility is assumed to be 70 dBA. Additionally, an 8-hour workday is divided into four equal work periods. From the data, combined noise levels at the five worker locations are found to be 93.44, 92.95, 92.81, 91.78, and 93.40 dBA, respectively. Suppose that each worker is assigned to one worker location and job rotation is not allowed. It is seen that all five workers are exposed to noise hazard and an effective noise hazard prevention program must be implemented.

Table 2 shows methods for reducing machine noise

Table 1. Location coordinates of machines, machine noise levels, and location coordinates of worker locations

Machine	Location Coordinate (m)		Machine Noise (dBA)	Worker Location	Location Coordinate (m)	
	x-coordinate	y-coordinate			x-coordinate	y-coordinate
M1	3.0	2.0	96	WL1	3.0	3.5
M2	6.0	2.0	94	WL2	6.0	3.5
M3	9.0	2.0	95	WL3	9.0	3.5
M4	4.5	6.5	89	WL4	4.5	5.5
M5	7.5	6.5	92	WL5	7.5	5.5

Table 2. Methods for reducing machine noise, costs, and noise attenuation levels

Machine	Method 1		Method 2	
	Cost (Baht*)	Noise Attenuation (dBA)	Cost (Baht)	Noise Attenuation (dBA)
M1	6,000	8	12,000	14
M2	8,500	10	10,500	13
M3	9,000	10	11,000	13
M4	4,000	5	6,000	10
M5	5,000	7	7,500	10

*USD 1.00 is approximately equivalent to 40 baht

at the five machines, costs, and noise attenuation levels. Three types of barrier for blocking the noise transmission path are also available. Type-1 barrier costs 7,500 baht and it reduces the noise levels at worker locations WL1 and WL4 by 9 and 4 dB*A*, respectively. Type-2 barrier costs 10,500 baht. It reduces the noise levels at worker locations WL2, WL4, and WL5 by 9, 3, and 3 dB*A*, respectively. Type-3 barrier costs 7,500 baht. When it is installed, this barrier reduces the noise levels at worker locations WL3 and WL5 by 9 and 4 dB*A*, respectively.

Additionally, there are two types of HPD, type-A and type-B, which can be worn at any of the five worker locations. Type-A HPD costs 200 baht and its NRR is 7 dB*A*. Type-B HPD costs 800 baht and its NRR is 13 dB*A*.

5.1 Engineering−based Noise Hazard Prevention Program

Model E1 is applied to determine a set of feasible engineering controls that prevent the noise levels at the five worker locations from exceeding 90 dB*A* such that the total engineering control cost is minimized. The engineering-based procedure recommends the following noise hazard prevention program.
- Reduce machine noise at machine M2 using engineering control method 1
- Use type-1 barrier and type-3 barrier to block the noise transmission path

As a result, the reduced noise weights per work period at all five worker locations are 0.10927, 0.24517, 0.09916, 0.17217, and 0.22006, respectively. Converting them into 8-hour TWAs using Eq. (2), the noise levels at worker locations WL1, WL2, WL3, WL4, and WL5 are 84.03, 89.86, 83.33, 87.31, and 89.08 dBA, respectively. Additionally, the total noise control cost is found to be 23,500 baht.

5.2 HPD−based Noise Hazard Prevention Program

For this industrial facility, all worker locations have the noise levels that exceed 90 dB*A*. Thus, HPDs must be worn at all five locations. Since the maximum combined noise level is 93.44 dB*A*, it is clear that type-A HPDs (NRR = 7 dB*A*) if worn at all five locations are sufficient in protecting the workers from noise hazard.

Using five type-A HPDs, the total noise control cost is 1,000 baht. The *reduced* noise exposures at the five worker locations are 86.44, 85.95, 85.81, 84.78, and 86.40 dB*A*, respectively.

5.3 Mixed Noise Hazard Prevention Program

Initially, the total budget of a noise hazard prevention program must be defined. Here, we use a rule-of-thumb approach by setting the total budget equal to one-half of the upper bound of the total noise control cost obtained from the engineering-based procedure. For the HPD budget, we use the total noise control cost obtained from the HPD-based procedure. As a result, the total noise hazard prevention budget for the mixed program is set at 11,750 baht, with the HPD budget of 1,000 baht.

Next, an upper bound of the number of workers for job rotation is defined using the mFFD heuristic. Based on the given noise levels at the five worker locations and using Eq. (2), their noise weights per work period are 0.40299, 0.37636, 0.36919, 0.32013 and 0.40058. The mFFD heuristic suggests that eleven workers ($M = 11$) are needed if only job rotation is applied. Readers should note the if some engineering controls have been implemented prior to job rotation, the actual number of workers for job rotation will be fewer than eleven.

After solving model E1 in Step 1, the solution recommends the following engineering controls:
- Reduce machine noise at machine M2 using engineering control method 1
- Install type-1 barrier and type-3 barrier to block the noise transmission path

The *reduced* noise weights per work period at the five worker locations are 0.10927, 0.24517, 0.09916, 0.17217, and 0.22006, respectively. Since each noise weight per period is less than 0.25, the workers' daily noise exposures do not exceed 90 dB*A*. The total noise control cost is 23,500 baht. Since the total cost exceeds the given budget, the solution is infeasible.

Next, model E2 is used to determine a set of engineering controls that will minimize a maximum noise weight per work period under the given total budget (11,750 baht). The new solution recommends that the machine noise levels at machines M1 and M5 be reduced using engineering control method 1, incurring the total cost of 11,000 baht. As a result, the *reduced* noise weights per work period at the five worker locations are 0.19781, 0.32704, 0.34538, 0.27195, and 0.22126, respectively. Since some noise weights per work period still exceed 0.25, noise hazard has not yet been prevented.

Assuming that the above recommendations has been followed, job rotation is next considered with the number of workers $m = 5$ (i.e., the current workforce) using model A1. However, each noise weight per work period is still greater than 0.25. Thus, job rotation with only five workers is insufficient.

With eleven workers who are available for job rotation, model A2 is utilized. The solution not only shows

Table 3. The work assignment solution for six workers (with engineering controls and job rotation)

Worker	Work Period				8-hour TWA (dBA)
	1	2	3	4	
W1	WL4	WL4	WL4	-	88.53
W2	-	WL2	WL2	WL2	89.86
W3	WL1	-	WL3	WL3	89.15
W4	WL3	WL3	-	WL4	89.73
W5	WL5	WL5	WL5	WL5	89.12
W6	WL2	WL1	WL1	WL1	89.40

that only six workers are required ($m^* = 6$) but also generates their safety work assignments. The total worker-location changeover F is found to be 9 times. All daily noise exposures are also below 90 dBA.

To further enhance work efficiency, model A1 is used to determine the work assignment solution with a minimum total worker-location changeover for the six workers. The resulting work assignment solution is shown in Table 3, with the minimum total worker-location changeover $F^* = 4$. Also, all 8-hour TWAs are below 90 dBA.

In summary, an optimal noise hazard prevention program based on the given total budget is as follows.
- Reduce the machine noise levels at machine M1 and M5 using engineering control method 1.
- For six workers, apply job rotation and schedule their work assignments according to those shown in Table 3.

The total noise control cost is found to be 11,000 baht. No HPDs are required at any of the five worker locations.

6. CONCLUSION

In this paper, we explain three analytical procedures for designing a noise hazard prevention program. The program must prevent the daily noise exposure at any worker location from exceeding 90 dBA. An engineering-based procedure emphasizes only engineering controls and, therefore, yields an upper bound of the total noise control cost. An HPD-based procedure, on the other hand, determines an appropriate set of HPDs and the worker locations where the HPDs must be worn. Thus, this procedure gives a lower bound of the total noise control cost. A mixed procedure that follows the OSHA's hierarchy of noise control is developed to design an optimal noise hazard prevention program. Based on a given total budget and available workforce for job rotation, the mixed procedure employs six optimization models to determine a set of feasible noise control methods and an optimal work assignment solution such that none of the workers receives the daily noise exposure beyond 90 dBA.

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